Saarland University
Department of Computer Science

A User-Centric QoS Management System for Wireless Home Networks

Dissertation

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Eidesstattliche Versicherung

Hiermit versichere ich an Eides statt, daß ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen order indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet.

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Saarbrücken, ___.___._____ _______________________

(Aleksej Spenst)

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To my beloved wife Svetlana

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Kurzzusammenfassung

Die Entwicklung von Heimnetzwerk-Technologien hat in den letzten Jahren erheblich zugenommen. Allerdings kann die Medienverteilung in drahtlosen Heimnetzen die Qualitätserwartungen des Nutzers immer noch nicht befriedigen. Aufgrund der variablen Bandbreite und der hohen Fehlerrate werden verschiedene Mechanismen im Netzwerk eingesetzt, um ein gewisses Maß an Qualität sicher zu stellen. Im Gegensatz zu den traditionellen QoS-Ansätzen, die für Multimedia-Anwendungen auf Grund ihrer strengen Latenz- und Verlust-Anforderungen immer im Voraus festgelegte hohe Prioritäten ansetzen, klassifiziert das vorgeschlagene Konzept Netzwerk-Verkehr nach Benutzereinstellungen, um eine bestimmte Qualität, unabhängig von den Anwendungsanforderungen zu garantieren. Die QoS Netzwerkkonfiguration wird nach Benutzerprofilen durchgeführt und im Falle von Änderungen in der Netzwerk- oder Nutzerumgebung automatisch aktualisiert. Gesondert von der vorgeschlagenen Architektur, einschließlich Systemkomponenten, Kommunikationsschnittstellen und QoS-Strategie basiertem Management, erweitern wir das System mit Ansätzen zur Zugangskontrolle für die flexible Regelung der Zugriffe auf das Netzwerk. Die Implementierung sowie experimentelle Ergebnisse demonstrieren praktische Anwendungen und Vorteile des vorgeschlagenen Konzepts auf dem Gebiet des drahtlosen Heimnetzwerks.

Short Abstract

The popularity of home networking technologies has been considerably increased in recent years. However, media distribution is still not ready to satisfy users' quality expectations in wireless home networks. Due to bandwidth variations and high error rates, a number of Quality of Service (QoS) mechanisms have to be deployed in the network in order to guarantee a certain level of quality. In this work, we study a user-centric QoS management approach aimed at providing QoS services primarily satisfying user requirements rather than traffic constraints. Unlike traditional QoS approaches that always give multimedia applications pre-determined high priority due to their strict latency and loss requirements, the proposed approach classifies traffic according to user preferences, thereby ensuring a certain quality regardless of the application requirements. The QoS network configuration is performed according to user profiles and automatically updated in case of changes in the network or user environment. Apart from the proposed architecture including system components, communication interfaces and QoS policy-based management, we enhanced the system with an admission control approach aimed at flexible regulating of traffic load on the network. The implementation details and experimental results demonstrate practical applications and advantages of the proposed approaches in wireless home networks.

Zusammenfassung

Heimnetzwerke werden immer beliebter, um digitale Medieninhalte im Haushalt zu verteilen und zu konsumieren. Viele Standard-Entwicklungsorganisationen (z. B. DLNA, UPnP, DVB), Unternehmen und Forscher arbeiten an neuen Lösungen, um die Anforderungen moderner und zukünftiger Anwendungen zu erfüllen und das Anwender-Erlebnis im Heinetzwerk zu verbessern. Allerdings kann die Medienverteilung in drahtlosen Heimnetzen die Qualitätserwartungen des Nutzers immer noch nicht befriedigen. Aufgrund der variablen Bandbreite und der hohen Fehlerrate werden verschiedene Mechanismen im Netzwerk eingesetzt, um ein gewisses Maß an Qualität sicher zu stellen. Derzeit beruhen drahtlose Heimnetzwerke im Allgemeinen auf der Klassifizierung von Paketen auf einer Per-Strom Basis und der Priorisierung einzelner Stromtypen übereinander. Dadurch wird sicher gesetellt, dass die Pakete mit hoher Priorität vor den Paketen mit niedrigerer Priorität übertragen werden. Allerdings entspricht diese klassenbasierte Priorisierung möglicherweise nicht der Ansicht des End-Benutzers über die relative Bedeutung einer bestimmten Dienstleistung. In zukünftigen Heimnetzwerken sollte ein Benutzer die Services nicht auf Grundlge der Stromtypen unterscheiden, sondern auf Grundlage anderer Kriterien, wie verschiedene Benutzereinstellungen, Benutzeraktivitäten oder Servicepreisen. Es kann zum Beispiel nur der Nutzer selbst entscheiden, welche Dienstleistung für ihn im Neztwerk wichtig ist: Ob es ein Datei-Download ist oder eine Nachrichtensendung, die im Hintergrund läuft. Daher können traditionelle Ansätze für das Netzwerkmanagement, die ausschließlich auf den Anforderungen von Traffic Types basieren, die Anforderungen für ein zukünftiges Heimnetzwerk, in dem die Höhe der Dienstgüte einer Anwendung durch ihren Wert für den Nutzer statt nach den Netzwerkanforderungen bestimmt wird, nicht mehr erfüllen. Wir schlagen deswegen einen Nutzer zentrierten Ansatz für das QoS-Management vor, der darauf zielt, QoS-Dienste anzubieten, die eher Benutzeranforderungen als Traffic Constraints erfüllen. Im Gegensatz zu den traditionellen QoS-Ansätzen, die für Multimedia-Anwendungen auf Grund ihrer strengen Latenz- und Verlust-Anforderungen immer im Voraus festgelegte hohe Prioritäten ansetzen, klassifiziert das vorgeschlagene Konzept Verkehr nach Benutzereinstellungen, um eine bestimmte Qualität, unabhängig von den

Anwendungsanforderungen zu garantieren. Die QoS-Netzwerkkonfiguration wird nach Benutzerprofilen durchgeführt und im Falle von Änderungen in der Netzwerk- oder Nutzerumgebung automatisch aktualisiert.

Gesondert von der vorgeschlagenen Architektur, einschließlich Systemkomponenten, Kommunikationsschnittstellen und QoS-Strategie basiertem Management, erweitern wir das System mit Ansätzen zur Zugangskontrolle (Admission Control) für die flexible Regelung der Zugriffe auf das Netzwerk. Im Allgemeinen erachtet man heutzutage Zugangskontrolle als das einzige Mittel, die Überlastung des Netzes zu verhindern, und sieht sie als eine Grundlage für eine erweiterte QoS-Lösung. Die Standard-Entwicklungsorganisationen wie UPnP, DVB und DLNA definieren Standards, mit Anforderungen und architektonischen Lösungen in Bezug auf die Zugangskontrolle für Heimnetzwerke. Die Designphilosophie des in dieser Arbeit vorgeschlagenen Ansatzes ist eine sogenannte Post-Admission Control. Das bedeutet, dass alle Neztwerk-Zugriffe zunächst zugelassen werden. Die Regeln der Admission Control werden nur dann durchgesetzt, wenn die Netzwerkbelastung eine bestimmte Schwelle überschreitet. Mögliche Regeln für die Zugangskontrolle können unterschiedlich konfiguriert werden. Man kann beispielsweise die Priorität für einige Ströme ändern oder einige Ströme stoppen. Wenn sich der Zustand des Netzes verbessert hat, können die zuvor abgelehnten Ströme (oder Ströme mit reduzierter Priorität) automatisch wieder mit dem ursprünglichen Service-Level gestartet werden. Insgesamt bietet die vorgestellte Zugangskontrolle ein gutes Mittel zur Vermeidung von überlasteten Netzwerken und zur Verbesserung der Dienstleistungen zugelassener Anwendungen.

Um weitere Probleme im Zusammenhang mit Aufgaben der Zugangskontrolle auf dem Gebiet der drahtlosen Netzwerke zu begreifen, haben wir ein analytisches Modell der Enhanced Distributed Channel Access (EDCA) Funktion für Durchsatz-Schätzungen in 802.11e-basierten Netzwerken entwickelt. Das Modell kann für die Aufgaben der Zugangskontrolle nützlich sein, wenn es notwendig ist, zu schätzen, wie viel Bandbreite im Netz verfügbar ist, wenn eine neue Anfrage zugelassen wird. Normalerweise ist dies nicht einfach, da das Hinzufügen eines Stroms in einer der 802.11e Access Categories die Netzwerkbelastung in anderen Access Categories in nicht-linearer Weise beeinflusst. Die experimentellen Ergebnisse zeigen, dass das analytische Modell sehr gut mit den praktischen Messungen übereinstimmt.

Die Ergebnisse der Forschung in dieser Arbeit wurden implementiert und in der Praxis validiert. Die implementierten Softwarepakete umfassen die Umsetzung des User-centric QoS Managementsystems mit der Post-Admission Control Methode und die Umsetzung von Graphical User Interfaces (GUI), die komfortable Konfigurationsschnittstellen für einen Netzwerknutzer im Haus bieten. Die Implementierung sowie experimentelle Ergebnisse demonstrieren praktische Anwendungen und Vorteile des vorgeschlagenen Konzepts auf dem Gebiet des drahtlosen Heimnetzwerkes.

Die Hauptergebnisse dieser Arbeit wurden in mehreren IEEE-Symposien und Workshops in den Jahren 2007-2008 veröffentlicht und auch für die Veröffentlichung in einer der IEEE Journals im Jahr 2009 angenommen.

Abstract

Home networking technologies are becoming very popular for consuming and distributing digital content within the home. Many standards development organizations (e.g. DLNA, UPnP, DVB), companies and researchers work on new solutions for satisfying the requirements of modern and future applications and for improving home users' experience. However, media distribution is not ready yet to satisfy users' quality expectations in wireless home networks. Due to bandwidth variations and high error rates, a number of Quality of Service (QoS) mechanisms have to be deployed in the network in order to guarantee a certain level of quality. Currently, the wireless home networks generally rely on classifying packets on a per-stream basis and prioritizing one stream type over another. This ensures that high-priority packets get transmitted at the expense of lower priority stream types. However, this traffic class based prioritization might not match the end-user's view of relative importance of a particular service. In the forthcoming home networks a user may need to differentiate the services not on the basis of traffic types, but on the basis of other criteria such as different user preferences, current user activities or service prices. For example, only a user can decide which service is more important for him in the network, a file downloading operation or video news clip running in the background. Therefore, traditional network management approaches based entirely on traffic type requirements will no longer satisfy requirements for a future home network where a quality service level of an application will be determined by its value for the user rather than by its network requirements. Thus, we propose a user-centric QoS management approach aimed at providing QoS services primarily satisfying user requirements rather than traffic constraints. Unlike traditional QoS approaches that always give multimedia applications a pre-determined high priority due to their strict latency and loss requirements, the proposed approach classifies traffic according to user preferences, thereby ensuring a certain quality regardless of the application requirements. The QoS network configuration is performed according to user profiles and automatically updated in case of changes in the network or user environment.

Apart from the proposed architecture including system components, communication interfaces and QoS policy-based management, we enhanced the system with an

admission control approach aimed at flexible regulating of traffic load on the network. Many believe today that admission control is the only means to prevent overload of the network and a basis for an advanced QoS solution. The SDOs such as UPnP, DVB and DLNA define standards with requirements and architectural solutions regarding admission control for home networks. The design philosophy of the approach proposed in this thesis is a post-admission control. That is, all traffic is provided with the access to the network and admission control policies are enforced only if the traffic load exceeds a certain threshold. Possible enforcement policies can be configured differently and may include, for example, changing priority for some flows or terminating them. If the state of the network has improved, the previously rejected flows (or flows provided with lower priority than requested) might be automatically granted with the initially requested service level. In overall, the presented admission control approach provides good means for preventing network overload and improving the services for admitted flows on the network.

To further address problems related to admission control tasks in wireless networks, we developed an EDCA analytical model of the Enhanced Distributed Channel Access (EDCA) function for throughput estimations in 802.11e-based networks. The model can be useful for admission control tasks when there is a need to estimate how much bandwidth will be available in the network if a new request is admitted. Normally, it is not a trivial thing to do as adding a stream in one of the 802.11e access categories, influences the traffic load in other access categories in a non-linear way. The experimental results show that the analytical model gives a good match when compared with the practical measurements.

The research achievements presented in this work have been implemented in practice. The implemented software packages include implementation of the user-centric QoS management system with the post-admission control method and implementation of the Graphical User Interfaces (GUIs) providing convenient configuration interfaces for a home network user. The implementation details and experimental results demonstrate practical applications and advantages of the proposed approaches in wireless home networks.

The core results of this work were published in several IEEE symposiums and workshops held in 2007-2008 and also accepted for publication in one of the IEEE journals in 2009.

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Abbreviations

AC	Access Category
ACK	Acknowledgment
ACM	Admission Control Mandatory
ADDTS	Add Traffic Stream
AIFS	Arbitration Interframe Space
AL-FEC	Application Layer Forward Error Correction
AP	Access Point
AF	Assured Forwarding
ATIS	Alliance for Telecommunications Industry Solutions
AV	Audio-Video
BE	Best-effort
BK	Background
CCK	Complementary Code Keying
CE	Consumer Electronics
CFB	Contention Free Bursts
CP	Control Point
CS	Class Selector
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection

CSPR	Content Service Provider Requirements
CTS	Clear to Send
CW	Contention Window
DA	Device Architecture
DCF	Distributed Coordination Function
DELTS	DELete Traffic Stream
DHCL	Digital Home Compliance and Test Lab
DiffServ	Differentiated Services
DIFS	Distributed Inter-Frame Space
DLNA	Digital Living Network Alliance
DSCP	Differentiated Services Code Point
DSL	Digital Subscriber Line
DSSS	Direct Sequence Spread Spectrum
DVB	Digital Video Broadcasting
DVB-C	Digital Video Broadcasting-Cable
DVB-H	Digital Video Broadcasting-Handhelds
DVB-S	Digital Video Broadcasting-Satellite
DVB-T	Digital Video Broadcasting-Terrestrial
DVD	Digital Versatile Disc
EBU	European Broadcasting Union
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunications Standards Institute

EF	Expedited Forwarding
FCFS	First Come First Serve
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
GENA	General Event Notification Architecture
GUI	Graphical User Interface
HCF	Hybrid Coordination Function
HC	Hybrid Coordinator
HCCA	HCF Controlled Channel Access
HDTV	High Definition Television
HGI	Home Gateway Initiative
HN	Home Network
HNED	Home Network End Device
HomePNA	Home Phoneline Networking Alliance
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
IPI	Internet Protocol Infrastructures
IPTV	IP Television
IR	Infrared
ITU	International Telecommunication Union

ITU-T	International Telecommunication Union-Telecommunication
LAN	Local Area Network
LCFS	Last Come First Serve
LLC	Logical Link Control
MIMO	Multiple Input Multiple Output
MoCA	Multimedia over Coax Alliance
MOS	Mean Opinion Score
MPEG	Moving Pictures Experts Group
MPLS	Multi-Protocol Label Switching
MSDU	MAC Service Data Unit
OFDM	Orthogonal Frequency-Division Multiplexing
OSI	Open Systems Interconnection
PCF	Point Coordination Function
PCR	Program Clock Reference
PER	Packet Error Rate
PHB	Per-Hop Behavior
PHY	Physical layer
QoE	Quality of Experience
QoS	Quality of Service
RTS	Request to Send
SD	Standard Definition
SDO	Standard Developing Organization

SDTV	Standard Definition Television
SIFS	Short Inter-Frame Space
SOAP	Simple Object Access Protocol
SSDP	Simple Service Discovery Protocol
STB	Set-Top Box
SVC	Scalable Video Codec
TCP	Transmission Control Protocol
TISPAN	Telecommunication and Internet converged Services and Protocols for Advanced Networking
TM	Technical Module
ToS	Type of Service
TSPEC	Traffic Specifications
TXOP	Transmission Opportunity
TV	Television
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
UPnP	Universal Plug and Play
VI	Video
VHT	Very High Throughput
VO	Voice
VoD	Video on Demand
VoIP	Voice over IP
W3C	World Wide Web Consortium

Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMM	Wi-Fi Multimedia
WMM-SA	WMM-Scheduled Access
XML	eXtensible Markup Language

1 Introduction

1.1 Introduction

The large-scale growth in digital services over the last years has increased the need to find new solutions for distributing digital media content around the home. In the near future the home networks will have to satisfy a number of users when delivering audio, video and data services. Multiple users with different activities and service requirements will share the home network to get the broadband, broadcast and local network services. There have been many efforts in the past made by a number of Standards Development Organizations (SDOs) to define new solutions and standards for home networking. Some SDOs play today a crucial role in the development of the home networking technologies. The SDOs such as Universal Plug and Play (UPnP)[1], Digital Living Network Alliance (DLNA)[2], and Digital Video Broadcasting (DVB)[3] are currently working in tight collaboration with each other on defining interoperable solutions for wide-spread adoption of different home network devices and technologies. New wireline and wireless standards for home networking are under development. Even though wireless technologies have become more mature and popular, the wired medium still remains more reliable for video transmission. The existing wireless networks are not ready yet to satisfy users' quality expectations in spite of the fact that the modern technology offers attractive wireless solutions with high throughput performance. Due to fading, interference, noise and user mobility, error-free distribution of high quality multimedia services over wireless is still a challenging task. To improve user experience in wireless home networks, a number of Quality of Service (QoS) mechanisms have to be deployed in the network in order to guarantee a certain level of quality. Since wireless networks have always suffered with respect to QoS, the interest to resolve the respective problems has been very strong and many QoS mechanisms have already been proposed at different levels of the protocol stack.

[1] UPnP Forum, http://www.upnp.org
[2] The Digital Living Network Alliance website, http://www.dlna.org/
[3] Digital Video Broadcasting (DVB) project, http://www.dvb.org

For successful development and common adoption of the wireless home networks with enhanced QoS support, there is a need in the development of a unique and standardized QoS management solution considering how to manage the home network traffic based on the existing and new QoS mechanisms. The UPnP forum has recently made a big step forward by defining a general architecture for QoS management in the home networks [35]. There has been also an effort in DVB on defining a home network QoS functional reference model published lately as a DVB Blue Book [37]. The proposed UPnP QoS architecture and DVB QoS reference model do not propose new QoS mechanisms. Rather, they offer high level management solutions defining how to manage QoS in home networks. Therefore, these proposals do not address the peculiarities of the underlying technologies such as specific problems in wireless networks. Neither do they propose any policy strategies with respect to how to manage particular traffic and QoS requests on the network such that the user experience is improved. The work presented in this thesis, therefore, proposes various solutions for improving user experience in wireless home networks. Taking into account home users' requirements and following the last research and industrial trends towards designing user-centric media solutions [49], [50], [54], we developed a user-centric QoS management system for wireless home networks. Unlike traditional QoS approaches that are traffic and network oriented, the proposed solution is aimed at managing the traffic on the home network according to user preferences, thus, ensuring a certain quality regardless of the application and network requirements and improving the overall user experience.

1.2 Definition of QoS

The main subject of this work is related to Quality of Service (QoS) problems in wireless home networks. Throughout the thesis we extensively review various aspects of QoS including QoS fundamentals, its mechanisms and management approaches. For introductory purposes, a brief definition of QoS is also given in this section below.

QoS is usually defined as a measure of how well the delivery requirements of a particular content are fulfilled in terms of timeliness, error rate, reliability, etc. [37]. QoS refers also to the capability of a network to meet these requirements. For example, QoS capabilities of a network can include a set of mechanisms aimed at providing different priority levels to different applications, users or data flows in order to guarantee a differentiated level of quality. QoS guarantees are very important if network capacity is highly variable or insufficient for all applications. The modern network services such as IPTV, Video on Demand (VoD) and online games require strict QoS guarantees as these services often have fixed bit rate and tight delay constraints. Meeting such requirements in wireless networks is still a demanding task and active research topic of many papers over the last decade.

Whereas QoS is a measure of performance at the packet level from the network perspective, Quality of Experience (QoE) is a measure of end-to-end performance at the service level from the user perspective. QoE refers to the quality that an end-user perceives while consuming the service. Therefore, the level of delivered QoE is usually measured at the level of an individual application stream consumed by a user. One of the QoE measurement metrics is the Mean Opinion Score (MOS) that is used as a subjective measure to evaluate the quality of user experience. The measurement of MOS might be quite difficult as it is a purely subjective measure also influenced by the user's end device, environment, the nature of the content and other criteria. The objective metrics of QoE such as duration of periods of degraded service provide less information but may be easier to measure. Assessment of QoE using objective and subjective measures and relationship between network level QoS measures and user-perceived QoE are currently challenging research tasks. The extensive overview of the QoE engineering concepts and approaches is given in [100].

The contributions presented in this thesis can be considered as extensions to the existing QoS mechanisms and management approaches that are aimed at improving overall QoE of the home end users in wireless networks.

1.3 State of the art

Even though there are many QoS mechanisms proposed for wireless networks, the only QoS technique broadly implemented today in wireless networks is Wi-Fi Multimedia (WMM) [28] that mainly provides prioritization of traffic based on the IEEE 802.11e standard [30]. Therefore, the modern wireless home networks generally rely on classifying packets on a per-stream basis and prioritizing one stream type over another. This has the effect of ensuring that high-priority packets get transmitted at the expense of lower priority stream types. With this regard, it is important to note that the following problems still exist.

- This stream type or traffic class based prioritization might not match the end-user's view of relative importance of a particular service. The problem is that in the forthcoming home networks a user may need to differentiate the services not on the basis of traffic types (all traffic can be, for example, video traffic), but on the basis of other criteria such as different user preferences, current user activities or service prices. For instance, a user watching sports broadcast video while listening to the online news radio station may consider one more important than the other. Therefore, traditional network management approaches based entirely on traffic type requirements will no longer satisfy requirements for a future home network where a quality service level of an application will be determined by its value for the user rather than by its network requirements. Thus, an advanced management approach is required to address the user specific needs in the network.
- All streams of a particular type (also of high priority) might be impacted if the aggregate network demand exceeds capacity. For example, if the network is saturated with the high priority video traffic and the sum of transmission rates of all the flows is greater than the channel capacity, heavy channel contention occurs and QoS cannot be guaranteed for any flow. To cope with this problem, admission control mechanisms are needed for preventing network saturation and for maintaining the quality for already admitted services.

Therefore, it is acknowledged by many that more advanced QoS capabilities are required for the reliable carriage of future services across home networks. The SDOs such as UPnP, DVB and DLNA are working at present on standards with requirements and architectural solutions addressing the above stated problems. UPnP has recently completed the work on a QoS v3 architecture [35] that includes an admission control solution. UPnP QoS defines also means with the help of which a user can indicate an importance value of a service in relation to other services. DVB has also defined admission control functionality in its QoS functional reference model [37] and a concept of importance for indicating a value of the content in relation to other content flowing over the home network. DLNA has defined functional QoS requirements with respect to admission control as well. The SDOs, however, do not specify how exactly admission control should be implemented at the low levels, for example in wireless networks. They also do not define any network policies describing how to manage the traffic for example according to user preferences. The standards and requirements are meant to provoke developers and service providers to work out different technical solutions for forthcoming home network technologies. That is why it is very timely and important for us to provide a more advanced solution for wireless home networks.

1.4 Thesis contributions

While working on the problems described above, we have extended the current state of the art with the following main contributions.

- We developed the ***precedence model***, which is a QoS model that dynamically manages the service levels (precedence levels) of flows based on user preferences and user behavior. The precedence model includes definitions of user profiles and user usability rules expressed in terms of policy rules. Depending on the user profile each flow is assigned a precedence level that determines the level of service it receives. The model defines how to map user preferences to network precedence levels and how to manage precedence levels when certain events happen in the user or network environment. Therefore, the model contributes to defining a solution for future home networks where users will play a crucial role in the overall network management.

- Based on our precedence model we developed a ***user-centric QoS management approach*** for wireless home networks. The structural design of the approach is based on the UPnP QoS architecture [35] that defines components and interfaces for policy-based QoS management in home networks. The UPnP architecture does not, however, define any policy strategies with respect to how to manage particular traffic and QoS requests on the network. We extended this with functionalities and user-centric policy rules of the precedence model. Our management approach identified main components, interfaces and data models that are necessary to be deployed in the network for user-centric capabilities for enhancing QoS and user experience in future wireless home networks.

- To address problems related to admission control tasks in wireless networks, we developed an ***EDCA analytical model*** of the Enhanced Distributed Channel Access (EDCA) function for throughput estimations in 802.11e-based networks. This model is useful for admission control tasks when there is a need to estimate how much bandwidth will be available for each station in the network at a certain priority level if a new request is admitted with a particular priority level. This will make it possible to predict what we will have if we admit a new stream on the network. Normally, it is not a trivial thing to do as adding a stream in one of the 802.11e access categories, influences the traffic load in other access categories in a non-linear way.

- We also developed and implemented a ***post-admission control approach***, which is a measurement-based adaptive admission control method that can be very practical in wireless networks. This contribution addresses the following problem. Due to the variable nature of the wireless medium the network resources available to a service might change any time after the service has been admitted on the network. This might lead to network contention and degradation of all services on the network. This problem is also relevant in the UPnP QoS v3 architecture where a pre-admission control method is defined, which is more suitable for wired networks rather than for wireless. In our developed post-admission control method the enforcement decisions (e.g. downgrading or terminating service) are made after the new services have been provided with access to the network and only in case if the traffic load exceeds a certain threshold. Such approach allows us to continuously keep the network in the non-saturated case and considerably improve network performance for already admitted services.

- Our research achievements have been supported by verifying our proposals in practice. We implemented a number of ***software packages***. These include implementations of the precedence model and user-centric QoS system, Graphical User Interfaces (GUIs) for user-centric QoS system and implementation of the post-admission control method with 2915abg wireless card's driver.

- The core results of this work were published in several IEEE symposiums and workshops held in 2007-2008 and also accepted for publication in one of the IEEE journals in 2009. The full ***list of publications*** is given in Chapter 9.

These and other research and practical achievements are presented further in the thesis.

1.5 Thesis outline

The organisation of the thesis is as follows. Chapter 2 gives an overview of existing and evolving home network technologies and their associated problems. We describe a typical home network environment and Standards Development Organizations (SDOs) actively participating in the continuous progress of home networking. We also discuss the existing and evolving wired and wireless technologies and their applications for home networks.

Chapter 3 is focused on considering QoS problems in wireless home networks and on various solutions that exist today to improve the user experience in wireless networks. We mainly discuss the QoS extensions for the IEEE 802.11 standard and existing efforts in the development of various management QoS solutions for home networks (UPnP QoS, DVB QoS).

In Chapter 4, we present a user-centric QoS management approach. First, we give motivations for the necessity of designing a home network QoS solution in a user-centric way. Then, we introduce a set of use cases describing the desired system's operation and common user activities and requirements in home networks. Next, we present the main features of our user-centric QoS management approach including the precedence model and major architecture components. Finally, we present the demonstration scenarios showing the performance and advantages of the proposed user-centric approach.

In Chapter 5, a simple analytical model for throughput estimations in 802.11e-based networks is presented. The model can be useful for admission control tasks when there is a need to estimate how much bandwidth will be available in the network if a new request is admitted.

Chapter 6 discusses the admission control related problems in wireless networks and introduces a post-admission control approach. According to this approach, all new network applications are always granted network access and admission control decisions are made afterwards with respect to the already running applications. We study the applications of this approach in wireless home networks and present various demonstration scenarios displaying practical benefits for improvement of the overall user experience.

The presented approaches described in the thesis have been implemented in practice. For better understanding of the main functionalities and advantages of the system, some implementation details of our user-centric QoS management system with the post-admission control mechanism are described in Chapter 7.

Finally in Chapter 8, we make conclusions about the presented work and discuss some directions for future work.

The thesis is concluded with a list of publications resulted from this work, which is given in Chapter 9. The interface specifications and class diagrams for the main system's components are included as annexes in Chapters 10 and 11 correspondingly.

2 Modern home networking technologies

2.1 Introduction

The modern home network technologies are evolving to enhance the user's entertainment experience. An important user requirement for the modern network experience is the ability to enjoy multimedia content with appropriate quality from any location in the home, irrespective of where the content is physically stored. Today's home networking technologies provide various means for achieving this type of "anytime, anywhere" access to digital content. In practice however, the distribution of media content and delivered level of quality do not fully meet user requirements, especially in wireless networks. In this chapter, we describe a typical digital home environment relevant in the context of this study, discuss possible home network usage scenarios and provide an overview of existing and evolving home network technologies and their associated problems.

2.2 Leading home networking technologies

Traditionally, Personal Computers (PCs) and Consumer Electronics (CE) devices have been used in the home environment as stand-alone devices. More recently, however, a significant number of homes have acquired multiple PCs and CE devices and developed a strong desire to integrate all digital equipment for easier usage and sharing of personal content. Applications of a home networking include audio and video distribution, network gaming, file and photo sharing. A typical digital home environment is shown in Figure 2.1. Usually, it might include a TV with a Set-Top Box (STB), AV-Receivers, desktop PCs, laptops and printers connected to the home Local Area Network (LAN). The STB is connected to a satellite dish receiver acting in this example as a source for Digital Video Broadcasting-Satellite (DVB-S) content. A Residential Gateway (RG) is usually used for connecting the home network to the

Internet through a broadband pipe. Normally, a wired or wireless router or modem is acting as a RG.

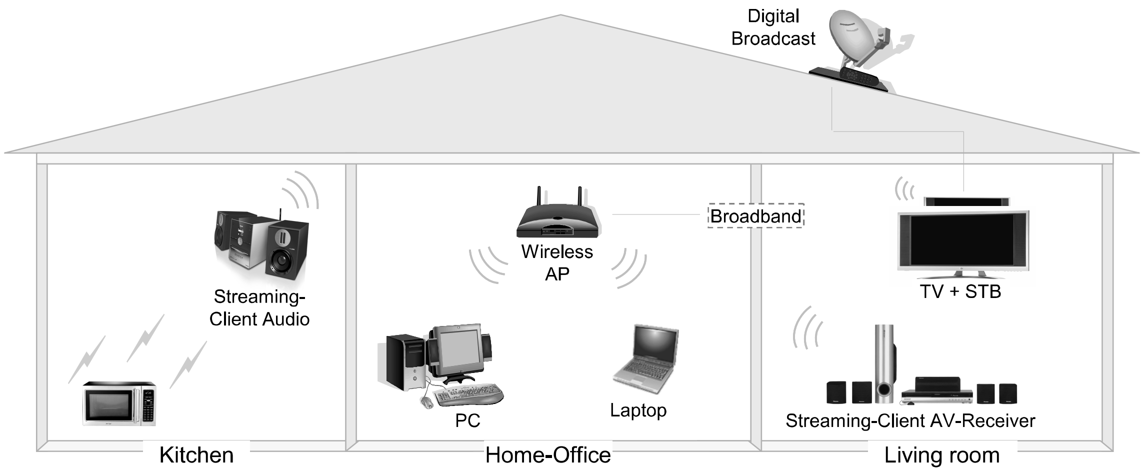


Figure 2.1: Typical digital home environment

As most computers and CE devices are likely located in different rooms and quite possibly on different floors, the wireless technology has become a very popular means for home networking due to its installation simplicity and convenient usage. In this example (Figure 2.1), a wireless access point is used for connecting all digital devices in the home and acting as a RG.

In general, users will expect to run various types of applications and services over the home network:

- Broadband internet connection.
- Reception and recording of TV and radio services via a range of DVB-S/T/C and analog TV tuner cards or via broadband connection (IPTV).
- Streaming of TV signals, DVD films and stored video content within the home network.
- Sharing music, photos and files between computers and CE devices.
- Remote access of live and stored media content and documents from outside the home.
- Network gaming.

When run simultaneously, many applications might experience service degradation due to the temporary lack of bandwidth. Consequently, users might encounter irregular and unacceptable behavior from those applications. There can be many scenarios in home networks when users run into difficulties with respect to the poor quality of the delivered services. These problems related to Quality of Service (QoS) are of great interest for this thesis and considered in more detail in Chapter 3. Other problems of home networking related to installation, device and service discovery, configuration and control are shortly presented below.

Wired and wireless networks most used in homes do not provide, by themselves, simple interconnection of home network devices and sharing of digital content between them. To satisfy the end-user requirements, network devices have to be installable and configurable without any help of a professional installer. This requires home network devices to be self-configurable. Moreover, devices have to be able to automatically discover other devices on the network with which they can communicate. The mass-market adoption of this kind of self-configuring system would be possible if a large number of device manufacturers supported a single interoperability technology that would be also supportable by a wide range of devices. However, most media distribution systems have been traditionally based on custom, end-to-end solutions that use proprietary technologies and network protocols for interconnecting network devices, which prevents such systems from wide-spread adoption. Therefore, there have been many efforts in the past made by a number of Standards Development Organizations (SDOs) to define such interoperable solution. Some SDOs play a crucial role today in evolvement of the home networking technologies. That is why in the next subsections, we present the SDOs that are very active now in developing solutions and defining various standards for home networking.

2.2.1 DLNA

Digital Living Network Alliance (DLNA)[1] is now one of the leading organizations defining the way of how our future digital homes will look like. It is an international, cross-industry collaboration of CE, computing industry and mobile device companies. The main goal of DLNA is creation of a wired and wireless interoperable network of PCs, CE and mobile devices in the home and enabling the easy sharing of new digital media and content services between home network devices. DLNA is focused on working on so called interoperability guidelines that contain a set of internationally recognized open industry standards. The DLNA guidelines specify the building blocks

[1] The Digital Living Network Alliance website, http://www.dlna.org/

(i.e. standards) that vendors have to use for providing compliant products for consumers when developing platforms and software infrastructure (Figure 2.2). The DLNA certified products allow consumers to have an easy “anytime, anywhere” access to digital content. In the DLNA-defined network, consumers can locate digital content anywhere and seamlessly move or stream the content between network devices (Figure 2.3).

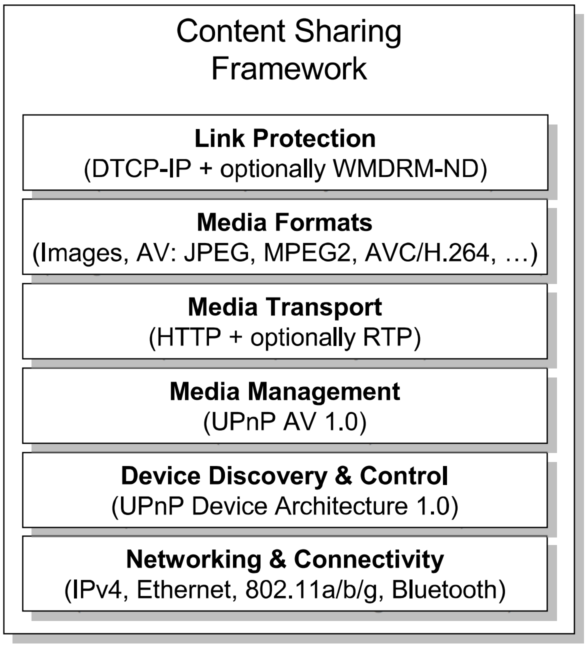


Figure 2.2: DLNA interoperability guidelines building blocks [1]

Originally founded by Intel and Sony in June 2003, the DLNA organization was supported by many other companies and currently it is comprised of more than 200 contributor members and 26 promoter members. DLNA published the first set of interoperability guidelines after one year of its work in June 2004. The initial version addressed the basic home devices acting as content servers and players. The current guidelines extend the capabilities of the DLNA-defined home network to include more device classes and functional capabilities including printers, mobile devices, controllers, etc. (Figure 2.4). Presently, there are more than 2000 DLNA certified products from 29 manufactures, out of which approximately 1000 are publicly listed on the DLNA website.

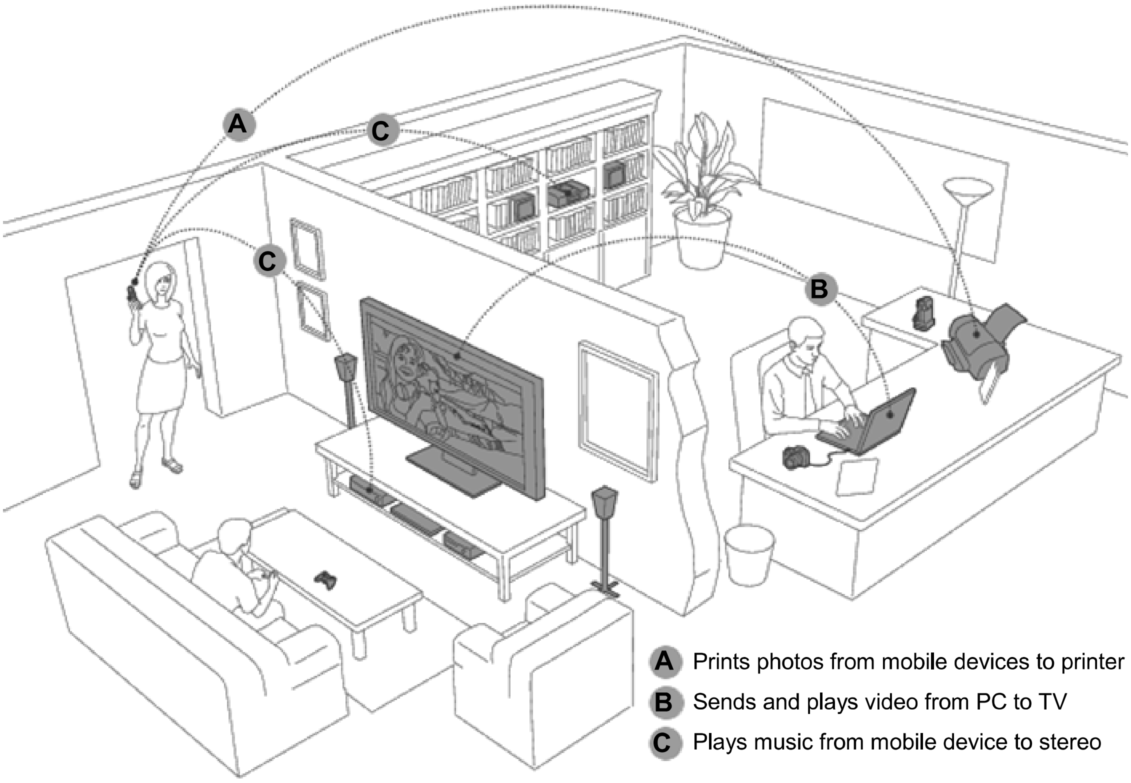


Figure 2.3: DLNA Digital Home [3]

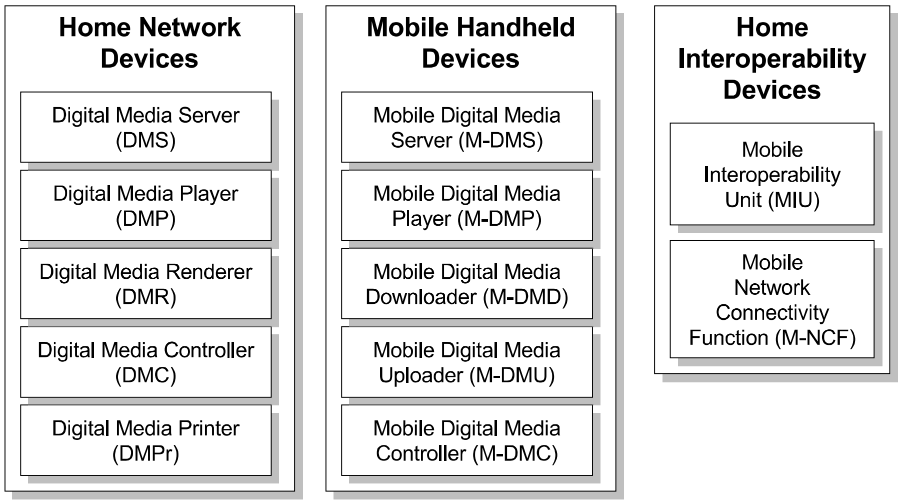


Figure 2.4: DLNA Device categories and device classes [2]

The DLNA architecture for digital home is mainly based on IP networking Universal Plug and Play (UPnP), Internet Engineering Task Force (IETF) and Institute of Electrical and Electronics Engineers (IEEE) technologies. The main building blocks needed to provide the interoperability between devices are depicted in Figure 2.2 and shortly described below.

- **Network connectivity**. For end-to-end connectivity between devices, appropriate layer 2 compatibility and layer 3 routing is defined. The main standards defined for layer 2 and layer 3 connectivity for wired and wireless networks are Ethernet (802.3), Wi-Fi (802.11) and IPv4 protocol suite.

- **Device discovery, configuration and control**. How devices discover other devices and services on the network, how they identify their functions and capabilities and how devices and services are configured is defined by the UPnP Device Architecture [4].

- **Media formats and streaming protocols**. To ensure that media content can be consumed and rendered by all devices in the home network, DLNA defines a set of mandatory and optional media formats for each Device Category for imaging, audio and AV. The devices also need to agree on a common streaming protocol in order to establish media. DLNA devices must mandatorily support HTTP as a transport mechanism and may optionally support RTP.

- **Media management and control**. The exchange and control of media information between devices from different vendors must be properly defined. Identification, management and distribution of media content across devices are addressed in DLNA by UPnP Audio/Video (AV) and UPnP Printer technologies.

- **Compatible QoS**. For enhancing the overall user experience and for taking full advantage of available QoS mechanisms, all devices have to share common usage rules, e.g. for QoS tagging. The DLNA QoS model defines how manufactures have to address QoS in the digital home.

With respect to this thesis the most interesting features of the DLNA network are related to the presently defined and planned for future guidelines QoS mechanisms for wireless home network. The current version of the DLNA interoperability guidelines includes a requirement that for QoS support in wireless networks, Wi-Fi enabled devices must be Wi-Fi Multimedia (WMM) certified [5]. For future guidelines, DLNA plans to include a requirement for UPnP QoS support for DLNA devices [6]. We give a short introduction in UPnP in the next subsection. The QoS issues of DLNA, UPnP and Wi-Fi and their relevance to this thesis are discussed in more detail in Chapter 3.

2.2.2 UPnP

Universal Plug and Play (UPnP) specifications offer an interoperability technology that has been widely accepted and deployed in the industry and also adopted by DLNA for home networks. UPnP is a set of computer network protocols defined by the UPnP Forum[1]. Formed in 1999, the Forum consists now of almost 900 vendors including industry leaders in computing, networking, CE and mobile products. The goal of UPnP is to provide seamless interconnection between various network devices and simplify home network operation with regard to communications, data sharing and entertainment. UPnP is focused on defining and publishing UPnP device control protocols using existing and open Internet standards including IP, TCP, UDP, HTTP, XML, etc. These open standards comprise the communication infrastructure of the UPnP architecture.

In the UPnP architecture, all nodes communicate in a client-server manner. Clients are named Control Points (CPs) and servers are named Controlled Devices. Devices expose a set of defined functions called actions. CPs always invoke actions on devices and devices respond to their requests. The protocols for communication between control points and devices are defined by the UPnP Device Architecture (DA) [7]. IP addressing is the foundation for UPnP networking. For discovery, description, control, eventing, and presentation, the UPnP DA uses the protocol stack depicted in Figure 2.5.

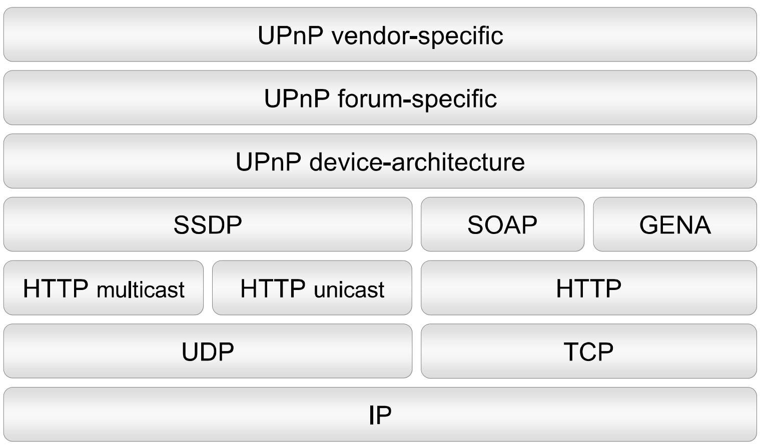


Figure 2.5: UPnP protocol stack [7]

Simple Service Discovery Protocol (SSDP) and General Event Notification Architecture (GENA) are UPnP specific protocols defined in UPnP DA. SSDP is a multicast discovery and search mechanism and GENA is an event subscription and

[1] UPnP Forum, http://www.upnp.org

notification protocol. For communication between various applications running on different nodes, UPnP adopts the Simple Object Access Protocol (SOAP)[1] protocol recommended by the World Wide Web Consortium (W3C). SOAP is a simple XML-based protocol running over HTTP and used by applications to exchange information.

The UPnP Audio Video (AV) specification [8] is specifically focused on CE devices that interact with entertainment content (TVs, DVD players, mp3 players, stereo systems, etc). The UPnP AV specification defines a set of UPnP device and service templates for making CE devices distribute entertainment content throughout the home network in the interoperable way. Figure 2.6 shows the UPnP AV architecture where three main logical entities are defined: Media Server, Media Renderer and AV Control Point (CP). An end-user uses a CP to play entertainment content stored on a Media Server (e.g. satellite STB) and transferred to a Media Renderer device (e.g. TV). Media Servers and Renderers implement a set of UPnP AV services that provide command and control functions to allow a CP to perform setup and configuration for transferring the desired content from a Media Server to a Media Renderer. Therefore, users can purchase a Media Server and Media Renderer from different vendors and seamlessly connect them to the home network and enjoy entertainment content.

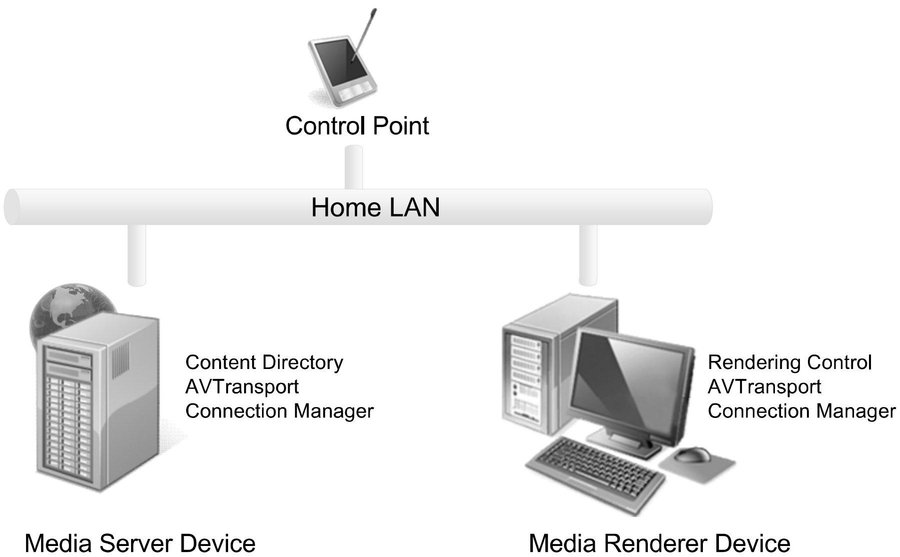


Figure 2.6: UPnP audio and video architecture

A joint alliance between UPnP and DLNA enables these organizations to share information and promote development of the home network. Over the course of this collaborative work, DLNA has adopted UPnP DA and UPnP AV into its certification process. That is, any device, which needs to be DLNA certified, has to pass the UPnP

[1] Simple Object Access Protocol (SOAP), http://www.w3.org/TR/soap

AV device certification. Meeting both the DLNA and UPnP specifications makes digital content easily available and consumable in almost any network. The problem that a user might encounter today when using the presented architecture is that UPnP does not ensure high-quality distribution. That is why UPnP has recently made a significant effort in developing a QoS architecture that aims at achieving a reliable high-quality user experience in home networks. The UPnP QoS architecture is presented in Section 3.5.2 when we discuss QoS mechanisms in more detail.

2.2.3 DVB

The Digital Video Broadcasting (DVB) project[1] is an international industry consortium founded in 1993 for developing open standards for digital television. In the course of recent years the scope of DVB work has broadened, and now DVB is developing specifications for broadcasting all kinds of information (video, audio, data) accompanied by all kinds of supplementary data and designed for both unidirectional and bidirectional communication channels. Also, DVB plays presently an important role in defining standards for distributing and consuming digital content in the future home networks.

The fundamental DVB specifications cover distribution of data using a variety of approaches: by satellite (DVB-S), cable (DVB-C), terrestrial television (DVB-T) and digital terrestrial television for handhelds (DVB-H). These core standards define the physical layer and data link layer of the distribution system. DVB does not standardize its specifications, rather it passes its work to the European Telecommunications Standards Institute (ETSI)[2] for integration into the regular standardization world.

The growing popularity of home networking and increasing network bandwidth resulted in evolvement of AV services delivered to and through the home via IP networking. In 2000 the DVB Technical Module (TM) started the TM-IPI working group (IP Infrastructures) aimed at developing specifications for DVB services over IP networks. One of the most important documents of the group is the DVB IP Handbook [9]. The handbook specifies technologies on the interface between an IP network and a digital TV receiver. The first version of the handbook published in 2005 enabled

[1] Digital Video Broadcasting (DVB) project, http//www.dvb.org
[2] European Telecommunications Standards Institute (ETSI), http://www.etsi.org

deployment of IPTV services and mass production of IPTV receivers by CE manufactures.

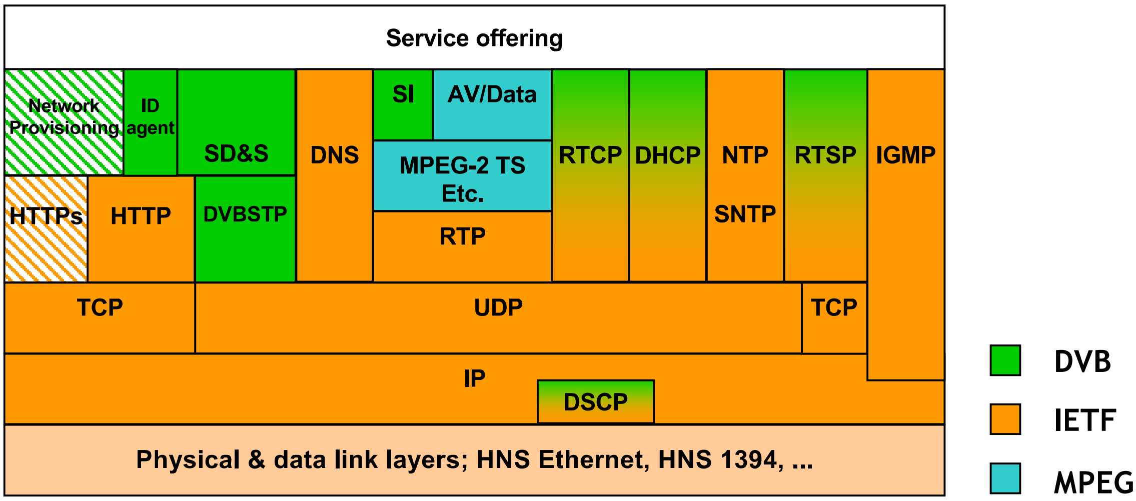


Figure 2.7: Protocol stack for DVB-IP services [9]

The IP Handbook covers the delivery of DVB MPEG-2 services encoded with MPEG-2 technology [11], [12] and encapsulated in MPEG-2 Transport Stream (TS) [13]. The addressed services are TV and radio live media broadcast, media broadcast with trick modes (enabling a user to pause, fast forward or reverse a service), and content on demand. The defined protocols and mechanisms allow a user to have a standard DVB Home Network End Device (HNED), plug it into an IP home network and consume DVB services. The high-level protocols specified on the interface between an IP network and TV receiver are depicted in Figure 2.7. These protocols are independent of physical media and can be used to access services outside home using all DVB physical layers (e.g. DVB-C/S/T) and to access services inside home using wired and wireless media (Ethernet, Wi-Fi).

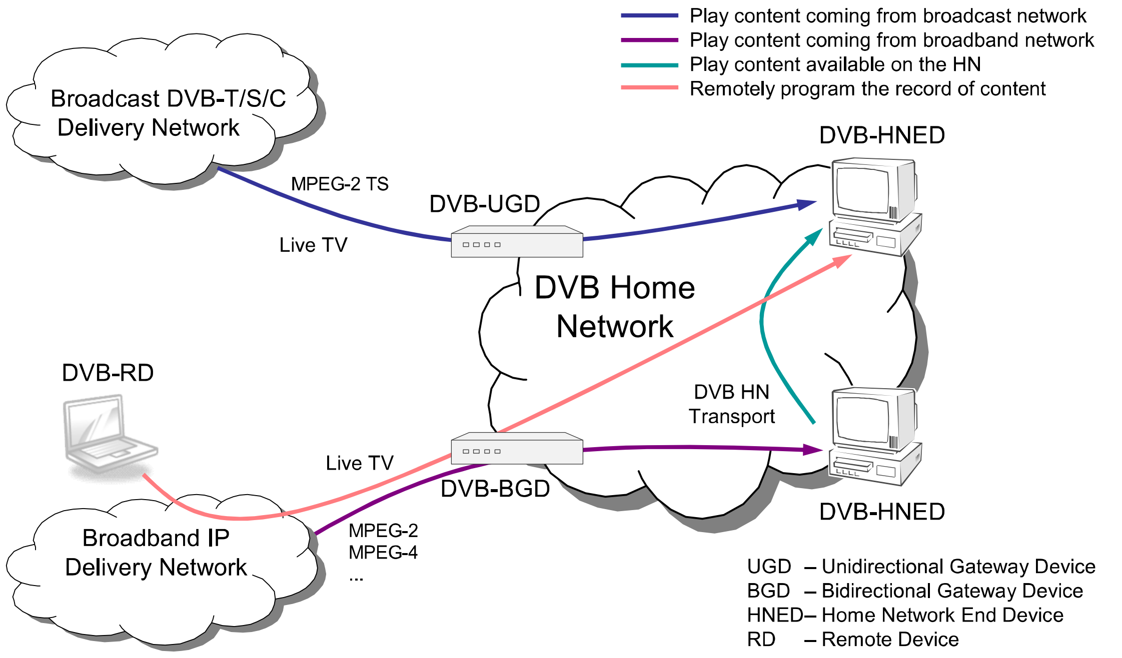


Figure 2.8: DVB HN use cases [10]

The main subjects addressed in DVB TM-IPI specifications are transport of DVB services, service discovery and selection, IP addressing, network provisioning and home networking. With respect to home networking the TM-IPI group is very actively now working on a specification defining the distribution of broadband and broadcast DVB services over a common home network to end user devices in a single home. The reference model of the DVB Home Network (HN) is published as a DVB Blue Book [10]. The HN reference model describes an abstract framework defining the significant entities and relationships among them within a home network. The use cases described in the HN reference model are shown in Figure 2.8. For global compatibility, DVB HN will be based on DLNA specifications. DVB device classes are very close to DLNA classes and offer similar functionality. Currently, DVB TM-IPI is working closely with DLNA to achieve full compatibility between DVB HN and DLNA compliant devices.

With respect to QoS, it is known from the HN reference model that DVB HN Phase 1 will define a prioritized QoS solution based on DLNA guidelines. A more advanced QoS solution is the subject of future phases. DVB efforts related to QoS mechanisms in home networks and their relation to our work will be considered in Section 3.5.3.

2.3 Distribution channels for home network

Currently, there are a number of options of how to interconnect home networking devices and distribute media within a home. As one of the most desirable requirements is to make it easier to connect new devices to the network, wireless technology has become dominant for this purpose. With the introduction of broadband and development of home networking, the IEEE 802.11 based (Wi-Fi) equipment has become very popular for householders due to its simple installation and mobility. However, with the evolvement of new high bandwidth network applications (e.g. HDTV streaming) and due to shortcomings of wireless media (e.g. noise, interference), various wired technologies are also considered at the moment for home networking.

The subject of this thesis concerns more wireless networks, but for complete picture we give below also a short review of the existing wired technologies, keeping in mind as well that the main principles presented in this work can be also applied to the wireline home networks.

2.3.1 Wired home networking technologies

Due to the higher robustness and throughput of wired networks in comparison to wireless, many see that a digital home in the near future will be a hybrid with wired and wireless medias employed. For example, the performance of today's Ethernet based technology is truly high. It seems that the currently available Gigabit Ethernet, emerging 10 Gigabit Ethernet and under early development 100 Gigabit Ethernet will solve the problem of bandwidth for all network application. The IEEE 802 working groups are also completing Ethernet AV specification[1] containing enhancements to the existing Ethernet standards with respect to audio-video streaming and related QoS problems. However, if companies can spend money to install and manage wired networks in their offices to increase productivity, the most householders will choose a simpler way. That is why it is broadly agreed that for mainstream success, home networks have to be either wireless or operate over existing phone lines, coax cables or power lines. The most well known wireline home networking technologies are being developed and promoted by HomePNA, MoCA and HomePlug Alliances. A short

[1] IEEE 802.1 Audio/Video Bridging Task Group, http://www.ieee802.org/1/pages/avbridges.html

description of these technologies is given below followed by the review of the recent ITU-T effort to develop one global standard supporting all types of wiring existing in the home.

2.3.1.1 HomePNA

Home Phoneline Networking Alliance (HomePNA)[1] develops and standardizes home networking technology over existing phone wires and coaxial cables in a home. The industry specifications created by HomePNA are standardized under the International Telecommunication Union (ITU)[2]. The newest HomePNA standards are focused on new emerging applications such as IPTV, which require high data rates and advanced QoS features. The most recent products provide data rates up to 320Mbps with enough capacity to carry High Definition TV (HDTV) video streams. This type of technology is used today by some providers for commercial "triple play" services (video, voice and data).

2.3.1.2 MoCA

Multimedia over Coax Alliance (MoCA)[3] develops specifications for home networking over existing coaxial cable, which is usually used in the home for antenna and cable connections to TVs, STBs and other entertainment devices. The technology specified by MoCA provides the building blocks for distribution of high-quality multimedia and high-speed data with throughput of 175Mbps. Furthermore, MoCA is the first among the home network standards, who developed and deployed parameterized QoS. The advanced QoS mechanisms ensure that best effort data do not interfere with the delivery of time sensitive multimedia streams.

Just recently DLNA has approved the MoCA technology standard for inclusion in the next version of DLNA interoperability guidelines that are scheduled for release in 2009[4]. Up to now this makes MoCA, Wi-Fi and Ethernet be the only LAN technologies included in the DLNA guidelines.

[1] HomePNA Alliance, http://www.homepna.org/en/index.asp
[2] International Telecommunication Union (ITU), http://www.itu.int
[3] Multimedia over Coax Alliance (MoCA), http://www.mocalliance.org
[4] http://www.dlna.org/news/pr/view?item_key=e63d0cef875537d34bf7694efdd39cd8961aa8eb

2.3.1.3 HomePlug

HomePlug Alliance[1] defines specifications for power line communications. By means of HomePlug certified products, PCs or other devices that use Ethernet, USB or Wi-Fi can be simply connected to each other through the existing power lines in a home. The new HomePlug AV specification delivers up to 150Mbps effective data rate over home electrical wiring, which can be sufficient for carrying HDTV video streams. The HomePlug AV Medium Access Control (MAC) layer supports both Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) methods. The TDMA access provides QoS including guaranteed bandwidth reservation and strict control of latency and jitter.

HomePlug is organization of about 50 companies. Apart from their specifications there are also some competing proprietary powerline technologies from Panasonic and DS2 offering similar speeds. HomePlug, its competitors and many others work presently together on a unified power line communication standard IEEE P1901 [14].

2.3.1.4 G.hn

From the previous sections it is seen that there is one or more different standards today for each type of wiring. Due to this fragmentation of the wired home network market, some service providers and companies do not commit to any technology. That is why there is an effort under ITU-T to develop a universal wired home networking standard. G.hn, in which 'hn' stands for 'home networking', is the first global standard to support all three types of wires: coax, powerline and phone wires. G.hn is supposed to coexist with and maybe extend the existing home networking technologies like HomePNA, MoCA and HomePlug. The G.hn specification has targeted throughput rates ranging from 50 to more than 700 Mbps (depending on media). The first recommendation for the standard, which has been recently approved by ITU-T (Dec 2008), includes the physical layer needed to start development of G.hn chips. Now ongoing work is focused on the MAC layer and is expected to be completed at the end of the year 2009. To support the G.hn standard and promote it on the market, HomeGrid Forum[2] was founded. The Forum was created to assist the ITU-T working group, promote

[1] HomePlug Alliance, http://www.homeplug.org
[2] HomeGrid Forum, http://www.homegridforum.org

worldwide adoption of G.hn and address certification and interoperability issues. It is expected that G.hn complaint products can be available on the market already in 2010.

2.3.2 Wireless home networking technologies

It is seen from the previous sections that there is no so far any leading wired home networking technology available for householders. In the absence of a global wired standard, Wi-Fi has become a dominant technology and it will always remain essential due to its natural features such as mobility and installation simplicity. According to the user research conducted in consumers' homes [48], one of the major users' complaints is the difficulty of wiring. That is why the users envision a network home using wireless technology. The present effort of research and industry communities is directed towards solving the limitations of today's wireless networks that are not ready yet for carrying error-free high quality video across the home. In the next subsections we give an introduction into the Wi-Fi technology.

2.3.2.1 Wi-Fi Alliance

Wi-Fi Alliance[1] is an organization of separate and independent companies founded in 1999 to support interoperability between different wireless devices based on the IEEE 802.11 standards[2]. Originally, the term Wi-Fi was used as 'Wireless Fidelity', but now the Wi-Fi Alliance discourages the use of this term stating that 'Wi-Fi' is just a brand name that stands for nothing. The purpose of Wi-Fi is to allow consumers to buy 802.11 Wi-Fi certified products from different manufactures and be able to use them in an interoperable way. Since the start of the Wi-Fi certification program in 2000, Wi-Fi products have widely penetrated the market. Today, they are used not only in PCs and access points, but also in handheld computers, game consoles, cameras, and numerous fixed and mobile devices. The adoption of Wi-Fi certified products on the market will be further increasing, and partially due to the fact the DLNA requires all WLAN-enabled home networking devices to be Wi-Fi certified for DLNA compliance.

Initially, Wi-Fi certification focused on MAC and PHY layers functionality (802.11a/b/g), but it includes now more than 10 certification programs (Table 2-1). We

[1] Wi-Fi Alliance, http://www.wi-fi.org
[2] IEEE 802.11 Working group, http://www.ieee802.org/11

will review below the 802.11a/b/g/n wireless interfaces and their applications for home networking. The Wi-Fi Multimedia suitable for latency-sensitive applications (e.g. voice, video) and based on 802.11e is essential for this work and will be considered in detail in Chapter 3.

Table 2-1: Some of the Wi-Fi certification programs [15]

Certification program	Start date	Mandatory /optional	Description
IEEE 802.11b	2000	Mandatory (one of the 802.11a, b or g)	Wireless interface
IEEE 802.11g	2001		Wireless interface. Requires IEEE 802.11b
IEEE 802.11a	2002		Wireless interface
IEEE 802.11n	2007	Optional	Wireless interface based on 802.11n draft 2.0
WPA	2001	Mandatory	Wi-Fi Protected Access. Security
WPA2	2003	Mandatory	Wi-Fi Protected Access 2. Security
WMM	2004	Optional	Wi-Fi Multimedia, QoS features based on a subset of 802.11e elements
WMM Power Save	2005	Optional	Power saving based on a subset of 802.11e elements. Requires WMM

2.3.2.2 IEEE 802.11 standards for home networking

802.11 is an IEEE working group[1] developing standards for Wireless Local Area Networks (WLANs). The 802.11 specifications define an over-the-air interface (including PHY and MAC layers) between wireless clients and base stations. The worldwide adoption of the 802.11 standards started when high-speed broadband Internet access became available in the home and it is still the easiest way to share broadband connection between several computers in the home.

2.3.2.2.1 802.11

The first WLAN standard called 802.11 was released in 1997. (Now along with all its amendments described below it is available as 802.11-2007 standard [16].) Originally, the standard specified only two possible data rates of 1 and 2 Mbps to be transmitted at 2.4 GHz by one of the three signaling methods defined at the PHY layer: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) or Infrared. At the MAC layer the standard defined a medium access method called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The weakness

[1] IEEE 802.11 Working group: http://www.ieee802.org/11

of the standard was its low data rate and the fact that it offered too many transmission methods at the PHY layer, which resulted in the lack of interoperability between products of different vendors.

2.3.2.2.2 802.11b

The original 802.11 standard was extended in 1999 with the 802.11b amendment [16]. 802.11b uses the same radio frequency 2.4 GHz and DSSS version of the legacy 802.11 standard supplemented with Complementary Code Keying (CCK) to achieve the data rates of 5.5 and 11 Mbps. Due to the increased data rates and Wi-Fi certification program, 802.11b was widely adopted and implemented all over the world.

2.3.2.2.3 802.11g

The 802.11g amendment [16] to the 802.11 specification extended the data rate up to 54 Mbps while using the same frequency band 2.4 GHz. This is due to the Orthogonal Frequency-Division Multiplexing (OFDM) modulation mode used for producing data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. For operating with data rates of 1, 2, 5.5, and 11 Mbps the 802.11g standard reverts to the defined in 802.11b modulation modes: CCK and DSSS. As a result of this, 802.11g and 802.11b hardware is fully compatible.

2.3.2.2.4 802.11a

The 802.11a amendment [16] to the legacy 802.11 standard operates in the 5 GHz band and uses OFDM modulation mode with the possible data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. 802.11a hardware is not interoperable with 802.11g and 802.11b hardware as they operate in the different frequency bands. The 5 GHz frequency band has its advantages: it is not so heavily used as the 2.4 GHz band, which means less interference for 802.11a, and it provides 19 non-overlapping channels as opposed to 4 non-overlapping channels in the 2.4 GHz band (for Europe). The disadvantage of the higher frequency band is that 802.11a has a slightly lesser transmission range. The main performance features for the main 802.11 standards are given in Table 2-2.

Table 2-2: IEEE 802.11 standards

		802.11	802.11b	802.11g	802.11a	802.11n
Operating frequency		2.4 GHz	2.4 GHz	2.4 GHz	5 GHz	2.4 or 5 GHz
Modulation		FHSS/ DSSS/IR	DSSS	OFDM	OFDM	OFDM
Max. data rate	raw	2 Mbps	11 Mbps	54 Mbps	54 Mbps	600 Mbps
	net	0.9 Mbps	5.5 Mbps	17-22 Mbps	22-26 Mbps	74 Mbps
Typical range	indoor	20 m	38 m	38 m	35 m	70 m
	outdoor	100 m	140 m	140 m	120 m	250 m
Non-overlapping channels (EU)		4	4	4	19	4 or 19

2.3.2.2.5 802.11n

The data rate of 54 Mbps achieved by the 802.11a/g standards is still not enough to meet all requirements of upcoming home applications. That is why the 802.11n standard providing considerable transmission range and throughput improvements (up to 600 Mbps) is now one of the most anticipated technologies to support high quality video streaming, gaming, voice and data applications in home. 802.11n is a proposed amendment to the IEEE 802.11-2007 standard [16], which is going to be finalized only in December 2009. However, there are many 802.11n products already available on the market and even Wi-Fi certified products based on the draft 2.0 of the standard.

The higher throughput of the 802.11n technology is achieved due to the following features [17], [18]:

- **More subcarriers**. The 802.11a/g standards have 48 OFDM data subcarriers. The 802.11n standard increases the number of data subcarriers up to 52, which results in increasing of throughput up to 58.5 Mbps: $54Mbps \cdot (52/48) = 58.5Mbps$.

- **Forward Error Correction (FEC)**. The maximum FEC coding rate of the 802.11a/g standards is 3/4. 802.11n defines a possible coding rate of 5/6 with less redundancy increasing the throughput up to 65 Mbps: $58.5Mbps \cdot (5/6)/(3/4) = 65Mbps$

- **Shorter guard interval**. The guard interval between 802.11a/g transmissions is 800 ns. The 802.11n standard defines an option to reduce the guard interval to 400 ns boosting throughput from 65 Mbps to 72.2 Mbps: $65Mbps \cdot (4/3.6) = 72.2Mbps$, where 4μ and 3.6μ – OFDM symbol durations with 800ns and 400ns correspondingly.

- **Multiple Input Multiple Output (MIMO)**. 802.11n uses MIMO technology, which is based on a technique called spatial multiplexing to transport multiple data streams simultaneously in the same frequency channel. With MIMO, the throughput of the system increases linearly with each antenna added at the transmitter and receiver. Two antennas at each end double the throughput, three antennas triple it and so on. The maximum number of antennas specified in 802.11n is four at each end. This makes it possible to transmit four 72.2 Mbps streams simultaneously producing the total throughput of 288.9 Mbps: $72.2Mbps \cdot 4 = 288.9Mbps$.

- **Channel bonding.** All 802.11 standards have a channel bandwidth of 20 MHz. In 802.11n there is an optional mode, in which two 20 MHz channels can be bound together to form a 40 MHz channel. In this case 802.11n increases the number of available data subcarriers from 52 to 108. This finally boosts the total throughput to 600Mbps: $288.9Mbps \cdot (108/52) = 600Mbps$.

- **Lower MAC overhead**. 802.11n integrates also all previous amendments to 802.11. It includes MAC layer enhancements of the 802.11e standard (block acknowledgements) and other MAC layer improvements such as frame aggregation mechanisms and reduced interframe spacing, which reduces overhead of the 802.11n MAC.

To improve user experience with multimedia applications it is a must for 802.11n Wi-Fi certified products to pass also the WMM QoS certification based on 802.11e. Therefore, with the increased range and throughput, and 'built-in' WMM features, the 802.11n standard can theoretically significantly improve HD video and AV multimedia applications in the home environment.

2.3.2.2.6 802.11 VHT

Even though 802.11n promises to increase throughput up to 600 Mbps, actual throughput can be much less due to overhead, interference, noise or other traffic. The 802.11 Very High Throughput (VHT) study group[1] is currently developing a proposal for a standard aimed at providing the throughput of at least a gigabit per second. The

[1] Status of Project IEEE 802.11 VHT Study Group, http://www.ieee802.org/11/Reports/vht_update.htm

new standard will be operating over 60 GHz frequency band. It is proposed to be an amendment to 802.11 with the possibility to fallback from 60 GHz to 2.4 or 5 GHz 802.11n networks if needed. It is known that the 802.11 VHT group is working in cooperation with the Wi-Fi Alliance. The use cases presently considered for the new upcoming gigabit Wi-Fi standard include in-home distribution of HDTV streams, wireless displays, rapid download and upload of large files and others. It is expected that the 802.11 VHT standard can be ratified already in 2011 or 2012 with the first products available on the market shortly after.

2.4 Conclusion

The modern technologies and services bring new experience into the home. The introduction of broadband Internet, digital broadcast services and evolvement of CE and PC industries led to the rapid development of the home networking technologies. To maintain the progress of the evolving technologies, many SDOs such as DLNA, UPnP and DVB are currently working together towards defining interoperable solutions for wide-spread adoption of the approaching home network devices and better user experience. Along with evolvement of new services and high level protocols, new means for media distribution are actively investigated. New wireline and wireless standards for home networking are under development. To address the current fragmentation of wired home technologies (HomePNA, MoCA, HomePlug), the recently started work by ITU-T on G.hn standard is going to define a universal protocol for all home wired media (phone lines, coaxial cables, powerline). To improve user experience in wireless home networks and to boost adoption of the high throughput 802.11n standard, the Wi-Fi Alliance created certification program of so called pre-N products based on the current draft 2.0 of the 802.11n specification. Moreover, the work on Gbit Wi-Fi standard is started to fulfill high demanding requirements of HD video and AV multimedia services in the future wireless home networks.

The work presented in this thesis proposes various solutions for improving user experience in this rapidly developing and highly demanding home network environment. Even though the main ideas of this work can be applied to both wireline and wireless networks, we chose wireless 802.11 networks as a target technology of our research. Although it is generally believed that our future home will be a hybrid with wired and wireless networks, today we can say that Wi-Fi is a dominant technology for home networking. It has always been and will be the easiest way to interconnect home network devices. Unfortunately, due to the nature of wireless media, errorless distribution of high quality multimedia services over wireless is still a challenging task. In the next chapter, we will consider what problems and challenges the developers and consumers face in today's wireless networks and what solutions exist to address these problems.

3 A view on QoS in wireless home networks

3.1 Introduction

Even though home network technologies are evolving, many problems still exist especially in wireless networks. Due to the nature of the wireless media, wireless networks have always suffered with respect to the delivered quality of service (QoS). In this chapter we consider what mechanisms exist today to address the problems and to improve the user experience in wireless networks.

3.2 Problems in wireless

The modern home networking applications including gaming and HD video streaming across the rooms put high demands on the underlying network technologies not only in terms of connectivity and interoperability but also in terms of the delivered quality of content. For high quality TV streaming, Voice over IP (VoIP) applications and fast file downloads, the network has to provide high bandwidth and meet certain latency, jitter and packet loss requirements. Comparing with the wired technology, wireless medium has much more problems to meet all these requirements of modern applications. Wireless networks have relatively limited bandwidth, high error-rates and low efficiency due to high packet overheads. Because of the complex nature of wireless propagation, wireless networks are also more sensible to environmental factors such as obstructions and interference. Due to high levels of wireless absorption in various building materials and constantly changing performance caused by interference from other devices, the coverage and availability of wireless media is considerably affected.

All these factors limit the capability of wireless networks to provide high level of quality for today's home network applications. One of the reasons of why this is not still properly addressed by modern technologies is that wireless protocols were developed before the strong need of strict quality guarantees for multimedia applications. As a result, there have been many solutions proposed and extensions developed for originally designed wireless protocols.

3.3 General overview of QoS mechanisms

Optimization of the limited bandwidth and meeting the resource requirements of different applications are the main objectives of the Quality of Service (QoS) mechanisms in wireless networks. According to ITU-T definition, QoS is defined in general as the collective effect of service performance which determines the degree of satisfaction of a user of the service [19]. QoS mechanisms include any means contributing to general improvement of the system performance and consequently to improvement of end user experience. Looking at the network stack, QoS mechanisms can be implemented at different network layers (Figure 3.1).

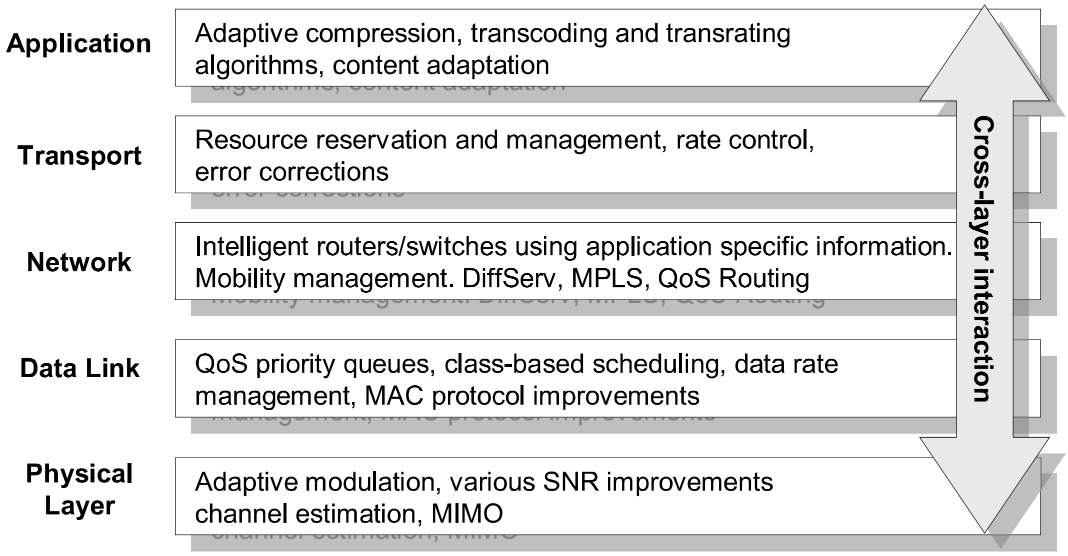


Figure 3.1: QoS mechanisms at different network layers

For example, at the application layer there are various methods of adapting different compression parameters of the audio-video encoder to follow the changing network quality. Video transcoding [21], [22], Scalable Video Codec (SVC) [23], [24] and Application Layer Forward Error Correction (AL-FEC) [25], [26] techniques are some examples of these methods. At the transport and network layers there are various mechanisms of packet classifications. Based on the parameters such as source IP, destination IP, source port, destination port or protocol, packets belonging to different applications can receive different treatment in the network and QoS can be delivered on a per-flow basis. With the help of techniques such as Differentiated Services (DiffServ) [20], packets are marked according to certain classification rules and provided with the different level of service when going through the network.

With respect to the wireless networks the main QoS mechanisms reside at the bottom of the stack. Link adaptation is an important mechanism matching the parameters of the radio link (modulation, coding) to the changing link conditions. The goal is to achieve the optimal performance in terms of data rate and packet delay for any state of the channel. Each data rate corresponds to a certain modulation and coding scheme, which provides different balance between throughput and link connectivity. At the MAC layer there are several parameters that have effect on the overall performance. Maximum number of retransmissions, packet fragmentation threshold and RTS/CTS scheme can be used to improve the link quality in a certain situation. Moreover, the IEEE 802.11e standard [30] defines a set of extensions for the MAC layer to address QoS problems. We consider 802.11e extensions in the next section in more detail.

One of the methods to improve QoS is to make network layers exchange information between each other. A cross-layer interaction can help better to react to the network or channel state changes. For example, the application layer can make use of the link quality data from the link layer to make a decision about some video compression parameters. To achieve optimal performance, cross-layer optimization is needed between layers of the protocol stack. Such optimizations [65], [66], [67] might include adaptive modulation schemes to find more robust modes at base layers, retry-limit adaptation at the MAC layer to find balance between queue drops and link losses, AL-FEC to compensate for packet losses at the MAC layer, traffic reshaping to handle varying bit rates, dynamic resizing of buffers, joint source-channel coding and others [68].

QoS mechanisms are required in both broadband access networks and home networks. The network layer QoS mechanisms (DiffServ, MPLS, QoS routing) are mostly used by service providers for guarantied delivery of media content over access networks (e.g. for IPTV services). In home networks, QoS is mainly required for supporting high quality video and voice traffic. Video streaming has high bandwidth requirements and voice traffic is very latency sensitive. Typical QoS requirements for multimedia applications are given in Table 3-1. It is seen that latency and jitter requirements impose a significant design challenge to the distribution network. The only QoS mechanism broadly implemented today in WLAN devices is prioritization of traffic based on the 802.1D tags [27] and Wi-Fi Multimedia (WMM) standard [28]. Prioritization allows the high priority traffic to be transmitted ahead of the low priority traffic, but there are no any guarantees with respect to the bandwidth or latency. We give a detailed review of WMM features in the next section. As opposed to the prioritized approach, in the parameterized QoS all devices and applications are guaranteed of some amount of network resources for their data transfers. However, implementation of such an approach is a quite complex task. Even though the general trend in home networking is to migrate to parameterized QoS (UPnP QoS v.3 [29]), it can be not appropriate for wireless networks where throughput, latency and jitter are strongly influenced by the variable nature of the wireless channel.

Table 3-1: Typical QoS requirements for multimedia network applications [34]

Input parameters of performance testing			Output parameters of performance testing			
Service	**Number of streams**	**MAC payload rate (per stream)**	**Packet size (bytes)**	**Max PER**	**Max Latency**	**Max Jitter**
Multiple streams (1HDTV/2SDTV)	3	35 Mbps	228	$3.6 \cdot 10^{-5}$	90 ms	± 10 ms
HDTV (MPEG-2)	1	20 Mbps	228	$3.6 \cdot 10^{-5}$	90 ms	± 10 ms
SDTV/DVD	1	3-8 Mbps	228	$3.6 \cdot 10^{-5}$	90 ms	± 10 ms
HQ Video Conf. Call	2 per call	1.5 Mbps	228	$3.6 \cdot 10^{-5}$	10 ms	± 5 ms
CD Quality Audio	1	256 Kbps	360	$5.8 \cdot 10^{-5}$	100 ms	± 10 ms

3.4 QoS extensions in 802.11

To address QoS problems in wireless networks, the IEEE 802.11 group developed the 802.11e standard [30], which defines the MAC layer extensions for more efficient streaming of multimedia data. Below we give a short description of the legacy 802.11 MAC and a more detailed review of QoS extensions specified in 802.11e.

3.4.1 Original 802.11 MAC

The legacy 802.11 MAC defines two channel access mechanisms called coordination functions: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). These coordination functions define when a station is allowed to transmit data and when it has to be prepared for data reception. The key mechanism is the DCF function, which is based on the Carrier Sense Multiple Access (CSMA) mechanism. The CSMA mechanism is a protocol specifying how a station can transmit data on a medium shared with other stations. According to CSMA, a station tries to detect first the absence of other traffic before initiating its own transmission (listen-before talk). While in wired networks the CSMA mechanism is implemented with collision detection (CSMA/CD), in wireless networks it is implemented with collision avoidance (CSMA/CA) mechanism due to the nature of the wireless medium, which does not allow for any reliable collision detection mechanism. In DCF this is implemented in the following way. A station begins transmission after detecting the medium to be idle for Distributed Inter-Frame Space (DIFS) interval of time. If the medium is busy a station defers transmission. To prevent several stations from transmitting simultaneously, each station selects a random backoff interval when deferring transmission. The range from which a random interval is drawn is called the Contention Window (CW). If the medium is detected idle during the backoff period, the backoff counter is decremented. If the medium is detected busy the count down is suspended. When the backoff interval is run out a station begins its transmission. After transmitting one MAC Service Data Unit (MSDU), a station waits for a time interval called Short Inter-Frame Space (SIFS) for the Acknowledgment (ACK) from the MSDU receiver. The SIFS interval is shorter than DIFS, which ensures that none of the other stations can start transmission while ACK is expected. If ACK is not received after SIFS, a station can retransmit the MSDU when winning contention next time. If after a certain number of retransmissions the MSDU is still not successfully delivered, it is discarded. Figure 3.2 shows an example of the DCF frame exchange.

Collision avoidance is accomplished in DCF by means of a virtual carrier sense mechanism. At each station there is a timer called the Network Allocation Vector (NAV), which shows when the medium is busy (Figure 3.2). NAV is updated at a station using a duration value transmitted within each frame from other stations and indicating the length of transmission.

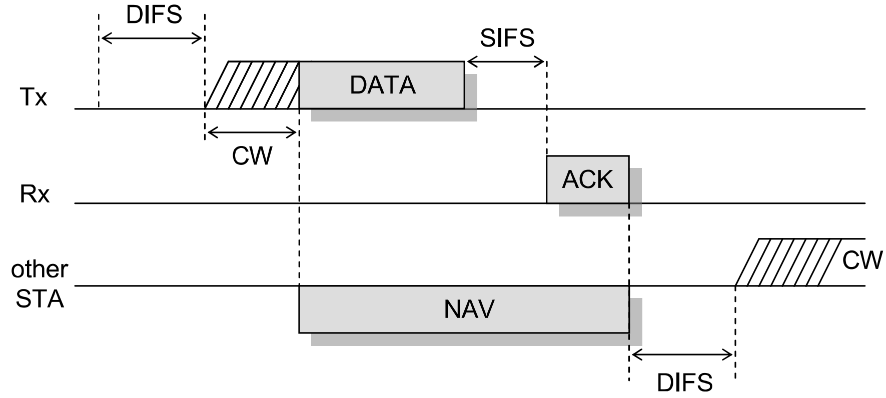


Figure 3.2: DCF frame exchange

Due to the nature of the CSMA/CA scheme, the total achievable throughput of the DCF function is far lower than the data rate. For example, Figure 3.3 shows the maximum achievable throughput for various 802.11b and 802.11a PHY modes as a function of the MSDU size [69]. A throughput analysis of the 802.11g mode can be found in [70]. From Figure 3.3 it is seen that for a MSDU frame of 1500 bytes and data rate 54 Mbps the maximum throughput is around 32 Mbps, which corresponds to the efficiency of 59% and which is obviously much lower than efficiency of the wired networks based on CSMA/CD. The 802.11e standard (described in the next section) defined some new features aimed at reducing the protocol overheads (e.g. block acknowledgments, contention free bursts, minimizing control frames and backoff). The efficiency improvements of the 802.11e MAC in comparison with the original 802.11 MAC are investigated in [71].

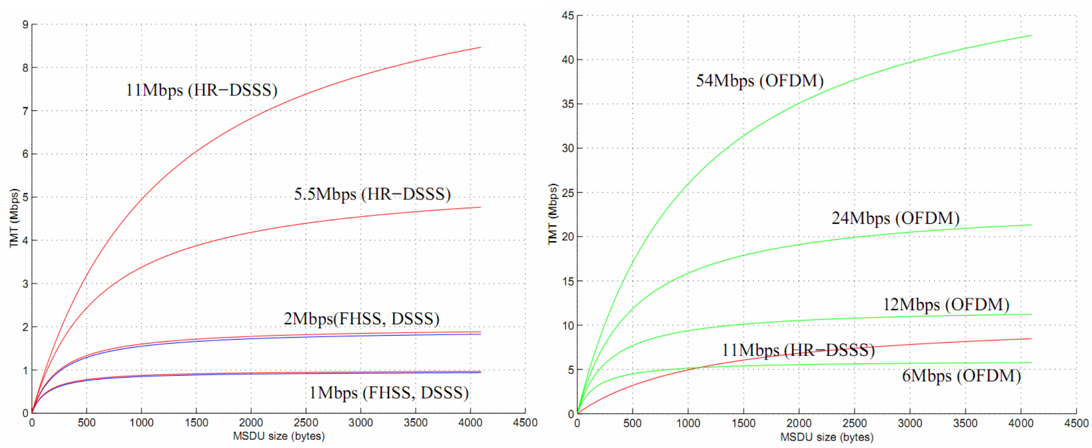


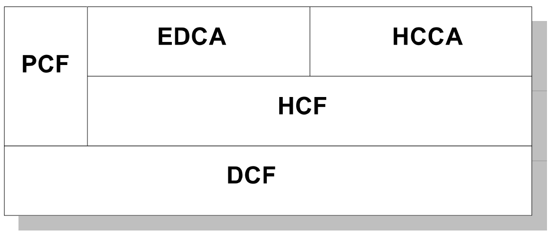
Figure 3.3: Theoretical Maximum Throughput (TMT) for DCF [69]

PCF is an optional function, which provides different access rules for contention-free media access based on polling by a point coordinator operating at the access point. PCF has not been widely implemented due to its implementation complexity, various limitations with respect to QoS and the lack of market demand.

Both DCF and PCF do not meet the QoS requirements demanded by multimedia applications. In DCF, there is no any differentiation mechanism and it can only be used for best-effort services. In PCF, there are no mechanisms defined for stations to communicate QoS requirements to the access point, also no management interface to setup and control contention-free periods and moreover, the polling schedule is not strictly managed. The 802.11e extensions address these limitations.

3.4.2 802.11e MAC

Trying to meet the shortcomings of the original 802.11 MAC, the IEEE 802.11 task group defined enhancements to improve performance of wireless networks with multimedia traffic. The 802.11e standard [30] defined a new function called Hybrid Coordination Function (HCF), which has two modes of operation: Enhanced Distributed Channel Access (EDCA) and HCF Controlled Channel Access (HCCA). These two functions are specific QoS extensions to DCF and PCF mechanisms of the original 802.11 MAC. EDCA is a contention based channel access function designed to support prioritized QoS services and HCCA is a polling-based channel access function designed to support parameterized QoS services. Figure 3.4 depicts the 802.11e MAC architecture and relationship between new and legacy coordination functions.



DCF - Distributed Coordination Function
PCF - Point Coordination Function
HCF - Hybrid Coordination Function
EDCA - Enhanced Distributed Channel Access
HCCA - HCF Controlled Channel Access

Figure 3.4: 802.11e MAC architecture [31]

One of the main concepts defined in 802.11e is the Transmission Opportunity (TXOP). A station acquires the right to transmit data through TXOP allocated by HCF. TXOP provides a time interval in which a station can transmit data. If TXOP is acquired during contention-based period then it is called EDCA TXOP. If TXOP is obtained during contention-free period then it is called HCCA polled TXOP. The EDCA TXOP is distributed by the access point to all stations in the beacon frames. The duration of the HCCA polled TXOP is controlled by a so called hybrid coordinator, which passes the TXOP values to the polled stations within the QoS contention-free poll frames.

3.4.2.1 EDCA

The EDCA function is an extension to DCF, which provides prioritized QoS services. To provide traffic differentiation, EDCA defines four Access Categories (ACs) that have different probabilities of accessing the channel. Each AC has its own set of channel access parameters and its own transmission queue (Figure 3.5). The mapping of frames to a certain AC is done according to the user priorities as defined in the IEEE 802.1D standard [27].

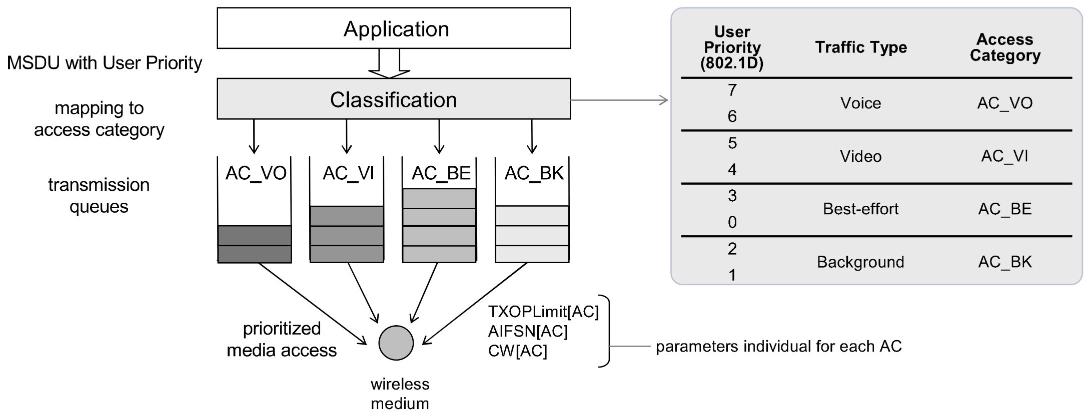


Figure 3.5: EDCA transmit queues

The differentiated channel access is achieved by setting different values for AC parameters. The most important AC parameters are given in Table 3-2 and explained below:

- Arbitration Inter-Frame Space (AIFS): the minimum time interval from the moment the wireless medium has become idle until the next frame transmission. Each AC has different AIFS values (denoted as AIFS[AC]) and, therefore, different waiting times between transmissions.

- TXOP Limit: the maximum allowable duration for frame transmissions after a station has received TXOP. The greater values of TXOP Limit guarantee that the high priority traffic gets the medium for a longer time.

- Minimum Contention Window size (CW_{min}). During the first attempt to transmit a frame, a random value for a backoff interval is selected from the interval

[0, CW_{min}]. The shorter CW_{min} the less time lasts the backoff period. That is why for high priority ACs the CW_{min} is shorter.

- Maximum Contention Window size (CW_{max}). After unsuccessful transmission the CW size is exponentially increasing with each transmission retry until it reaches the CW_{max} value. Therefore in the worst case, a random value for a backoff interval is drawn from the interval [0, CW_{max}]. Like CW_{min}, CW_{max} is normally shorter for high priority ACs. Figure 3.6 shows an example of how the CW interval is calculated at each transmission retry.

Table 3-2: Default EDCA parameters [31]

AC	CW_{min}	CW_{max}	AIFSN	TXOP limit	
				802.11b	802.11a/g
AC_BK	aCW_{min}	aCW_{max}	7	0	0
AC_BE	aCW_{min}	aCW_{max}	3	0	0
AC_VI	$(aCW_{min}+1)/2-1$	aCW_{min}	2	6.016 ms	3.008 ms
AC_VO	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$	2	3.264 ms	1.504 ms

aCW_{min}, aCW_{max}: [0, 32767]; AIFS=SIFS+AIFSN×SlotTime
Example for 802.11a : aCW_{min} = 15, aCW_{max} = 1023, SlotTime = 9μs, SIFS = 16μs

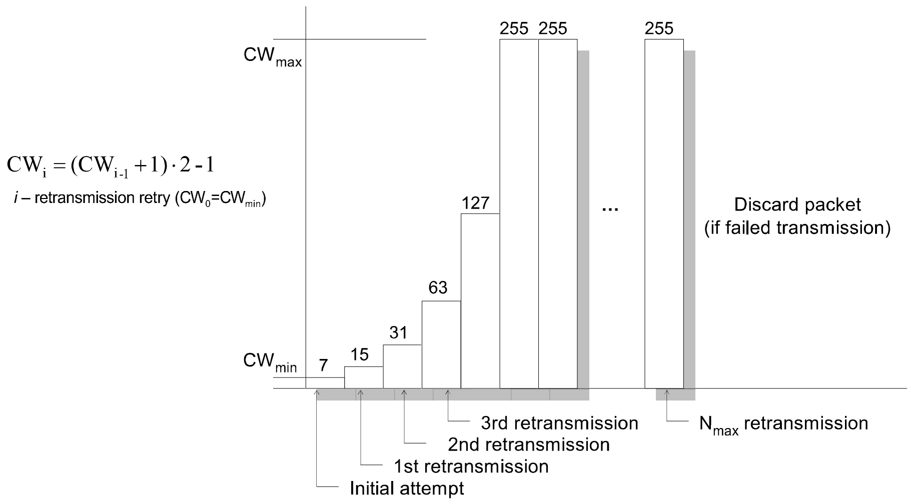


Figure 3.6: Example of exponential increase of CW [31]

Based on the above explained EDCA parameters, each AC competes independently for TXOP. When the AC detects the medium being idle for AIFS[AC] it starts its backoff period. If there is an internal collision between ACs within a station (virtual collision), then the AC with the highest priority receives TXOP, while ACs with the lower priorities behave as if it were an external collision.

Figure 3.7 shows the relationships between Inter-Frame Space values for different 802.11 coordination functions. It is interesting to note that default DIFS values are shorter than default AIFS values for some ACs, which leads to the fact that legacy DCF stations can have higher priority over EDCA stations. There are different approaches of how to configure EDCA parameters such that the fair sharing of the media between legacy and EDCA stations is achieved. In [32], the authors study such approaches and review the coexistence problem between EDCA and legacy DCF stations in detail.

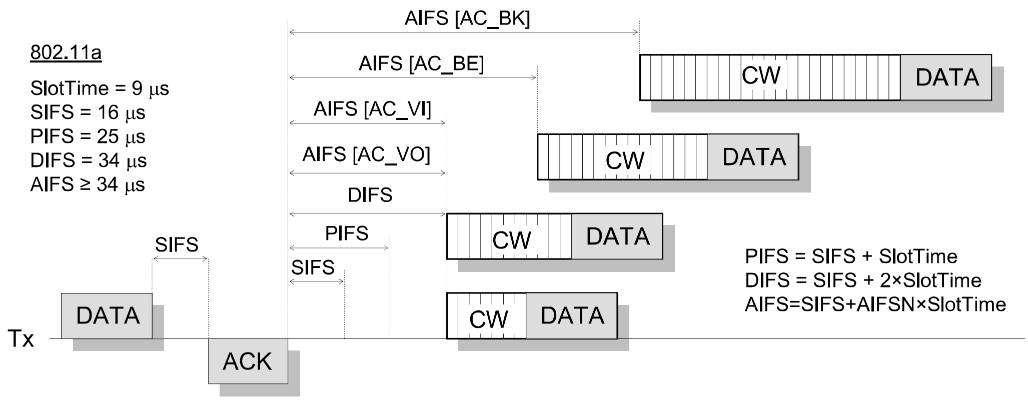


Figure 3.7: 802.11 Inter-Frame Space relationships

We also study the performance of the EDCA mechanism in Chapter 5 where our analytical model for EDCA function is presented.

3.4.2.2 HCCA

HCCA is an extension to PCF, which provides parameterized QoS services. HCCA uses a Hybrid Coordinator (HC) to centrally manage the wireless medium access among the stations. The HC controls the use of the media through the use of polled TXOPs. The TXOP specifies duration of time granted by the HC for transmission, which are transmitted within QoS control fields when the HC sends a poll to a station. The decisions about how much time to allocate for transmission to each station are made by the HC based on the Traffic Specification (TSPEC) used by stations to specify their specific traffic requirements such as data rate, latency and packet size. Therefore, the HC performs a role of a scheduler that manages the packets based on stations' TSPECs and provides contention-free frame exchange trying to minimize inter-frame delays. The 802.11e standard specifies the signalling protocols for exchange of information between the scheduler and wireless stations, but the standard does not define how the scheduler must work. This had made a widespread adoption of the HCCA standard more complicated and became the subject of interest mainly for researches. Different proposals for new scheduling algorithms for HCCA and problems of video transmission over HCCA are considered in [72], [73], [74], [75].

3.4.2.3 Optional 802.11e features

Apart from EDCA and HCCA functions, the 802.11e standard defines also other MAC enhancements. The main MAC enhancements are reviewed below.

3.4.2.3.1 Contention Free Bursts

Contention Free Bursts (CFB) is an optional feature in 802.11e, which allows a station to send several data frames in a row without competing for the medium. CFB can be used when a station has some remaining time in a granted TXOP. Rather than competing for the medium again as it would be required in the legacy MAC, a station can continue data transmission after the SIFS interval (Figure 3.8).

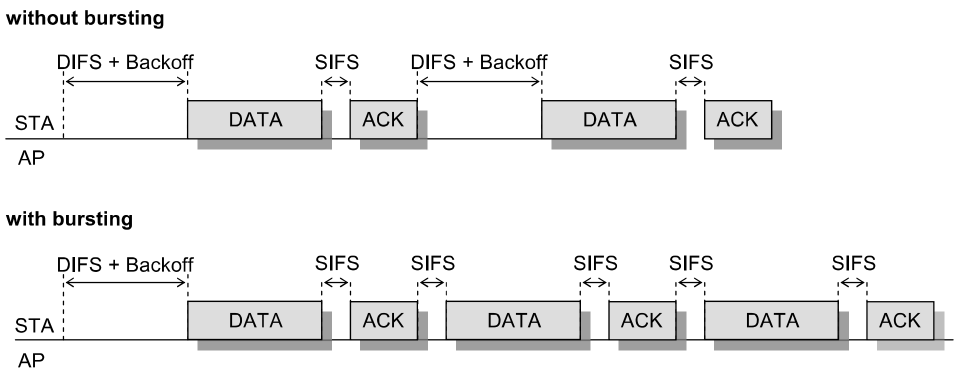


Figure 3.8: Data transmission with and without CFB

In general, CFB can considerably improve the network efficiency [71]. CFB can be also used to increase the performance of 802.11g devices in the presence of 802.11b legacy stations [76].

3.4.2.3.2 Block Acknowledgments

In the legacy 802.11 standard, each successfully received unicast frame requires an immediate ACK frame. The 802.11e standard adds the following new rules with respect to ACKs.

- **No ACK**. In this mode, the data frames are never acknowledged with ACKs. This increases the overall efficiency. It can be mostly useful for applications with very low delay requirements, which nevertheless can cope with considerable amount of packet losses (e.g. VoIP).

- **Immediate Block ACK**. In this mode, the sender can transmit multiple data frames in a CFB during TXOP separated by SIFS. After data transmission, the sender sends a block ACK request to the receiver. The receiver responds with a block ACK containing the status about all previously sent data frames.

- **Delayed Block ACK**. Similar to the immediate Block ACK mode, the receiver can acknowledge the reception of several data frame with a single Block ACK frame. However, a Block ACK frame is sent not immediately, but in a subsequent TXOP following the burst. This mode increases the latency, but ensures more time for calculating the ACK for systems with lower performance.

Immediate Block ACKs greatly improve the overall performance for some applications. The performance study of the 802.11e MAC enhancements including new block acknowledgement improvements are described in [71].

3.4.2.3.3 Admission Control

The admission control mechanisms are defined in the 802.11e standard for contention-based access and for controlled access. Therefore, the parameterized QoS can be provided in 802.11e not only by means of the HCCA function, but also with the help of the EDCA mechanism used in conjunction with the admission control functionality. As the HCCA function is not widely implemented in today’s products, we consider admission control with EDCA of greater interest for this overview and give a detailed description below.

In principle, admission control can be applied to any access category (AC), but the 802.11e standard contains a recommendation to not apply admission control to the best-effort and background ACs (AC_BE, AC_BK). When admission control is enabled for a certain AC, the corresponding Admission Control Mandatory (ACM) field is activated. The ACM field is always transmitted by an access point (AP) within a beacon. If the ACM field is activated, a station, which wants to use this AC, has to send an Add Traffic Stream (ADDTS) request to the AP with the TSPEC of the new flow. Based on the TSPEC and current network state, the admission control management entity at the AP decides whether to admit the new flow with the requested TSPEC, suggests another TSPEC or rejects the request. When decision is made, it is sent within an ADDTS response frame back to the station. If the AP accepts the request, it has to include the medium time in the ADDTS response, which specifies the granted time for EDCA access. If the station is satisfied with the response, the transmission is started. Otherwise, the station can try to send an ADDTS request later. When the transmission is over, the station sends a DELete Traffic Stream (DELTS) request to let the reserved resources for this flow released. Figure 3.9 shows a message sequence diagram for this process.

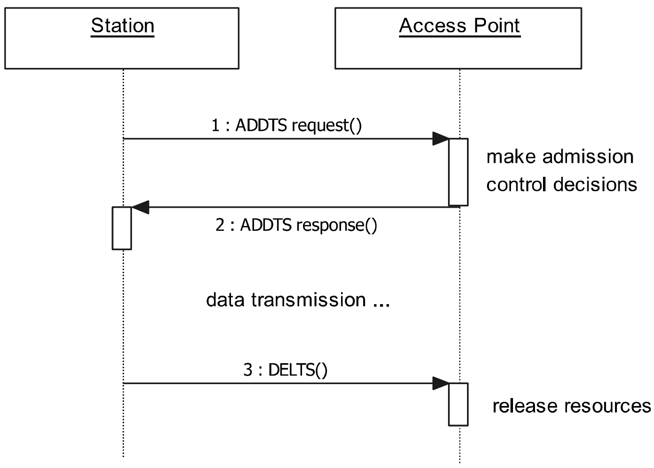


Figure 3.9: 802.11e admission control process for EDCA

The 802.11e standard thoroughly defines all signaling messages for admission control process. However, the algorithm used by the admission control management entity at the AP is not defined in the standard. In general, this is not a trivial task due to many different local factors and nature of the wireless media. Admission control algorithm normally depends on implementations of schedulers, available channel capacity, link conditions, retransmission limits, and the scheduling requirements of a given TSPEC [30]. The 802.11e standard gives some general recommendations for admission control, but in practice the AP can use any algorithm for making admission control decisions.

3.4.2.3.4 Direct Link Protocol

The legacy 802.11 standard allows traffic in the infrastructure network to flow only between access point (AP) and wireless stations. The Direct Link Protocol (DLP) defined in 802.11e permits the stations to directly send data to each other without sending the data through the AP. This feature increases available bandwidth for station to station by two times. The setup process for DLP is depicted in Figure 3.10.

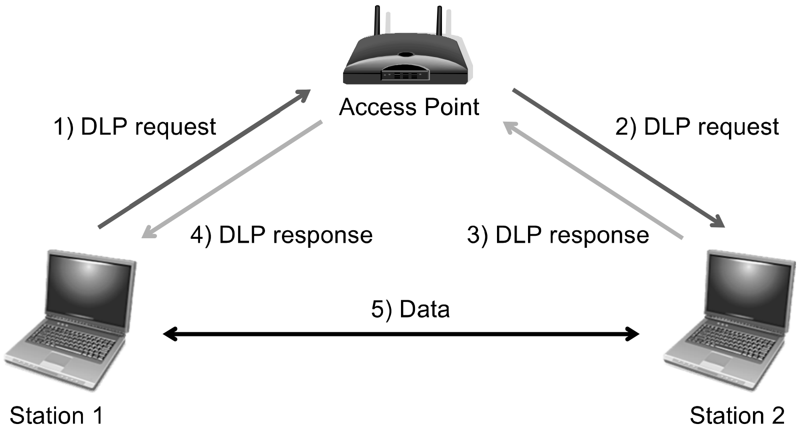


Figure 3.10: Direct link protocol

In spite of the obvious advantages, the DLP is not widely implemented so far and not supported by the WMM certification program (described in the next section), which is likely due to the complexity introduced by the direct link setup mechanism.

3.4.2.4 Wi-Fi Multimedia

Wi-Fi Alliance certifies 802.11e devices under the certification program called Wi-Fi Multimedia (WMM) [28]. WMM is a subset of the 802.11e standard, as it does not fully cover the standard. The WMM program includes only EDCA compliant products [40]. WMM provides four priority levels corresponding to different types of traffic: voice, video, best-effort and background (from highest to lowest priority). Other features are not part of WMM, but they are implemented in products by some vendors. The WMM compliant devices have been available on the market since 2004 and widely implemented in today's products.

The WMM-Scheduled Access (WMM-SA) is a subset of the 802.11e standard that was founded to develop a certification program for HCCA compliant devices. However, HCCA was not widely adopted in the industry because of the lack of infrastructure availability, and in 2006 the WMM-SA task group was closed. Unlike WMM-SA, WMM already had by that time all required infrastructure in place. WMM was also more applicable for existing applications and since then has become the only technology being certified by Wi-Fi Alliance to address QoS issues.

3.4.3 End to end priority-based QoS in WLANs

Since priority-based QoS (WMM) is the only QoS mechanism broadly available today in WLANs, we describe here how it works end to end within the home network.

For a network to provide differentiated services for particular applications or streams, first of all, the network requires a classification mechanism separating traffic into different groups or classes. Secondly, the network needs a mechanism providing differentiated medium access for identified classes so that each class of flows can be handled selectively (e.g. WMM). The classification mechanism performs usually tagging or marking of packets. Classification is possible at different layers of the protocol stack and based on different classification criteria (e.g. source address, destination address, source port, destination port, protocol). The example of existing classifications is given in Figure 3.11.

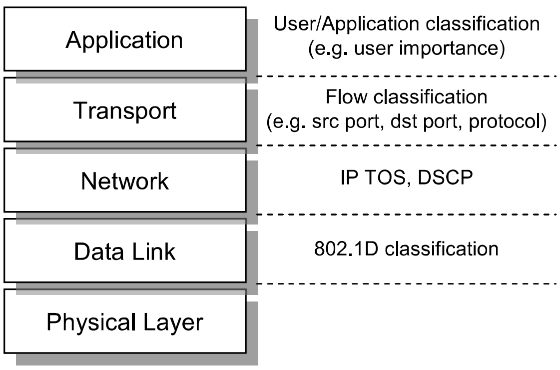
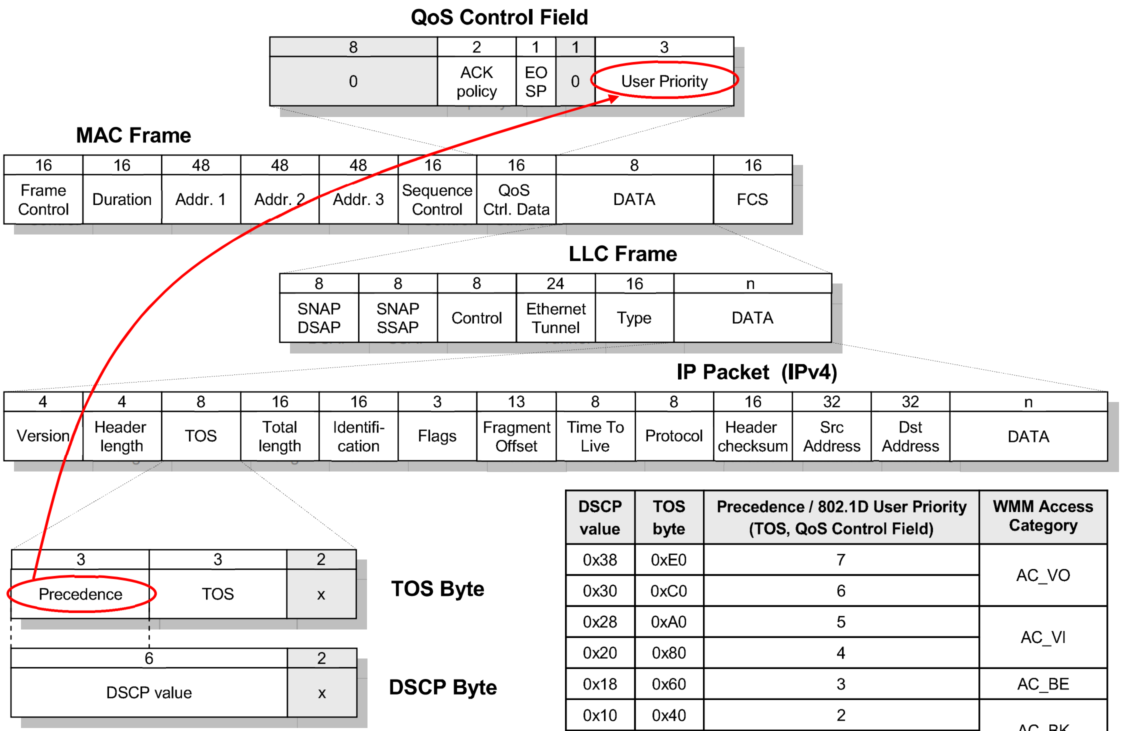


Figure 3.11: Existing classification mechanisms on OSI Layers

The WMM certification requires all packets to be marked with an appropriate IP TOS (Type of Service) or Differentiated Services Code Point (DSCP) tag in IP packets (layer 3). A wireless driver of the WMM certified device makes use of this information by putting the packets into one of the four WMM transmission queues and adding a QoS header to the 802.11 MAC frame (layer 2). The relationship of TOS, DSCP fields and WMM access categories is shown in Figure 3.12.



DSCP value	TOS byte	Precedence / 802.1D User Priority (TOS, QoS Control Field)	WMM Access Category
0x38	0xE0	7	AC_VO
0x30	0xC0	6	
0x28	0xA0	5	AC_VI
0x20	0x80	4	
0x18	0x60	3	AC_BE
0x10	0x40	2	AC_BK
0x08	0x20	1	
0x00	0x00	0	AC_BE

Figure 3.12: Relationship of TOS, DSCP fields and WMM access categories

According to the original definition of the TOS octet in the IP header in RFC 791 [42], the first 3-bit subfield was defined as Precedence and the second 3-bit subfield was defined as TOS field followed by the two unused bits at the end. In practice, only the Precedence field carrying 802.1D priority was in fact ever used. The definition of the entire field was completely changed in RFC 2474 [43], where DSCP fields were specified for DiffServ architecture [44]. The DSCP byte consists of a 6-bit Per-Hop Behavior (PHB) field used for packet classification purposes and 2 unallocated bits. Theoretically, a PHB field can be used for specifying up to 64 different DiffServ traffic classes. However, usually only the classes defined in RFC 4594 [45] are used (Table 3-3). For backward compatibility with the Precedence field the Class Selector (CS) codepoints are defined. These are the first 6 bits of the DSCP byte represented in the form 'xxx000', where the first 3 bits are the IP precedence bits. Thus, the Precedence values can be easily mapped into a DeffServ class. Sometimes, the network is configured such that only the first 3 bits of the DSCP field is analyzed and considered as the IP precedence field.

Table 3-3: DSCP to service class mapping [45]

Service Class Name	DSCP Name	DSCP Value	Application Examples
Network Control	CS6	110 000	Network routing
Telephony	EF	101 110	IP Telephony bearer
Signalling	CS5	101 000	IP Telephony signalling
Multimedia Conferencing	AF41 AF42 AF43	100 010 100 100 100 110	H.232/V2 video conferencing (adaptive)
Real-time Interactive	CS4	100 000	Video conferencing and interactive gaming
Multimedia Streaming	AF31 AF32 AF33	011 010 011 100 011 110	Streaming video and audio on demand
Broadcast Video	CS3	011 000	Broadcast TV and live events
Low-Latency Data	AF21 AF22 AF23	010 010 010 100 010 110	Client/server transactions, Web-based ordering
Management	CS2	010 000	Administration, management, provisioning
High-Throughput Data	AF11 AF12 AF13	001 010 001 100 001 110	Store and forward applications
Standard	CS0	000 000	Undifferentiated applications
Low-Priority Data	CS1	001 000	Any flow that has no bandwidth assurance

CS – Class Selector; AF – Assured Forwarding; EF – Expedited Forwarding

For prioritized services to work end to end the classification mechanism has to appropriately mark outgoing packets and the network has to correspondingly interpret and maintain the markings along the transmission path. For example, there might be a need to configure some policy rules at the access point specifying how to map incoming packets with DSCP tags (layer 3) into the layer 2 classes of services.

3.4.4 802.11aa Video Transport Study Group

The 802.11e standard was mainly designed to address the requirements of VoIP applications. The WMM certified AP can provide multiple VoIP calls with good quality minimizing the latency and jitter in the presence of other traffic of lower priority. The standard does not address all problems of the video traffic, though. Due to high bandwidth requirements of the video applications, video streaming is often performed in the network close to the saturated state. In the network saturated with the high priority video traffic it is not possible to provide a high quality service for any application. There is also a problem with multicast video streaming. In unicast mode, the 802.11e standard requires each successfully received frame to be acknowledged with the ACK. However in multicast mode, the frames are not acknowledged, which leads to significant packet losses and quality degradations. This can be addressed today with the help of error correction methods at the higher layers [26], [33]. To address this and other problems of video streaming at the MAC layer, the IEEE has recently founded the 802.11aa Video Transport Study (VTS) group[1]. The goal of the group is to design the MAC enhancements to provide robust streaming of audio and video transport streams. For reliable multicast and broadcast audio video services the following features will be considered.

- Smooth degradation of AV quality when there is insufficient channel capacity.
- Improved link reliability and low jitter characteristics.
- Efficient error control.
- Various EDCA and Block ACK extensions to improve multicast services.

The 802.11aa is now in the initial phase defining its goals and requirements. Hopefully, it will be the next big step in providing strict QoS services in the 802.11 networks.

3.5 QoS management solutions for home networks

Broadband access networks are usually professionally managed to guarantee high quality delivery of network services. Home networks, on the contrary, are typically not professionally managed by home owners, who normally do not want to be actively involved in management tasks. Furthermore, home networks come in many different flavors and consist commonly of a variety of various technologies offering different QoS capabilities. All these factors do not let the network and service providers deliver guaranteed services within the home networks. That is why many companies are interested now in unique solutions for supporting QoS services within the home. Below we describe some existing work and ongoing efforts performed by various SDOs towards the home network QoS management solutions.

[1] IEEE 802.11aa Task Group: Robust streaming of Audio Video Transport Streams http://www.ieee802.org/11/Reports/tgaa_update.htm

3.5.1 DLNA QoS

QoS is an essential part of the DLNA interoperability guidelines document. The last version of the document [39] defines a prioritized QoS solution based on existing industry standards such as 802.1D, WMM, DSCP. For interoperability purposes the guidelines document specifies layer 2 and layer 3 priority mapping. The DLNA QoS priority mapping of the specific DLNA traffic types is presented in Table 3-4.

Table 3-4: DLNA QoS priorities [38]

DLNAQOS_UP	DLNA Transfer Mode	802.1Q User Priority	WMM Access Priority	DSCP	DLNA Traffic Types
DLNAQOS_3 (Highest)	Streaming (Audio & Video)	7	AC_VO	0x38	• RTCP messages generated by Content Receivers
DLNAQOS_2	Streaming (Audio & Video)	5	AC_VI	0x28	• Audio-only or AV Streaming • UPnP AVTransport stream control • RTCP messages generated by Content Sources • RTSP messages
DLNAQOS_1	Interactive (Images)	0	AC_BE	0x00	• Default priority for any traffic • Interactive transfers (transfer of Images for immediate rendering)
DLNAQOS_0 (Lowest)	Background (All Media Classes)	1	AC_BK	0x08	• Background transfers (transfer for rendering at another point in time)

It is envisioned that in the forthcoming home networks a prioritized QoS solution will not be able to meet all requirements of home users and service providers. If the total network demand exceeds network capacity, all streams (also of high priority type) might be impacted. That is why in DLNA there are currently some activities towards addressing the QoS issues at a more enhanced level. It is expected that for future DLNA guidelines, more advanced QoS solutions providing parameterized QoS like UPnP QoS v3.0 (described next) might be considered.

3.5.2 UPnP QoS

The description of the UPnP QoS architecture is important for this thesis since many general concepts from the architecture were adopted for our work.

During the last several years, UPnP has been working on a QoS management system for home networks. Starting in 2005 with the first standard specifications describing the general QoS network architecture, it has already issued the third version, UPnP v.3 QoS [35], enhancing the original framework with new functionalities. UPnP QoS defines mechanisms for managing QoS in heterogeneous home networks with different Layer 2 technologies. Initially, it was defined as a priority-based QoS architecture with the policy-based management. Afterwards, it was extended with the admission control and flow pre-emption functionalities to provide parameterized QoS, Figure 3.13.

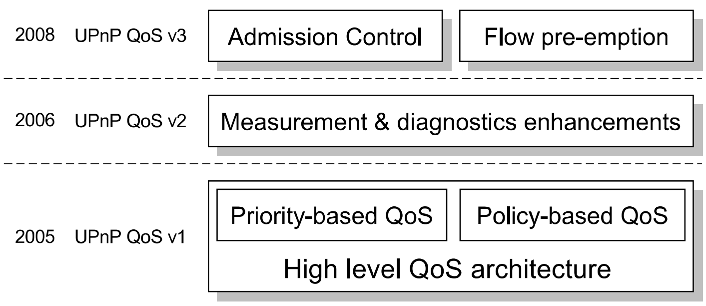


Figure 3.13: UPnP QoS specification versions

The high level UPnP QoS architecture is depicted in Figure 3.14. The key components defined in the architecture are the three services: QoS Manager, QoS Device and QoS Policy Holder. The QoS Manager service is the central entity of the architecture, which requests, updates and releases QoS resources for all traffic streams in the network. The QoS Device is responsible for managing its local QoS resources in accordance with the QoS Manager's decisions. UPnP QoS is a policy-based system and QoS Policy Holder is a QoS policy repository used by the QoS Manager for making decisions with respect to traffic classifications, resource reservations and admission control.

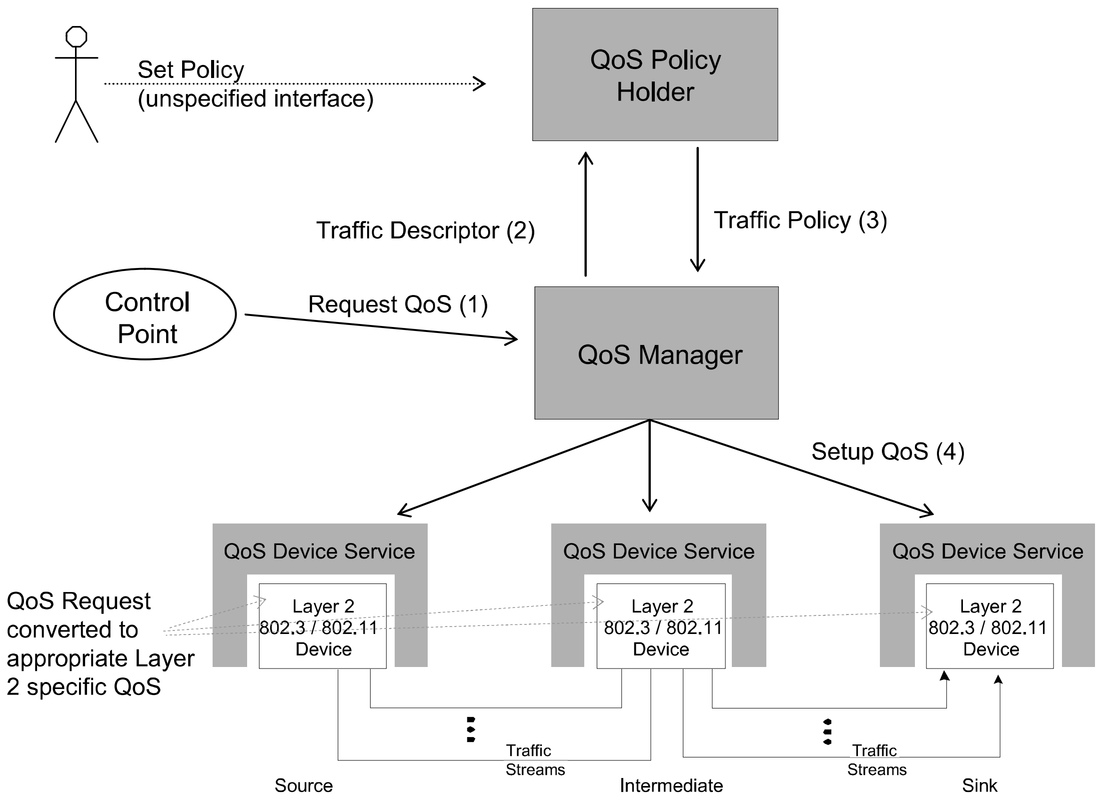


Figure 3.14: High level UPnP QoS architecture

The theory of operation is explained next (numbering of steps as in Figure 3.14).

1) Based on the knowledge about the source, sink and streamed content, the control point constructs a traffic descriptor structure, which is sent as a response to the QoS Manager to set up QoS for a traffic stream.

2) The QoS Manager requests the QoS Policy Holder service to provide an appropriate policy for the traffic stream described by the received traffic descriptor.

3) Acting as a policy repository, the QoS Policy Holder returns the QoS Manager an appropriate policy for the requested stream.

4) The QoS Manager configures all QoS Devices within the stream path to handle the traffic according to the issued traffic policy.

The structure of the QoS traffic policy returned by the QoS Policy Holder to the QoS Manager is shown in Figure 3.15. Mainly, it contains a traffic importance number and user importance number. The admission policy value is ignored for UPnP QoS v.3 as it is always “enabled” for parameterized QoS. The user importance value is used by the

QoS Manager for making admission control and preemption decisions. It ensures that the traffic streams that are most important for users receive access to the network resources. If the network resources are saturated, the insufficient resources can be taken from the blocking traffic streams with the lower user importance numbers, which is called *preemption*.

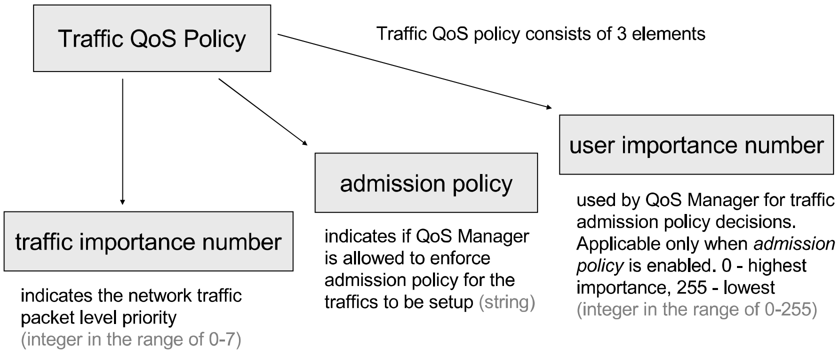


Figure 3.15: Traffic QoS Policy description

The traffic importance value specifies a traffic stream's priority, which is mapped finally by the QoS Device service to a Layer 2 priority and used as a basis for providing prioritized QoS services. The relationship between traffic importance values, DSCP tags, 802.1D and WMM priorities is shown in Table 3-5. The QoS Device addendum [36] contains other recommendations of mapping UPnP traffic importance numbers to various Layer 2 technologies such as HomePlug, HomePNA and MoCA. Further in this thesis, we also use a concept of traffic importance number, which is mapped to the WMM priorities according to Table 3-5.

Table 3-5: UPnP traffic importance mapping

UPnP traffic importance	VLAN / IEEE 802.1D priority	DSCP tag	WMM priority
0	0	0x00	AC_BE
1	1	0x08	AC_BK
2	2	0x10	AC_BK
3	3	0x18	AC_BE
4	4	0x20	AC_VI
5	5	0x28	AC_VI
6	6	0x30	AC_VO
7	7	0x38	AC_VO

While providing powerful means for prioritized and parameterized QoS services in home networks, UPnP QoS considers some important functionality to be out of scope. In Chapter 4, we analyze what essential features are not addressed by the UPnP QoS architecture.

3.5.3 DVB QoS

The main concern of DVB with respect to home networking is delivering and distributing IPTV services. As home users are expected to distribute the incoming TV services within the home environment along with other traffic, there can be contention for home network resources leading to inability to deliver audiovisual data reliably and consistently. As stated in the DVB home network reference model [10], the first phase of the DVB home network specification will define only a prioritized QoS solution based on the DLNA interoperability guidelines [39]. This might not be enough for providing reliable services in case of network congestion when the quality cannot be guaranteed for any service, including high priority flows. Thus, DVB recognizes that currently there is a strong need for developing QoS mechanisms to improve the quality of streamed content through the home network and to deliver IPTV services to home users reliably. In September 2008, DVB has published a DVB Blue Book with the high-level QoS requirements for the home network [37] as input to technical groups and other SDOs for development of such QoS mechanisms. Along with the general technical high level QoS requirements this document also proposes a new framework for QoS management. This framework, depicted in Figure 3.16, is described as a logical reference model including a set of logical entities and interfaces for enhanced QoS management.

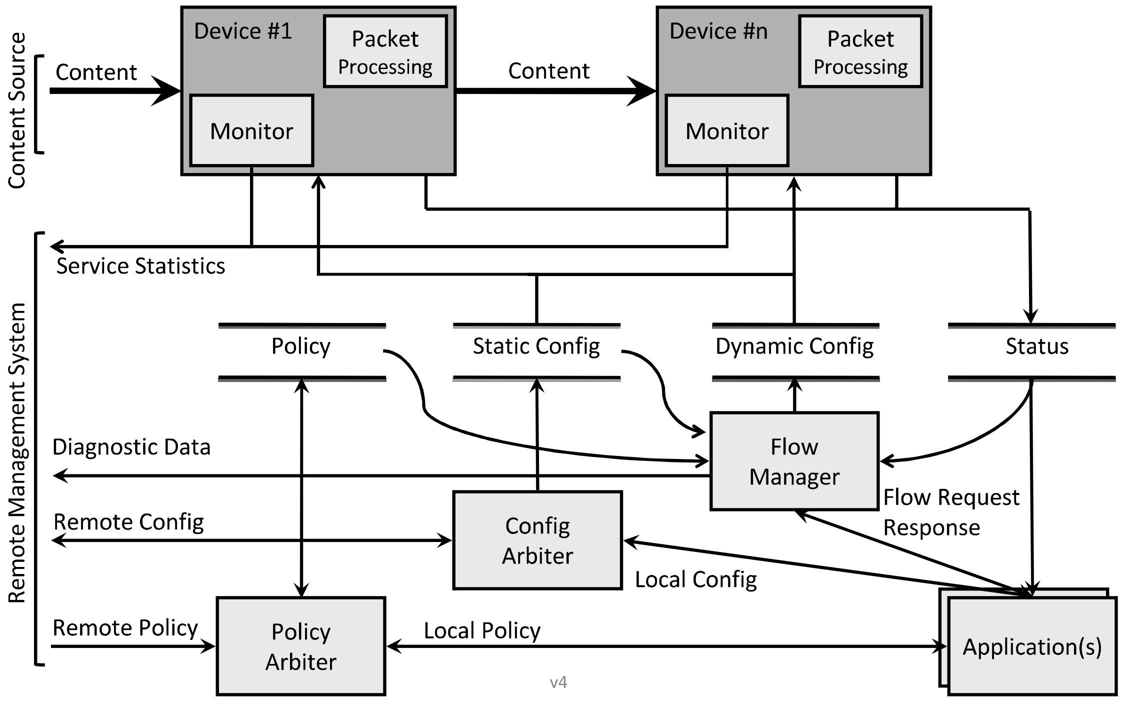


Figure 3.16: DVB home network QoS functional reference model

Below we give a short overview of the main DVB QoS framework's entities. All entities are not directly associated with any physical devices and can be distributed within the home network.

- **Flow Manager**. Based on the incoming flow requests from the applications, the Flow Manager centrally manages the content flows and network resources such that the QoS requirements of services are satisfied as much as possible.

- **QoS repositories**: Static Config, Dynamic Config, Status, Policy. These are data sets used for storing status, policy and configuration information for network, devices and content flows.

- **Packet Processing**. This entity is supposed to be a part of each device to perform the following functions on the incoming IP packets: classification, marking, policing, routing, queuing and other application specific functions such as conversion of multicast to unicast.

- **Monitor**. This entity is also supposed to be a part of each device. The Monitor collects various service statistics about content flows for remote diagnostics and service monitoring.

- **Policy Arbiter**. The QoS policy in the home network can be set according to the rules of a service provider (*opt-in*, Remote Policy) or a home user (*opt-out*, Local Policy). The Policy Arbiter is a logical process with the help of which the QoS policy is set in the network based on the current local and remote policies.

- **Config Arbiter**. This is also a logical process that merges the user configuration provided by the Application entities (Local Config) and the service provider configuration provided by the remote management system (Remote Config).

As an example of how this reference model can be used in DVB home network, DVB also provides mapping of all entities to the logical DVB HN devices defined in the DVB HN reference model [10]. For general alignment in development of an enhanced QoS solution for home networks, DVB contributed this model to many other SDOs (DLNA, UPnP, HGI, ATIS, TISPAN, EBU, Open IPTV Forum). Therefore, there are some reasons to believe that the future home networks will include many of the technical concepts presented in the DVB QoS reference model. There are also many common concepts in the DVB QoS framework and the work presented in this thesis.

3.6 Conclusion

The modern applications impose stringent requirements on the underlying technologies. Strict latency and jitter requirements for video and voice applications, high bandwidth demands for HDTV streaming and fast file downloads make the delivery of high quality services over wireless networks a truly challenging task. Various SDOs and research communities have been trying to address the QoS problems over wireless with a number of mechanisms at different network layers. For general interoperability, many approaches have been standardized and also globally accepted (e.g. WMM, DLNA QoS). Many new solutions are on their way towards standardization and widespread acceptance (e.g. SVC, DVB QoS, UPnP QoS v3). There are also some new efforts to design 802.11 enhancements for providing robust streaming of audio and video transport streams (802.11aa VTS group). Along with the evolvement of wireless technologies considered in the previous chapter (802.11n, Gbit Wi-Fi), the currently under development and upcoming QoS mechanisms might considerably improve the user experience in wireless networks. In the next chapter, we introduce our work and discuss how the contributions of this thesis can facilitate to the general process of the development new mechanisms improving user experience in wireless home networks.

4 User-centric management approach

4.1 Introduction

In the previous chapter we discussed the existing and evolving QoS mechanisms and QoS management approaches. It is seen that in general, a QoS solution might include a set of QoS mechanisms at different OSI layers (e.g. scheduling, transcoding techniques, MAC enhancements) and a management approach specifying how a system can use the available QoS mechanisms for improving the delivered quality of services. The question we are going to raise in this chapter is about how a system decides how to use the existing QoS mechanisms and how to manage network resources such that the user experience is improved. For example, the current state of the art relies mainly on classifying packets on a per-flow basis and prioritizing one type of traffic over another. How do end-hosts and applications decide what priority a certain data stream should have? For appropriate packet classification and end-to-end QoS support a corresponding network policy has to be deployed and properly maintained between devices on the home network. The QoS management approach that we present in this chapter is policy based and user-centric meaning that network resources are handled according to user preferences. Unlike traditional QoS approaches that always give multimedia applications a pre-determined high priority due to their strict latency and loss requirements (e.g. Wi-Fi Multimedia), the proposed approach classifies traffic according to user preferences, thus, ensuring a certain quality regardless of the application requirements. The application priorities are assigned according to user profiles and automatically updated in case of changes in the network or user environment. The implementation details and experimental results presented in this chapter demonstrate a practical application of the described approach and improvement of the user experience in wireless home networks.

4.2 User-centered design

Before we describe our user-centric QoS management approach, we would like to shortly introduce a user-centric or user-centered design approach in general. The term "*user-centric*" has been used recently in a broad context. Originally, it became widely used as "*user-centered design*" in 1986 after the publication of a book entitled "User-Centered System Design: New Perspectives on Human-Computer Interaction" [47]. User-centered design is a broad term for a philosophy and variety of methods which focus on designing for users and sometimes involving users in the design of computerized systems. This implies placing the user at the center of the system design (in our case network design). The role of the designer is to address key user requirements and to make sure that the user will be able to use the system as intended with intuitive interfaces and with a minimum effort to learn how to use the system. With respect to home networks, user research studies showed that home network technologies will be successful only if they will provide a user-centered network design that can truly make in-home communication more effective and consumers' lives more harmonious [48].

The term "*user-centric*" has also been widely used recently in a broader sense with respect to the role of a user in the future internet. Currently, eighteen collaborative European projects exclusively aim at developing new user-centric media solutions [49]. These projects are members of the User Centric Media cluster organized by the European Commission. In [50], user centricity is listed among the most important research topics. It is recognized that users will be at the center of the future internet and there is a need to develop service models, concepts and tools such that users will be able to easily customize service behaviors (not just content). Obviously, this user-centric role in relation to the internet services has a tight connection with the home network services, where users consume and distribute both internet and intranet services. Therefore, new approaches are also required for personalization and personalized delivery of services within the home networks.

With regard to the user-centric multimedia access in home networks the related work is reviewed in [51]. The authors describe the main requirements for a user-centric multimedia access system, which include easy access to the available content, seamless consumption of the content, content adaptation and user mobility. The authors also propose an approach for a user-centric home multimedia system based at the moment on the UPnP AV architecture. A personalized media access is also described in [52], where authors consider a user-centric media environment, which includes mobile networking, user-centric interfaces and multimedia content manipulation. In particular, the authors consider the problems of the seamless content delivery for mobile users, handover mechanisms across different communication networks and adaptable content management. In [53], another side of user-centricity is considered, namely, personalized media streaming. The authors describe a user-centric personalized broadcasting platform, which enables users to select certain actors and objects of interest within real-time broadcasted scenes. For example, a user watching a large scale athletic event is considered to be able to request streaming of data concerning a particular athlete in a race.

Along with the research community, enterprises and service providers also reveal a great interest in the user-centric approaches. For example, Alcatel-Lucent is well known for pushing its user-centric broadband access solutions [54]. The user-centric broadband experience is supposed to give the users the ability to use all the services to which the users have subscribed from any location and using any device. Today, there is a variety of broadband access options such as DSL, UMTS, satellite and public WLAN. To improve the user experience when using these multiple technologies, there is a move to deploy some access solutions that could enable users to always access their applications from anywhere via the best available network, at the highest possible data rate, through a single subscription and using any device. Alcatel-Lucent provides such solutions to internet service providers and enterprises for delivering voice, data and video services. The idea of the user-centric broadband access concept is well expressed in Figure 4.1.

While the user-centered design has been considered in networks for addressing various problems, it has not been so widely considered for solving QoS management tasks. Only some recent IETF drafts address this problem. In [59], [60], [61] the authors consider the user-centric QoS policy management for heterogeneous Internet environment including requirements for users, service providers and network operators. They consider how to manage user-centric business polices, which can enable the users to dynamically configure QoS mechanisms at transport and network layers according to user and network QoS preferences. For example, a user policy can define how to handle a particular application in the DiffServ enabled access network based on the provided DSCP field for this user's application. The scope of our work is different. Our effort is aimed at addressing user-centric QoS requirements in home networks, which is described in detail in the next sections.

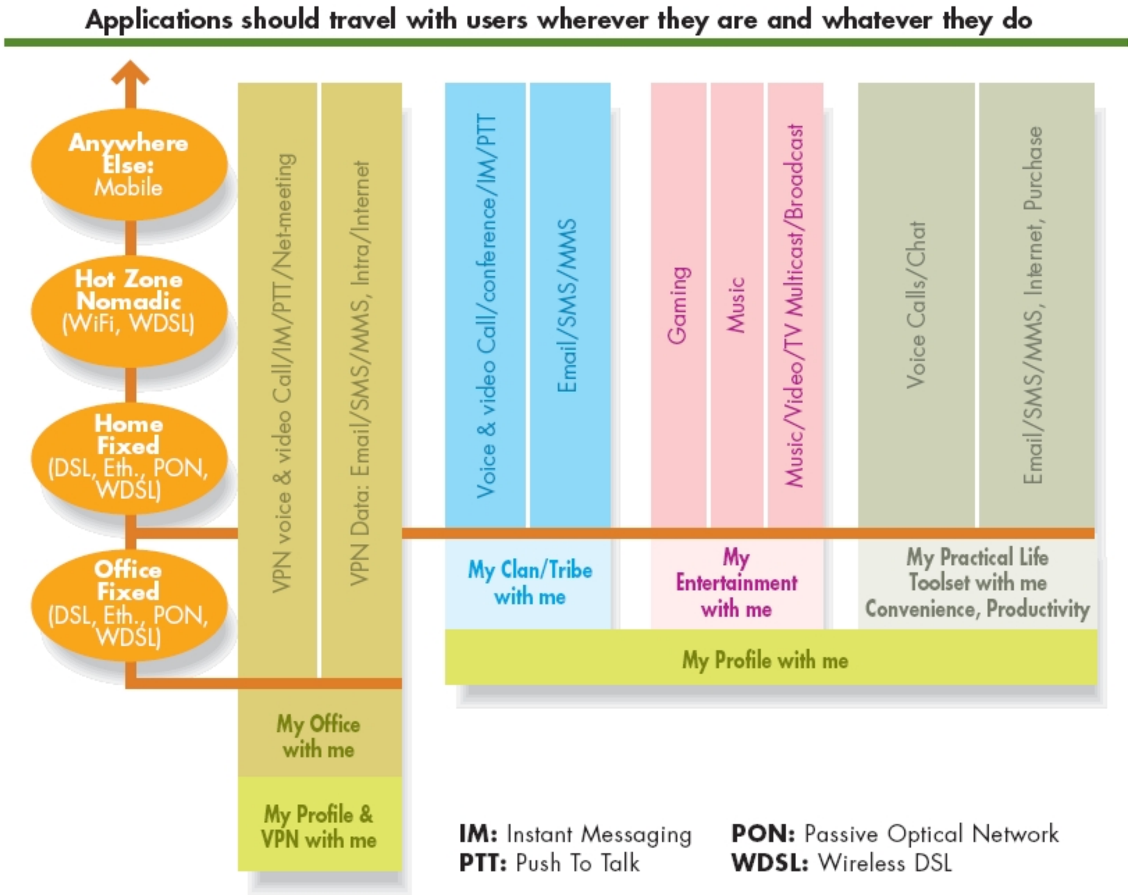


Figure 4.1: Example of a user-centric broadband access solution [54]

4.3 User-centric QoS management approach

Below we give motivations for developing a QoS management system for home networks in a user-centric manner and describe the related work.

4.3.1 Motivation

The growth of home networking recently has been phenomenal. Due to the increased number of home PCs, broadband availability and more efficient wireless technologies, there are many users now who can use their home network to browse the web, check e-mails, do business and play games from every room in the house. The variety of home network applications is even increasing now with the growth of IPTV services and convergence of broadband and broadcast technologies. However, in spite of the fact that the modern technology offers attractive wireless solutions with high throughput performance, the existing wireless networks are not ready yet to satisfy users' quality expectations in wireless networks. As was discussed in the previous chapter, due to bandwidth variations and high error rates, a number of QoS mechanisms have to be deployed in the network in order to guarantee a certain level of quality.

In order to meet the special needs of digital audio/video streaming, WMM [28] provides means to prioritize voice and video traffic above other data traffic. The WMM access categories are by default associated with the specific traffic types and priorities. Similarly, other technologies associate their relevant traffic classes with the particular priority levels. The default prioritization schemes for WMM, UPnP and DLNA are shown in Table 4-1. The highest priorities are normally allocated to the applications with the strict latency and throughput requirements (e.g. voice, video).

Table 4-1: Prioritization schemes IEEE 802.1D, UPnP, DLNA, WMM

Default Priority	802.1D Traffic Type	UPnP Traffic Class	DLNA Traffic Type	WMM Access Categories
7 (highest)	Network Control	Network Control Streaming Control	Network Control (RTCP)	Voice
6	Voice	Voice, Gaming	-	
5	Video	AV, Audio	AV, Audio, RTCP RTSP, Stream ctrl.	Video
4	Controlled Load	-	-	
3	Excellent Effort	Images	-	Best Effort
0	Best Effort	Data, Other	Images, Other	
2	-	-	-	Background
1(lowest)	Background	Background	Background	

The result of such prioritization is that non-multimedia flows such as web browsing, email and download traffic are the first to suffer in case of bandwidth limitations. While it is true that non-multimedia applications are more delay tolerant, in situations where one application needs to be sacrificed in favor of the other, different users may have their own preferences. For example, a user may prefer a lag-free text-chat and sacrifice his audio stream that is running in the background. In case of running several multimedia applications a user may also prefer one type of application over the other. For instance, a user running a sports broadcast while listening to the favorite internet radio station may consider one more important than the other. Taking into account the rapid development of digital broadcasting technologies and upcoming convergence of broadcast and broadband services, we expect that audiovisual applications will run in the background like today's radio and sometimes TV broadcasts, while the preferred application might be a game or a file download operation.

The need of assigning priority levels not according to the default schemes is also observed in small and medium-sized office LAN and WLAN networks. In [79] it is discussed that for companies that do not require streaming media for daily operations, the traffic on the network can be prioritized by giving high priority to e-mail, database, transactional and core business applications, and low priority to bandwidth eaters such as streaming media.

As typical application-oriented QoS prioritization schemes will fail in the scenarios considered above, we propose a user-oriented QoS management approach where user preferences are considered as a main part in determining the level of service the applications receive. While WMM is primarily meant to support multimedia applications, it is still possible for the network owner to freely choose the most appropriate priority for particular traffic. In our approach, the default priority levels for WMM access categories (Table 4-1) are modified such that specific user requirements are met.

Although there are different proposals in the literature for user-oriented QoS, our approach differs from others. A user can usually specify QoS requirements only with respect to the perceived application quality or cost related options. For example, user preferences may contain the preferred audio and video qualities (e.g. frame rate, resolution, audio quality). There can be also user policies for application adaptations, such as dropping the audio quality of a sport-clip before degrading the video quality when resources are limited [77]. The cost related preferences may include selecting the cheapest network service model based on the current location [78]. The novelty of our approach is that it takes into account user preferences with respect to application performance at the network level. Regardless of the traffic types, the applications specified as most important to the user, receive more prioritized services in the network.

Apart from considering user preferences when managing traffic priorities, our approach takes into account the user environment for adapting to the user behavior. It is well-known that human beings are inherently limited in their multi-tasking capabilities, which in turn limits the usability of running several applications concurrently. We identify conflicting applications as applications that hamper each others usability when run concurrently. This information defined in the form of usability rules is used to dynamically lower the priority level of conflicting flows and restore them when the cause of the conflict is removed. In that way it is possible to deal with the situations when some user's flows are unfairly penalized due to reckless usage of others.

Based on the principles of user preferences and application usability we propose in this chapter a user-centric QoS model that dynamically manages the service levels of flows. The model determines the level of QoS to be given to various applications according to their relative importance levels to the users. The level of QoS can fluctuate over time depending on who runs them, what other applications are also running and resource availability. The presented model is described by a set of rules (policies) defining how to manage network resources.

4.3.2 Related work

As we will see below, the idea of user-centric QoS management is not new. The first references that we have found date back almost 10 years. However, the subject has not received the proper support at that time due to the limited usage of home networking and wireless technologies. In [41] the authors describe a user-centric QoS-aware middleware framework aimed at providing personalized QoS management. In the framework, the QoS management functions are triggered not only by network resource fluctuations but also by user behavior, movement or user preferences. The framework defines some basic components such as *QoS Event Manager*, *QoS Controllers*, *User QoS Profiler* and *QoS Specification Parser*, Figure 4.2.

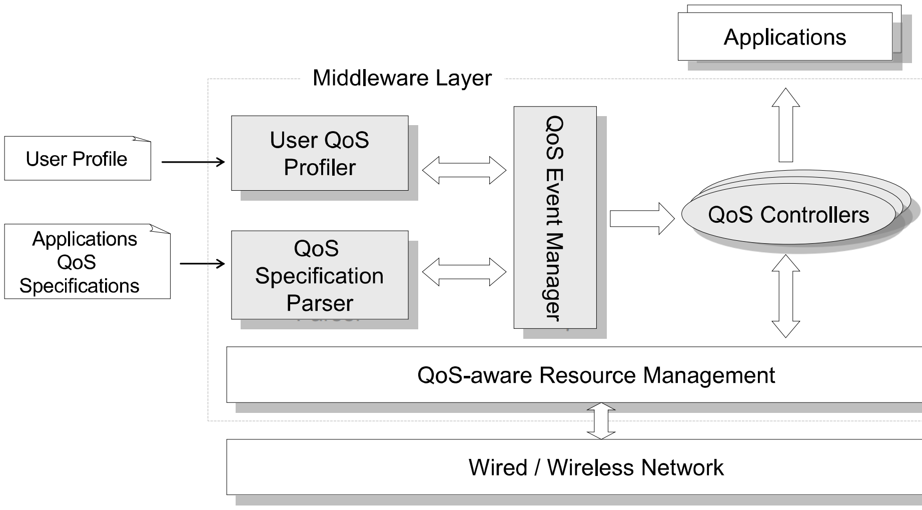


Figure 4.2: QoS-aware middleware framework [41]

- The *User QoS Policy Profiler* automatically derives user preferences based on the user behavior and user feedbacks.

- The *QoS Specification Parser* delivers application specific requirements to the *QoS Event Manager*.

- The *QoS Event Manager* keeps track of different application and user specific information received from *QoS Specification Parser* and *User QoS Profiler* and triggers *QoS Controllers* to perform corresponding QoS management functions.

- The *QoS Controllers* provide various QoS management functions (classification, scheduling, content adaptation, resource reservation, etc.).

The authors propose that the *User QoS Profiler* must be able to automatically derive and predict the user preferences and behavior based on Artificial Intelligence (AI) methods for making decisions (e.g. learning based on user behavior and user feedbacks). The authors even also assume deployment of different location sensors that could detect the user's movement in the house and generate corresponding events (e.g. redirecting video stream to a different display). While making such general and quite challenging assumptions, the authors, however, propose a quite reasonable and interesting high level architecture for user-centric QoS management.

In [46] the authors also propose a user-centric QoS management framework in which a user takes part in the process of resource allocation. The authors present a system architecture and describe the design requirements for each of the system's components. The proposed architecture is depicted in Figure 4.3.

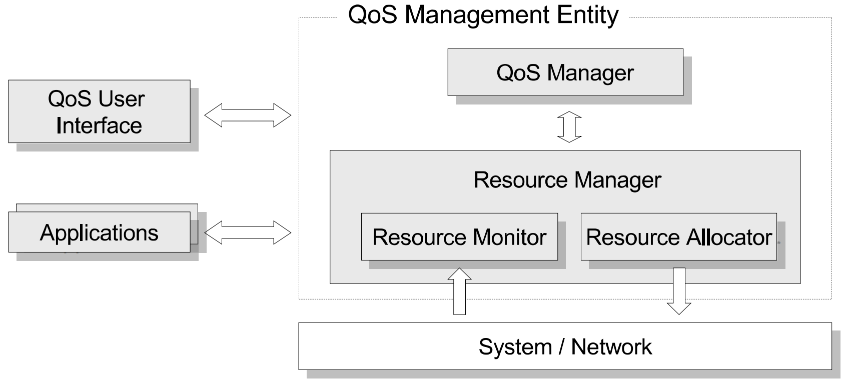


Figure 4.3: User-centric QoS management framework [46]

- The *Applications* are supposed to have an interface with the *QoS Management Entity* for indication of some parameters to the *Resource Manager* and for processing different commands coming from the *QoS Management Entity* (e.g. change video frame rate, image quality, size of display window).

- The *QoS User Interface* is an interface for a user to indicate the desired QoS level and to see the current QoS levels at which the currently running applications operate.

- The *QoS Manager* controls the achievable QoS level in the network and, based on the QoS level requested by the user, instructs the *Resource Manager* to allocate or deallocate resources in the network. The *QoS Manager* also informs the *Applications* about the allowable performance parameters (e.g. frame rate, image quality).

- The *Resource Manager* includes the *Resource Monitor* and *Resource Allocator*, which are correspondingly responsible for monitoring and allocating/deallocating system resources. Each type of resources is supposed to have its own *Resource Monitor* entity (*CPU Resource Monitor, Bandwidth Resource Monitor*, etc.). The *Resource Allocator* can be implemented as a scheduler that provides differentiated media access for various applications.

While this work thoroughly indicates the main components for the user-centric management, the following points can be named as the shortcomings and unfinished work of this architecture.

- The functionality of the above described framework is only demonstrated on providing QoS services to video applications where quality of video services is adjusted in terms of the variable video frame rate. How to regulate the level of mixed services (video, voice, games, data) that can be present in home network is not described.

- The adaptive user-centric QoS service is delivered with the continuous user participation. That is a user constantly interacts with the system to change the allocation of resources until the user is satisfied. The concept of the user personalization and automatic QoS management adjusting the system resources according to user preferences are mentioned, but not fully elaborated.

- The communication protocols for interaction between different network components are not described.

- No policy-based QoS concept defined which is very important in the multi-user environment with a variety of services and variable network resources.

- No graphical user interfaces are designed for demonstrating the practical simplicity of the system's usage.

The above presented user-centric QoS management approaches are quite old (2000, 2001). However, they have not found the appropriate support and attention before. We find that the reasons for this are the following. First, the home networks have not been so popular. Second, the wireless networks have not been so widely used, and QoS problems in wired networks have traditionally been solved with over provisioning. According to the fact that user-centricity is now one of the most important research subjects [49], [50] and due to the current progress of the modern home networking technologies, we believe that the subject of the user-centric QoS management in home networks is very important now. The development of the QoS management solutions for home networking is very well seen in the example of evolvement of the UPnP QoS architecture described in Section 3.5.2. Unlike the presented above approaches, the UPnP QoS framework clearly defines not only the main components of the architecture, but also communication interfaces for policy-based QoS management and admission control tasks. Taking into account the popularity and development of the UPnP standards for home networking, we base our system on the UPnP QoS architecture, which is described later in Section 4.8.

4.4 Use cases

To better understand the expected system's behavior and user requirements, we describe some common use cases below. The use cases are considered as *intra-* and *inter-user* scenarios. The intra-user scenarios describe the use cases for one home network user with multiple applications. The inter-user scenarios consider use cases for multiple users sharing home network resources. All use cases consider the network being heavily loaded (i.e. approaching saturation), or about to become overloaded.

The diagrams are used for better presentation of use cases and show how service levels of applications change with time. Each service level, or *precedence level*, corresponds to a user priority value reflecting the desired level of service. Higher precedence level numbers denote higher priorities on the network.

In these use cases, it is considered that a user can classify his applications as *preferred* and *non-preferred*, which expresses a relative importance of a particular application to the user. A user expects better services (i.e. higher precedence levels) for his preferred applications. Also, it is considered that applications can be grouped in different profiles for user convenience (explained further in Section 4.5.1). Therefore, we also distinguish between *preferred* and *non-preferred* profiles. All applications defined under the preferred profile are considered of high importance to the user and tend to receive better services.

4.4.1 Intra-user scenarios

Use case 1: Setting up user profiles and using network services according to user preferences

Description

A user arranges all frequently used applications in several profiles. Based on current activities, a user makes one of the profiles as his preferred profile. In case of the network contention, all applications belonging to the preferred profile receive more preferable treatment in comparison to all other network applications. A user can always choose any other profile as his preferred profile.

Example

A user is watching a sports broadcast with the *vlc* player while running several film downloads in the background with the *BitTorrent* application. The *vlc* player belongs to the preferred *Video* profile and therefore runs at the highest precedence level (Figure 4.4). After a while a user looses the interest in the football match and focuses on the downloading films. A user makes the *Download* profile as his preferred profile to finish downloading as soon as possible. The corresponding stream is upgraded continuing to run at the highest precedence level while the broadcast stream is downgraded to the lower precedence level continuing to run in the background.

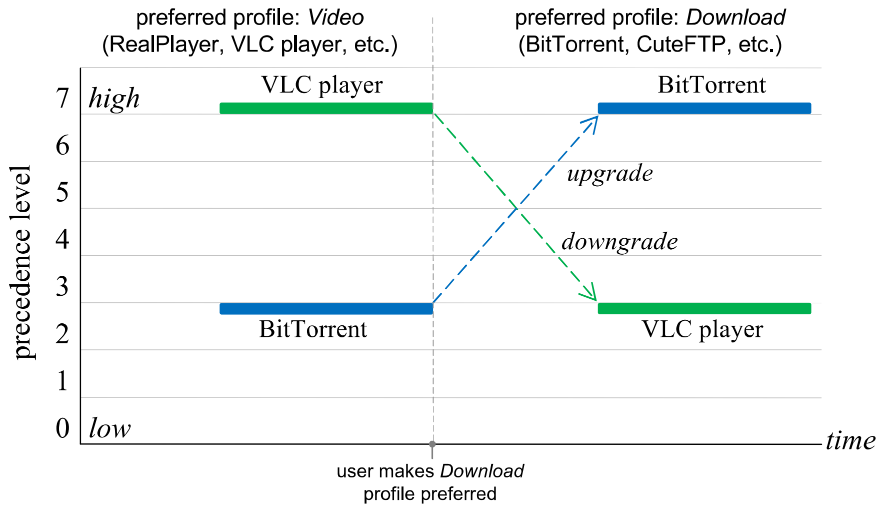


Figure 4.4: Applications from preferred profile receive preferable treatment

Note: In the scope of this thesis we use the terms *downgrading* and *upgrading* to refer to changes of priority. A service or application is downgraded when its priority becomes lower and upgraded when its priority becomes higher.

Use case 2: Running preferred applications in the network

Description

If a user runs too many preferred applications at once (i.e. several applications from preferred profile), the network might be overloaded with high priority flows and contention will occur. In this scenario, we consider the case when only one of the preferred applications always runs with the highest priority.

Example

A user starts one application from his preferred profile (e.g. streaming video with *vlc* player). Then, a user has an incoming call from an application that also belongs to the preferred profile (e.g. *skype* with web camera). To exclude the disrupted voice quality, the video streaming application is automatically downgraded to the best-effort service while the *skype* application starts running with the high priority. When the call is over and *skype* connection is turned off, the video streaming application is automatically upgraded to the previous service level and continues running with the high priority (Figure 4.5).

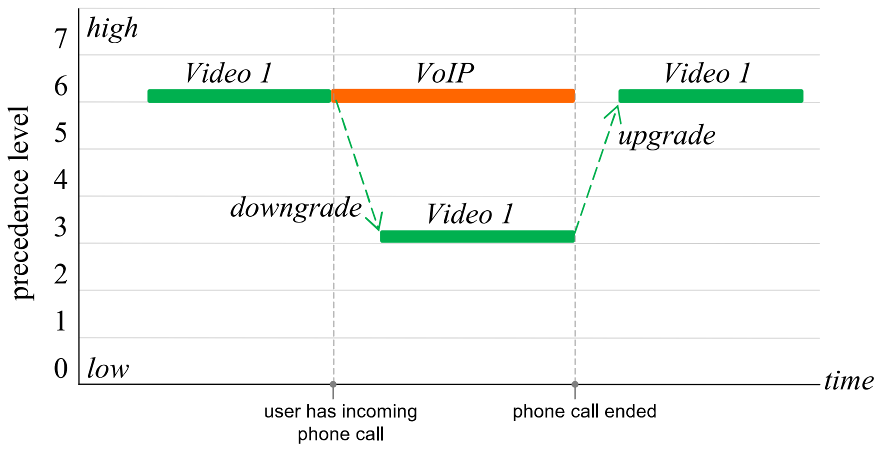


Figure 4.5: Only one preferred application is allowed at a time

Use case 3: Usability rules

Description

If a user runs two applications requiring similar interaction in terms of viewing, listening or operating, the applications are considered to be in conflict with each as the user will probably not be able to actively use them both (e.g. listen to two audio streams simultaneously). These kinds of conflicts are resolved by downgrading the precedence level of one of the applications.

Example

A user is watching a live TV channel. After a while the user starts playing a game over the network while leaving the TV application running in the background. A gaming application and real-time video streaming application are considered to be in conflict on the basis of viewing and operating. The TV streaming application is downgraded.

When the user finishes playing the game, the video streaming application is automatically upgraded to the previous service level and continues running with high priority (Figure 4.6).

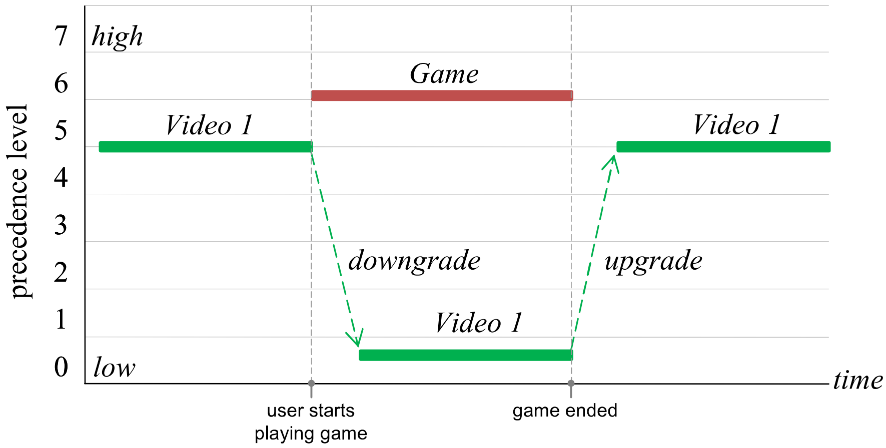


Figure 4.6: Usability rules

Use case 4: Admission control

Description

When the network is overloaded the quality of service cannot be guaranteed for any flows. In case of the network overload some applications are downgraded or terminated depending on user preferences and network policies.

Example

A user starts two applications with the required bitrate exceeding the network capacity. While downloading some films, a user decides to watch a video clip of news. The total bitrate requirement for two applications is more than the capacity of the network and file downloading application is downgraded automatically to the best-effort service according to the user's Last Come First Serve (LCFS) policy. When the user finishes watching the video clip the network resources are released and the file downloading application is upgraded automatically to the previous precedence level and continues downloading the film with the highest possible speed (Figure 4.7).

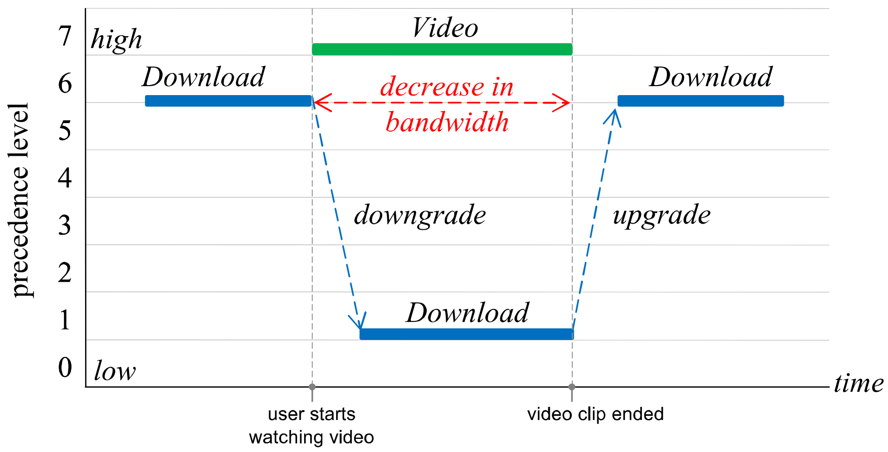


Figure 4.7: Admission control example

4.4.2 Inter-user scenarios

Use case 1: Conflict resolution

Description

When the network is overloaded, the conflicts between multiple users are resolved according to both user preferences and network policies.

Example 1: Conflict resolution according to user preferences

The users' non-preferred applications are downgraded or terminated first. For example, *User 1* has two running applications: a streaming video (preferred) and ftp download (non-preferred) (Figure 4.8). At some point *User 2* starts also a preferred video application, which makes the available bandwidth in the network not sufficient for all running flows. To free the bandwidth for the preferred applications the non-preferred download stream is automatically downgraded continuing to run at the lowest precedence level. When the bandwidth becomes sufficient the download flow is upgraded to the level of precedence, which was initially specified in the user profile.

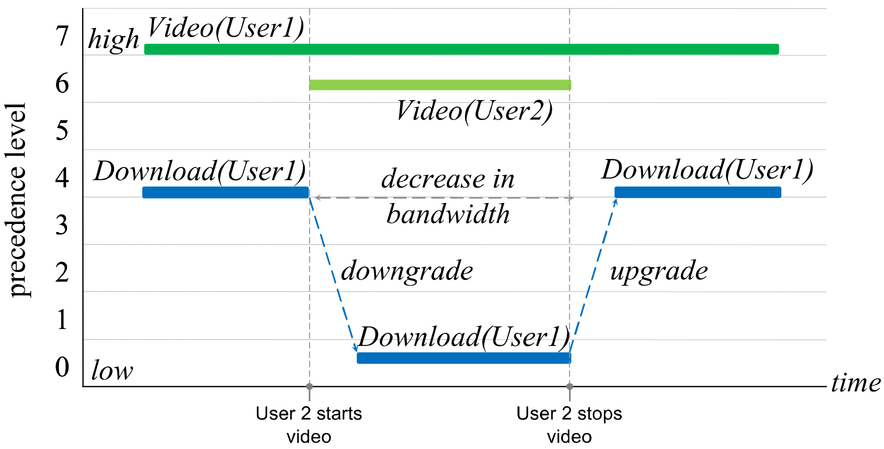


Figure 4.8: Conflict resolution according to user preferences

Example 2: Conflict resolution according to service policies

The service policy "First Come First Serve (FCFS)" is configured in the network. Two users run preferred video applications (Figure 4.9). When network resources decrease, the video application of *User 2* is downgraded according to the FCFS policy, as *User 1* started his application first. When resources are resolved, the downgraded application is upgraded to the previous precedence level.

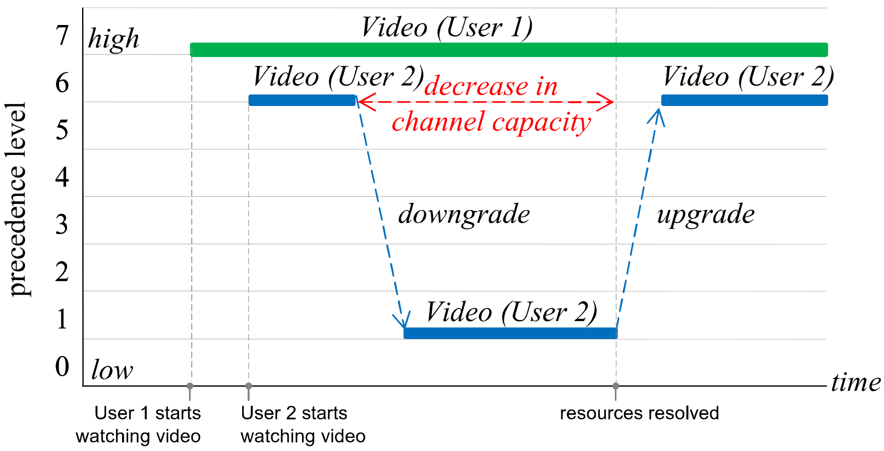


Figure 4.9: Conflict resolution according to FCFS policy

Example 3: Conflict resolution according to user ranks

The users might have different ranks in the system (e.g. administrator, home owner, guests). The higher the user rank, the more chances to win the network resources. In Figure 4.10 the video application of *User 1* is downgraded when there is a lack of resources, because *User 2* has a higher rank.

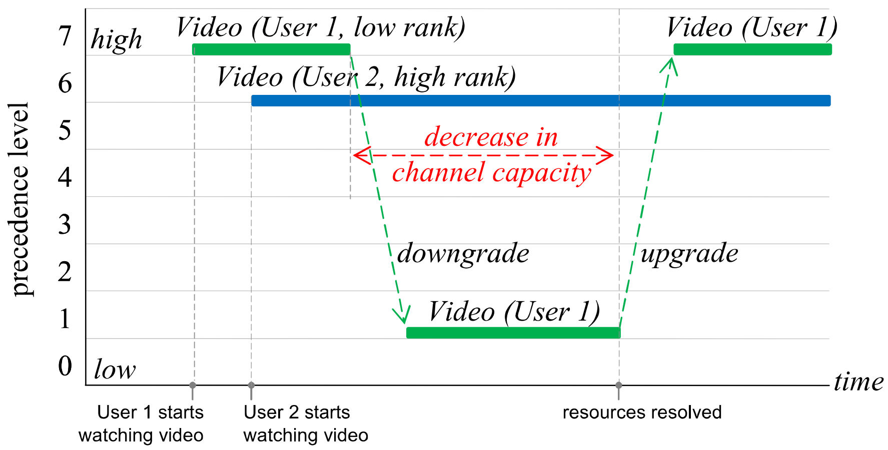


Figure 4.10: Conflict resolution according to user ranks

The user-centric QoS management system presented in the following sections address the described use cases.

4.5 Personalization and user profiling

Personalization is an important part in the user-centric environment, which is about configuring user services accordingly to the needs of individual users. The goal is to enable individuals to use and manage their home network resources in the way that best fits their current needs. Apart from providing easy to use user-centric interfaces for service management, the aim is also to allow services to be managed automatically according to user preferences. A set of preferences associated with a specific user is represented as a *user profile*. In general, user profiles are commonly used. They can be found on operating systems and websites, in computer programs and service providers' environment. On operating systems, user profiles are used to store information associated to a particular user including display and applications settings, network connections or different desktop options. On websites, user profiles are used to personalize the interaction and to store users' personal data and environment settings. User profiles can be also used for performing the personalized web search [56].

The ETSI Specialist Task Force 265 (STF 265) published a guideline document on user profile management [57]. According to ETSI, a *user profile* is defined as a set of preferences, information, rules and settings that are used by a device or service to deliver a customized version of capabilities to the user. Apart from defining the user profile concept, the ETSI guideline document describes some scenarios in which user profiles are useful and addresses the problems of profile management.

With respect to QoS, user profiles can be used to capture the desired QoS level including different service parameters such as Service Level Agreements (SLA)[1], authentication, authorization, accounting and charging. The desired level of quality can be represented at different level of complexity and can be described qualitatively or quantitatively. An example of the qualitative description can look like: "the transit delay experienced by a very high percentage of the delivered packets will not greatly exceed the minimum transmit delay experienced by any successfully delivered packet" [58]. Another option is a quantitative definition: "99 % of the packets will experience a maximum delay of 100 ms". Alternatively, the desired QoS level can be expressed simply as gold, silver or bronze.

Within the scope of this thesis, the personalized service configuration includes a process in which a user specifies a certain level of importance for his network applications and selects a set of user policies assisting the management system in providing the desired level of quality. The user profiles used to capture these personalized settings are presented and explained in the next section.

4.5.1 User profiles

While users of a home network are expected to run a wide variety of applications, research shows that they can be identified by the typical activities they pursue, which tend to be restricted. For example, only one in four consumers who shares digital photos also listens to music [80]. We use the concept of user profiles to capture the user preferences with respect to the nature of use rather than application parameters. A user profile contains a selection of applications that reflect certain usage behavior. Figure 4.11 shows an example of some possible profiles with typical applications for home networks. The selected applications under each profile name show the preferred application types, the rest are non-preferred. When users run various applications, their preferred applications will receive better services than others. A user can select one of the recommended profiles or create a new one by selecting individual preferred

[1] The Service Level Agreement Zone website, http://www.sla-zone.co.uk/

application types. Such user's input can be taken by means of a simple graphical user interface.

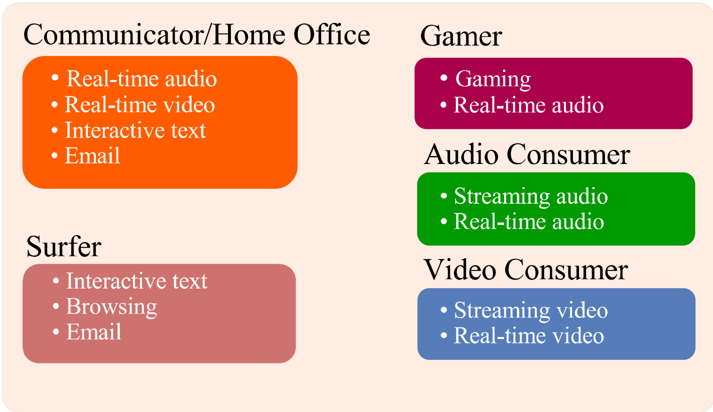


Figure 4.11: User profiles with preferred applications

There can be also an advanced user profile, where a user can specify a certain service level to each application or application type. Figure 4.12 shows an example of such a profile. Each application type is associated by a user with a certain level of *importance*, which indicates the relative importance of one application to others. The higher the importance level, the better service will be eventually provided. In this manner a user can differentiate among the applications in terms of the services that they receive. For example, a game is more important to the user than a VoIP application used for communication with other players or PayTV services are more important than free IPTV channels.

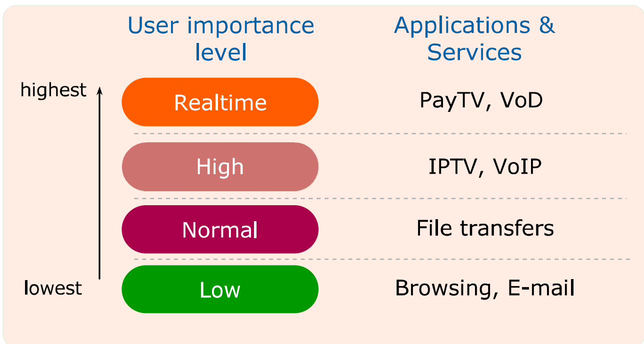


Figure 4.12: Application types assigned to certain levels of importance

A user profile defines importance levels for applications at a high level (user level). A decision about how these levels are mapped to the network is made by the QoS management system.

Apart from the relative application importance numbers, a user profile might contain different user policies discussed in Chapter 7. The example of such policies is FCFS and LCFS service policies. In the case when two applications with the equal levels of importance compete for the network resource, a user can specify according to which policy this conflict has to be resolved.

- First Come First Serve (FCFS) policy – the first started application has preference. This policy is more likely to be used for inter-user scenarios when the first user who started an application has preference. For inter-user scenarios, this policy is configured as a network policy, which is discussed in Chapter 7.

- Last Come First Serve (FCFS) policy – the last started application has preference. This policy might be more frequently used for intra-user scenarios, as the last started application is normally considered as an application of the current user's interest.

4.5.2 Usability Rules

The usability rules define some means for making the management system aware of the user environment. When determining an application's precedence, one aspect that is often ignored is the applications' usability, which can be greatly affected by other coexisting applications, causing interference in its usage. As human beings, there is a limited amount of sensory information that we are able to meaningfully process simultaneously – a limitation that is not translated into application requirements. For example, it can be assumed that a person will not be able to listen to two different audio streams simultaneously.

A user interacts with an application primarily in three ways: viewing the application's output, listening to the application's output or using the application by means of input devices. Two applications, both requiring similar interaction in terms of viewing, listening or operating are considered to be in conflict with each other. For example, an interactive game conflicts with a text chat on the basis of operating and real-time video conflicts with real-time audio in terms of listening. Some applications involve the same mode of interaction, but one of them may require only a passive level. For example, real-time audio requires active listening (presumably for responding), while streaming audio requires only passive listening. This is still a conflict, but of a lesser degree and is denoted as a mild conflict. Mild conflicts indicate that such applications may coexist, under the assumption that a user would make adjustments to compromise the effectiveness of one application in order to make it compatible with the other (for example, turning down the volume of a streaming video in order to concurrently run an audio stream).

By comparing application types with each other, we obtain a conflict matrix, as shown in Figure 4.13. The occurrence of a conflict is taken as an indication that the usability of one of the applications is hampered, and the traffic generated by that application is resulting in waste of bandwidth. As such, the policy management may not be obliged to provide it with a sustained level of service. The configuration of the conflict matrix along with the conflict definitions is the subject to policy rules.

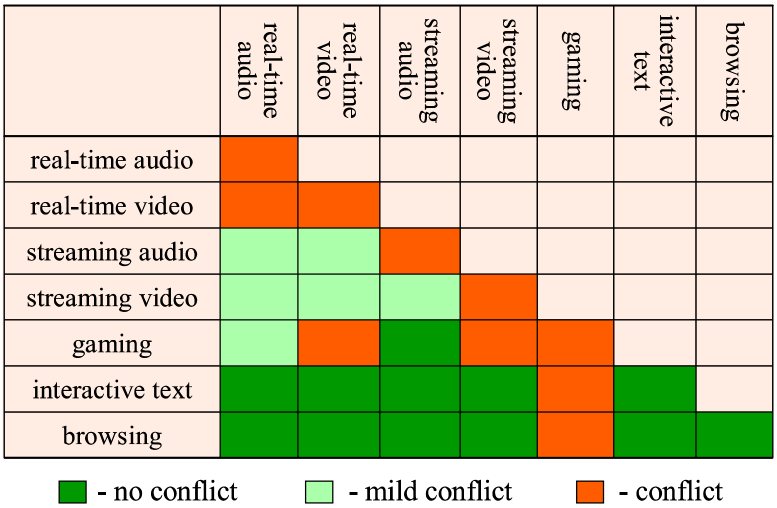


Figure 4.13: Usability matrix with conflict definitions

We define usability rules as a set of actions that have to be performed by the QoS management system if some changes occur in the user environment. For example, a priority level of one of the conflict applications may be lowered if it is hampered in its usability. Usability rules can be extended with other policies that consider user behavior and environment. For example, a broadcast video stream may be suspended if a user places the corresponding application window in the background while working with another application.

4.6 Precedence Model

The user profiles and usability rules described in the previous sections provide the groundwork for a formal precedence model. We propose the precedence model as a QoS service model that dynamically manages the service levels of flows based on the set of policy rules. Depending on the user profile each flow is assigned a precedence level that determines the level of service it receives. The higher the precedence level the higher priority will be eventually assigned to a flow on the network (Figure 4.14).

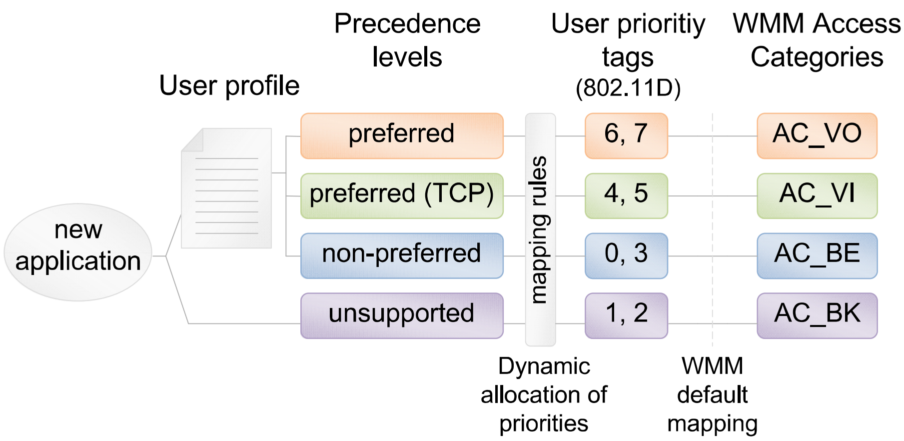


Figure 4.14: Mapping of user profiles to WMM access categories.

Any preferred flow that runs on TCP is re-classified as a TCP-based preferred flow. The bursty nature of TCP can introduce disruptive jitter in other application flows if allowed to run at a comparable level. Therefore, TCP based flows are given less precedence than rest of the preferred flows, but greater precedence than non-preferred flows. Unsupported flows represent the traffic of lowest importance. Such flows generally comprise background traffic and get only the left-over resources. The initially assigned precedence levels fluctuate over time adaptively responding to user activities and conflicts with coexisting flows, as described by the usability rules.

The translation of the user profile to the precedence levels is the subject to the policy rules and configuration of the QoS management system. Mapping rules allow for traffic management according to user preferences while still providing options for taking into account application requirements. For example, if a user makes e-mail traffic preferred, the QoS management system may not necessarily map it to the highest priority level such that it does not compete with delay intolerant traffic.

To take effect on the network the assigned precedence levels are mapped to the underlying QoS capable network. In the case of the wireless network with the 802.11e extensions, the precedence levels are mapped to the four WMM access categories by marking the traffic with the corresponding user priority tag as defined in Table 4-1. We discussed in more detail how this mapping works in Section 3.4.3.

The main components of the model are depicted in Figure 4.15. The central QoS management entity dynamically manages the precedence levels of the flows based on the user profiles, policy rules, network state information and user behavior described by the usability rules. Whenever a user starts a new network application, the QoS management entity determines its corresponding precedence level. The management entity then configures the network devices such that they classify all packets belonging to the application according to the assigned precedence level.

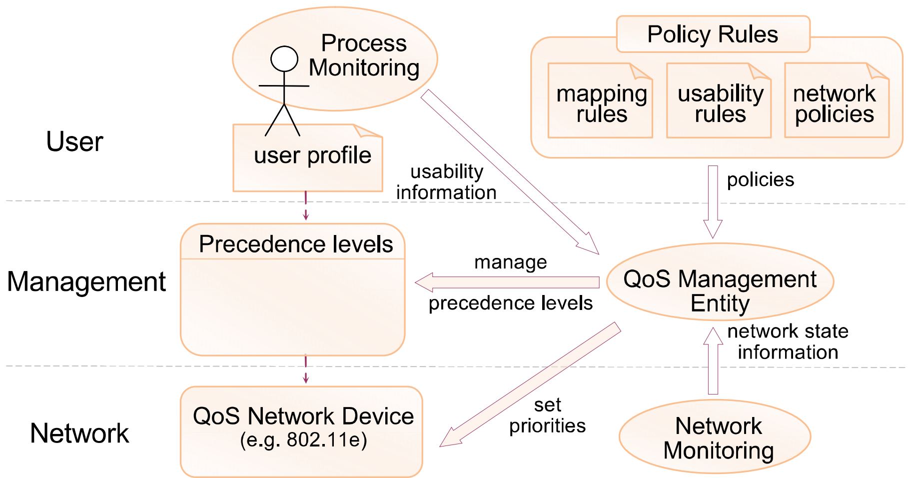


Figure 4.15: Main components of the precedence model

The precedence level of a flow can be changed several times over the course of the application's lifetime. This can happen in response to certain triggering events coming from the user or network levels (e.g. change in user activities or network state). Any event identified in Figure 4.16 (application started/stopped, new user preferences, new network state), can lead to one of the actions also shown in Figure 4.16 (downgrade/upgrade/terminate applications, penalize mild usability conflicts). The actions to be performed in response to certain events are determined according to the current policies, which is discussed in the next section.

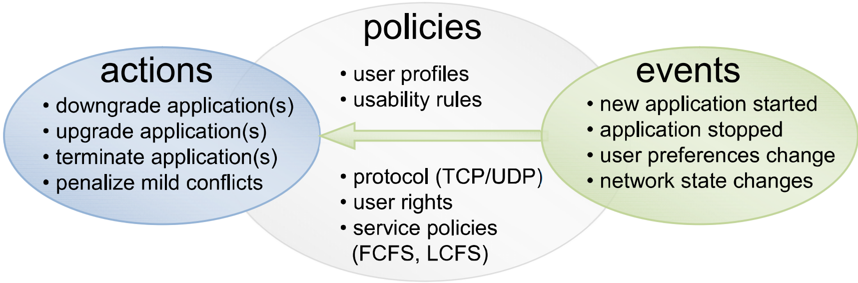


Figure 4.16: Actions performed in response to events according to policies

4.7 Policy-based QoS

Policy-based QoS provides a means for a system to allocate network resources according to the defined user and network preferences. It also provides a way to resolve conflicts when several applications compete for resources. The basis of the policy-based QoS is *policy*, which is defined in the DVB QoS document [37] as the aggregation of rules, methods and values that determines how the decisions about admitting services and resources are made by the management system. Policy assists the management system to answer the questions such as what resources the users and applications can access on the network, what precedence level should be assigned to a particular application, or what to do if there are not enough resources on the network.

QoS requirements and their corresponding policies can be defined at different levels, Figure 4.17. At the user level, the policies express various user preferences such as relative application importance, relation between the desired quality and service costs or reliability. At the application level, the policies might contain specific requirements for media streams (e.g. frame rate, frame size, color depth). Various system resource requirements can be expressed as system policies describing the usage of memory, CPU or disk resources. At the network level, the policies concern the bandwidth usage, maximum allowable latency, error rate or packet dropping rules. The connections between the policy levels (shown by arrows in Figure 4.17) demonstrate that policy rules might be applied and maintained within the whole network. For example, regardless of where in the network the user starts an application, it is run with the importance level specified in the user profile.

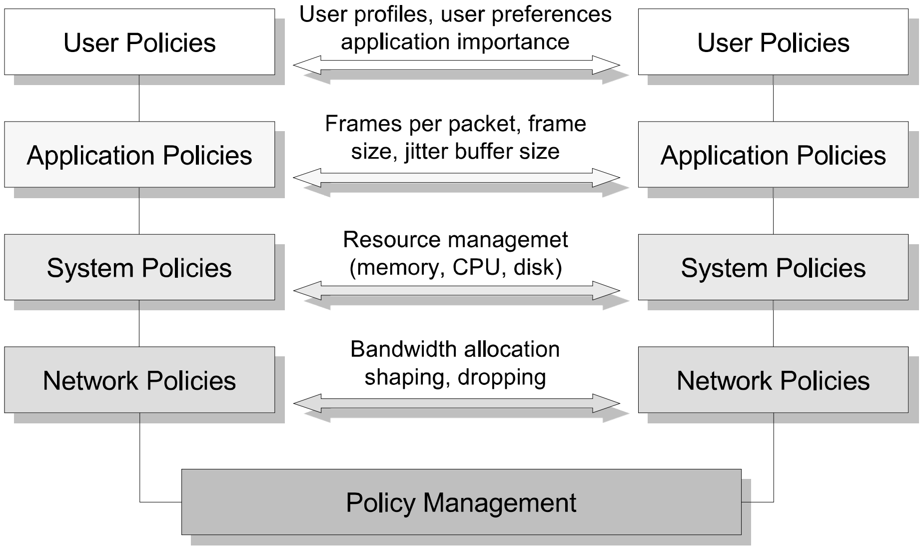


Figure 4.17: Different QoS policy levels

The policy-based management is very effective and widely used in big networks where a large number of devices and users are managed centrally by a network provider. IETF defined a management architecture and QoS information model [62], [63], [64] specifying the main concepts for the policy-based management in the internet. The policy-based approach in home networks, on the contrary, has not been so popular as home networking technologies have only recently started their rapid growth. UPnP QoS [35] is an example of a policy-based QoS system for home networks. To demonstrate the main IETF policy management concepts in context of home networks, Figure 4.18 shows the QoS policy information model components mapped into the UPnP QoS architecture. Policy management tool is normally implemented as a GUI used for specifying, editing and administering policies. Policy repository is a storage device for storing and retrieving policy information. Policy decision point (PDP) is an entity responsible for handling policy requests, making policy decisions and updating the Policy enforcement point (PEP) configuration. PEP is an entity residing on the network, which is used to enforce the policy rules received from the PDP. As we discuss further, the main concepts of the UPnP QoS architecture and IETF QoS policy information model are used for our system.

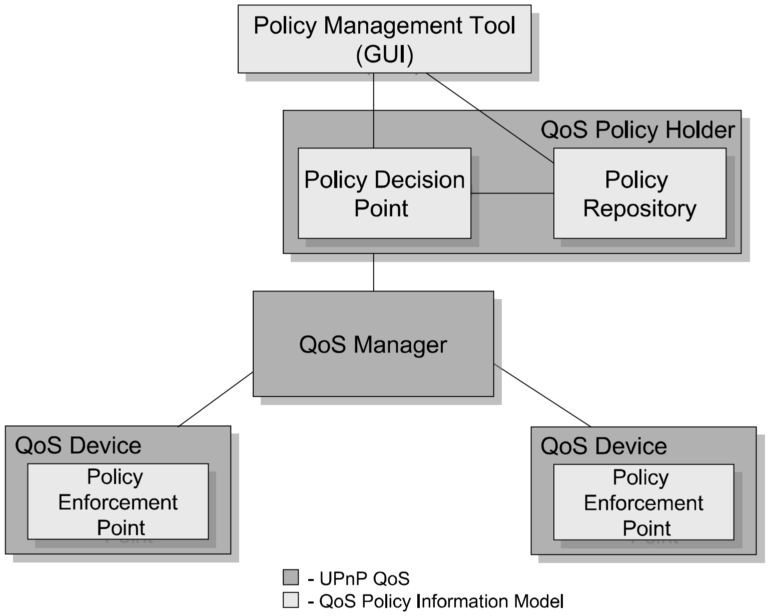


Figure 4.18: IETF QoS policy information model and UPnP QoS architecture

Policies are usually represented as "*if* condition *then* action" rules. The following are the policy examples at the user and network levels:

User level: **if** application = "vlc player" **then** importance level = high

Network level:

middleware (our system): **if** importance level = high **then** DSCP = 0x28
wireless driver: **if** DSCP = 0x28 **then** Access Category = AC_VI

The mapping of application types to importance levels is done by a user with the help of user profiles as was explained in Section 4.5.1. The mapping at the network level is about deciding to what precedence level, and eventually to which WMM access category, a certain user importance level has to be mapped. It was already discussed that if a user marks an application as preferred, the application might not be necessarily mapped to the highest precedence level. The following criteria are taken into account when mapping a particular importance level to the precedence level.

- Usability rules. If there are any usability conflicts, a lower precedence level might be assigned.
- Protocol (TCP/UDP). If a preferred flow is TCP-based, it might be assigned a lower precedence level. If it is the only flow present in the network, it might be provided with the highest precedence level.
- User rights. The users might have different rights (or ranks) in the system. For example, administrator, home owner or guests might have different privileges

on the home network, Figure 4.19. The higher the user rank is, the more chances there are for this user to have a higher precedence level for his applications.

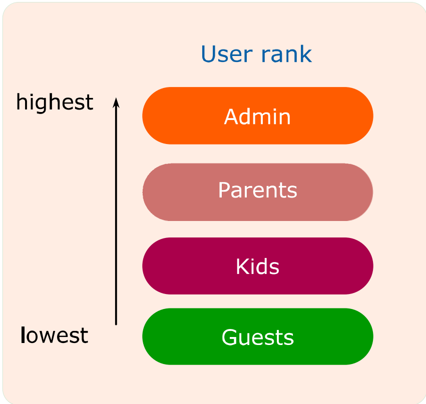


Figure 4.19: User ranks

- Service policies (FCFS, LCFS). If there are several running applications with the same level of importance, the precedence levels are assigned according to the order in which the applications were started and depending on which service policy is active: FCFS or LCFS.

When making policy decisions the above listed criteria can be considered in different orders defining which policy rule has a preference. For example, user rights are considered before considering the service policies such that if a user is a home owner and FCFS policy is active, the home owner still has preference in getting a higher precedence level over the guests, even if he was the last to start his application.

4.8 Architecture

As was discussed in Section 3.5.2, the UPnP QoS architecture defines the main components and communication interfaces for policy-based QoS management in home networks. Considering the popularity and evolvement of the UPnP standards for home networking, and very likely adoption of UPnP QoS v3 by DLNA in its future guidelines, we base our system on the UPnP QoS architecture. Namely, we adopt the key components of the UPnP QoS architecture and main concepts of its operation for our precedence model defined in Section 4.6.

Even though UPnP defined a policy-based QoS architecture for home networks, the policy enforcement, decision making and configuration of home network polices are out of scope for UPnP QoS. The rules that the UPnP QoS Policy Holder uses to generate the traffic policy values are not defined. Only some simple default policies are proposed. This is mainly a static mapping of UPnP traffic classes to priority values and traffic importance numbers (Table 4-1). Our goal was to extend this with the user-centric policies that can be used in UPnP QoS framework for better user experience.

The core components of the system are depicted in Figure 4.20. We consider the main components of the UPnP QoS architecture and extend them with functionalities and policy rules of our precedence model and user-centric QoS approach. In this approach, the QoS Manager dynamically manages the precedence levels of the flows based on the user profiles, policy rules, network state information and user behavior described by the usability rules. Whenever a user starts a new network application, the QoS Manager determines its corresponding precedence level with the help of the QoS Policy Holder. The manager then configures the QoS Devices such that they classify all packets belonging to the application flow according to the assigned precedence level. Below we describe each component of the architecture in more detail.

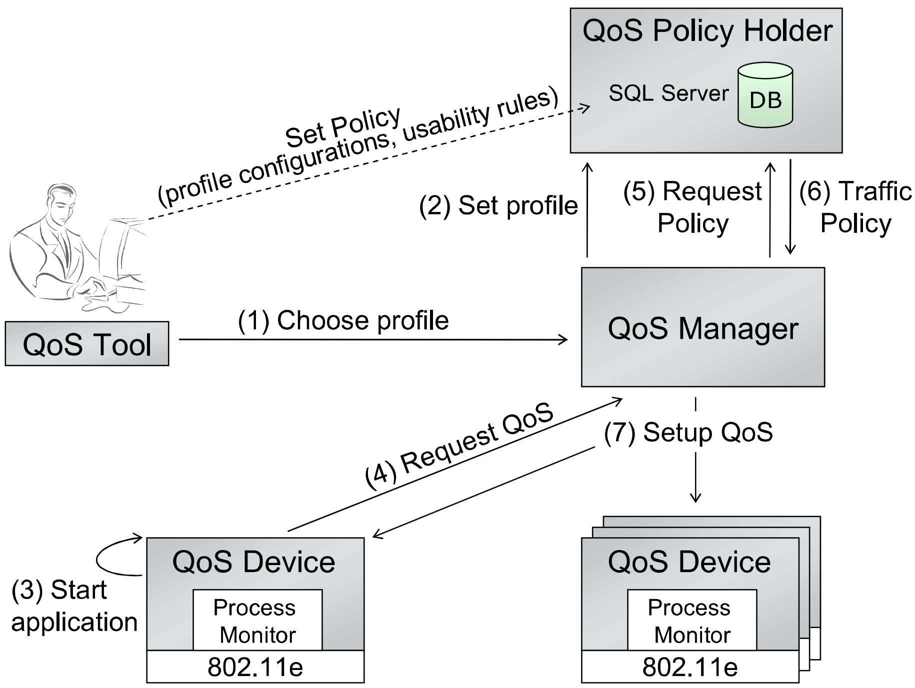


Figure 4.20: Main components of the implemented approach

4.8.1 QoS Tool

The QoS Tool is a profile configuration and policy management tool that can be implemented as GUI. With the help of the QoS Tool, a user can perform the following functions.

- Find the QoS Manager and QoS Devices in the network.
- Retrieve a list of available profiles known to the QoS Policy Holder.
- Choose one of the available profiles with the specified preferred applications or configure a new profile.
- Change the preferred profile or applications' importance levels at run time.

The QoS Tool can be started from any node in the network. After the start, the QoS Tool discovers the QoS Manager, through which all further communications are performed. When a user determines his preferred profile, all user's applications from this profile receive the network services accordingly.

4.8.2 QoS Device

All network nodes are represented as QoS Devices with WMM support. For example in our case, a QoS Device is implemented on the basis of Intel 2915abg wireless modems. The cards support some of the QoS extensions of the 802.11e specification such as Enhanced Distributed Channel Access (EDCA) that provides prioritized access to the wireless medium. All packets originating at QoS Devices are classified according to the user profile. The classification is done by assigning a certain user priority to the packets (as explained in Section 3.4.3). According to the policy received from the QoS Manager and depending on the network layer characteristics such as destination IP address or source port, the IP TOS priority field of individual packets is set to a specific value (e.g. with the packet filtering netfilter/iptables[1] mechanism). The IP TOS value is mapped further by the wireless driver into the corresponding access category (as explained in Section 3.4.3).

[1] The netfilter website, http://www.netfilter.org/

Each QoS Device has a *Process Monitor* entity that is responsible for monitoring what network applications are running on the node. When the user starts a new application opening network sockets, the Process Monitor detects it and the QoS Device sends a request to the QoS Manager asking for a policy for this new application.

4.8.3 QoS Policy Holder

The QoS Policy Holder is represented by an SQL database for policy storage. With the help of the QoS Tool a user can configure user profiles, usability matrix and other user policies stored at the SQL database. The SQL server is queried by the QoS Manager for gathering a list of profiles and for determining policies. The example of some SQL tables stored on the server is given in Figure 4.21. Given a certain user and application name, a policy is issued in terms of the corresponding precedence level (expressed in terms of the user priority value as defined in 802.1D).

Users

user_id	name
10	root
15	user1
17	user2

Application types

name	Type
mplayer	streaming video
vlc	streaming video
firefox	browsing
QoS-tool	management

Applications

profile_id	name
232	mplayer
232	vlc
232	QoS-tool
433	skype
112	QoS-device
112	QoS-manager

Profiles

user_id	profile_id	name	importance
17	232	Video Consumer	5
17	233	Audio Consumer	3
15	433	Communicator	3
10	112	Management	1

Running applications

user_id	name	type	importance	AC	address	start_time
17	mplayer	streaming video	5	5	10.1.14.112	2008-11-24 17:47:23
17	firefox	browsing	6	3	10.1.14.131	2008-11-24 16:16:28
17	QoS-tool	management	3	3	10.1.14.131	2008-11-24 16:15:09
10	QoS-device	management	6	6	10.1.14.112	2008-11-20 11:07:38
10	QoS-device	management	6	6	10.1.14.131	2008-11-20 11:07:35
10	QoS-manager	management	6	6	10.1.14.136	2008-11-20 11:07:30

Figure 4.21: Example of SQL tables

4.8.4 QoS Manager

The QoS Manager is the central management entity interconnecting all the components in the network. For connection and discovery functionalities with the QoS Tool and QoS Devices the manager implements a proprietary network protocol defining various control message formats. The connection to the QoS Policy Holder is implemented as exchange of SQL queries.

4.9 Theory of operation

The initial QoS configuration is performed with the QoS Tool. A user or system administrator connects to the QoS Policy Holder (via QoS Manager) and configures user profiles and usability rules. The configuration settings are stored in the QoS Policy Holder's SQL database. All QoS Devices connect automatically to the QoS Manager. The discovery of devices is implemented using fixed port numbers and UDP broadcasts. The following steps are numbered as in Figure 4.20.

1) By means of the QoS Tool a user requests a list of available profiles from the QoS Manager. The user chooses one of the available profiles or makes a new profile.

2) The QoS Manager redirects the user's request to the QoS Policy Holder that registers the user by making an entry in the database with the user's name and chosen profile. The user profile is stored at the SQL server.

3) The user starts an application on one of the QoS Devices. The QoS Device monitors all the processes and their respective network sockets. With the help of the Process Monitor the QoS Device detects that the user has started a new network application.

4) The QoS Device inquires the QoS Manager about a policy for the new network connection. For doing this, the QoS Device sends to the QoS Manager a request containing a traffic descriptor with information about a new application (user name, application name, transport protocol).

5) The QoS Manager appends the traffic descriptor with an IP address of the QoS Device requesting the policy. The manager constructs an SQL request and queries the SQL database of the QoS Policy Holder.

6) The QoS Policy Holder determines a policy from the SQL tables and sends the result of the SQL query back to the manager.

7) From the result of the SQL query the QoS Manager creates a response message containing the traffic policy with the priority level. The QoS Device that requested the policy performs priority tagging for all outgoing packets based on the application's socket source port number. The issued policy is also broadcasted to all QoS Devices in the network such that if any flow belonging to this application is originating from somewhere else it is also properly marked. Therefore, the rest QoS Devices also perform priority tagging for all outgoing packets directed to the IP address and source port of the application.

4.9.1 Message sequence diagrams

For better overview of the system operation, we describe here the message sequence diagrams illustrating the main system interactions.

When a new application is started, the QoS Device requests a policy from the QoS Manager, Figure 4.22. The QoS Manager requests a user importance number and network priority from the QoS Policy Holder. The user importance number is retrieved based on the user profile stored at the SQL server. The network priority level is derived based on the active policies. It might happen that the derived network priority level is lower than it is expected if according to the active policies there are other users or applications, which are more important on the network. Finally, the QoS Manager sends an appropriate policy (i.e. network priority level) back to the QoS Device.

Figure 4.23 shows the activity diagram of the process that takes place at the QoS Manager when the QoS Device requests a policy for a new application.

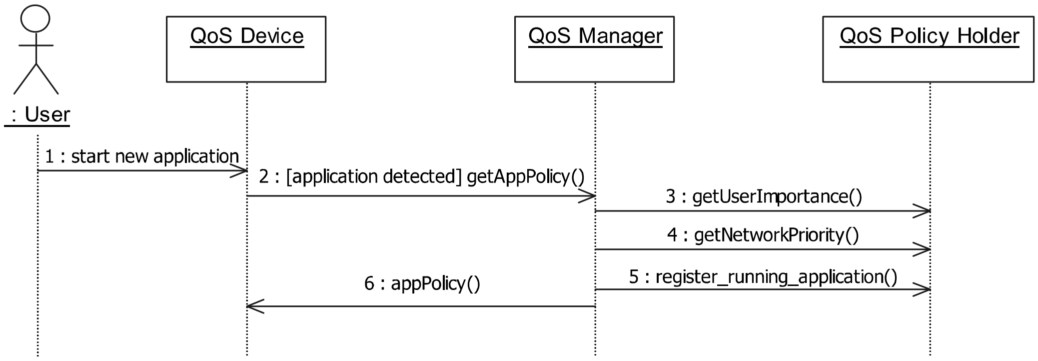


Figure 4.22 : QoS Device requests a policy for each new application

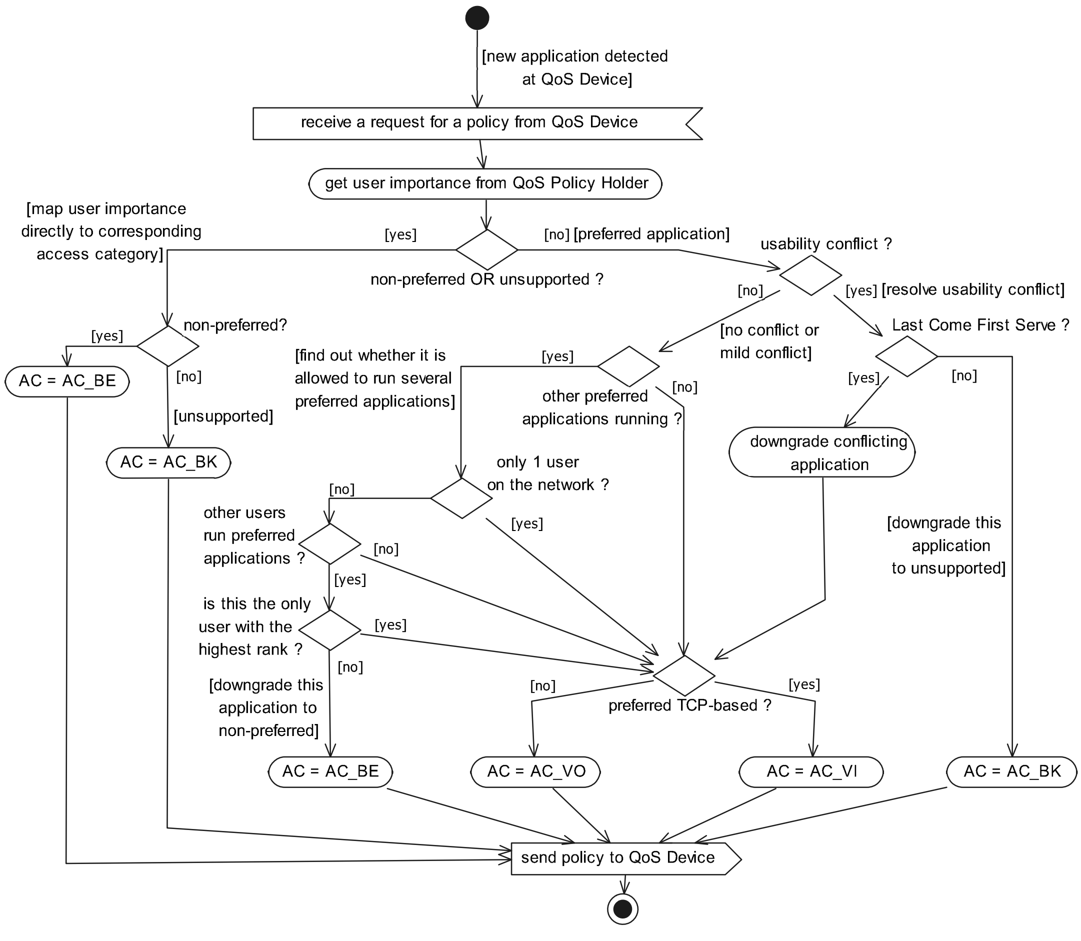


Figure 4.23: Activity diagram for making a policy decision at QoS Manager when new application started

A user can always change his profile. Whenever a user profile is modified (e.g. new application is added), an update request is sent to the QoS Manager, Figure 4.24. The QoS Manager performs two actions. First, it requests the QoS Policy Holder to update the user profile accordingly. Secondly, it updates all the user's running applications, because they might have new importance values.

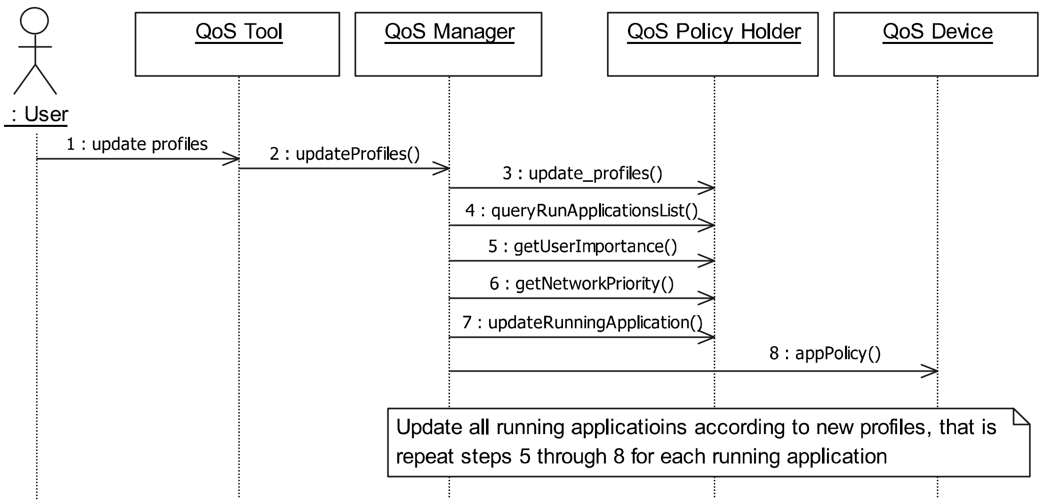


Figure 4.24 : QoS Manager updates system performance according to changes in user profile

Similarly, when a user makes any changes to the user policies (e.g. change the FCFS policy to LCFS), the QoS Manager updates QoS Policy Holder and all running applications, Figure 4.25.

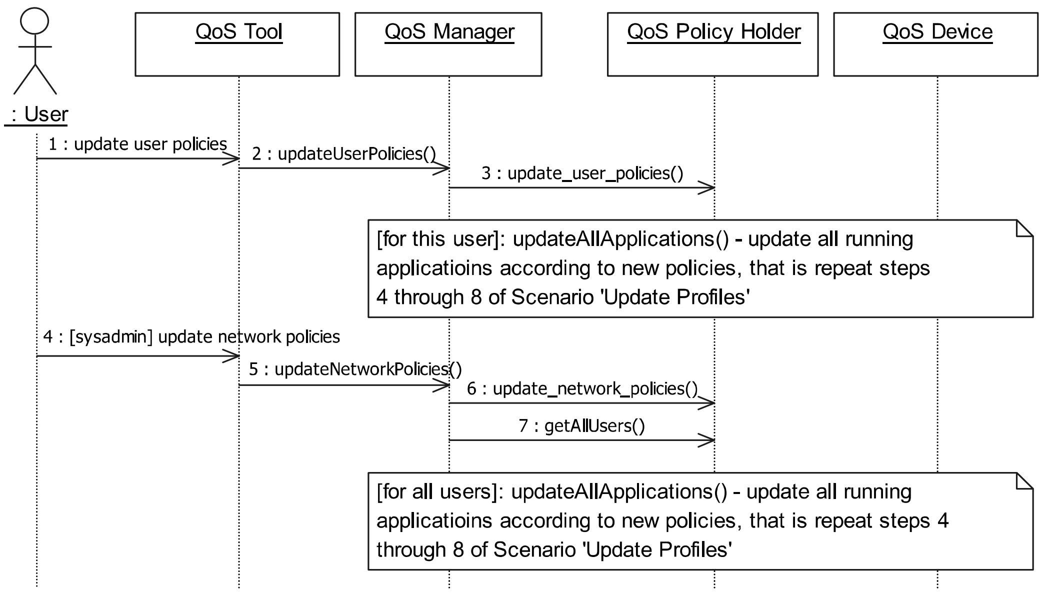


Figure 4.25 : QoS Manager updates system performance when user or network policies change

So that a user can observe all his running network applications and their run-time status, the QoS Tool periodically requests the corresponding information from the QoS Manager, Figure 4.26. For example, if one of the user's applications is downgraded in priority level, the user will be notified by the QoS Tool.

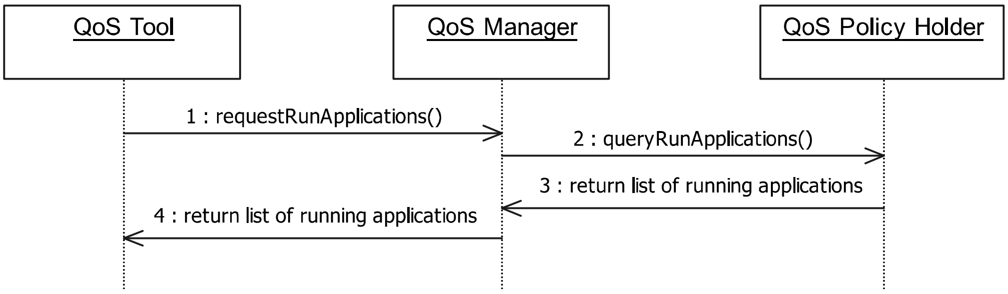


Figure 4.26 : QoS Tool requests periodically information about running network applications

When a user changes the preferred profile, the importance levels of all applications from this profile are also changed. In this case, an '*update profile*' request is generated, as it was explained in Figure 4.24. However, it is also possible for a user to change an importance value for a single application, Figure 4.27.

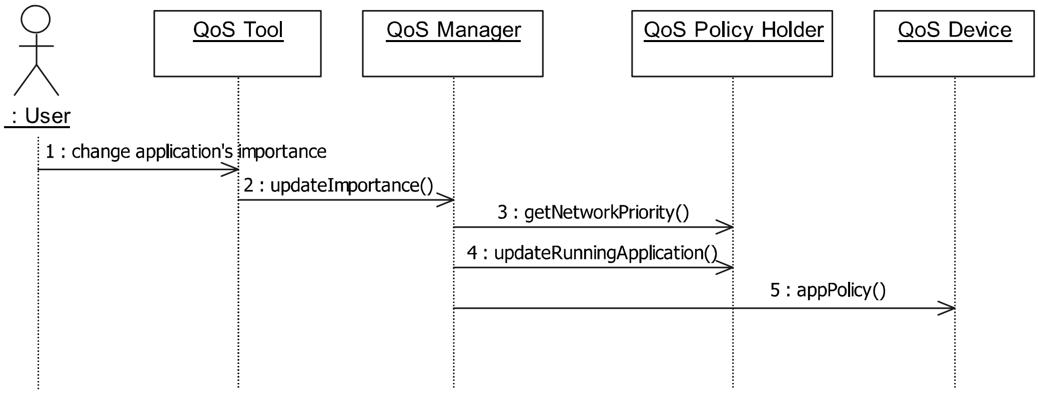


Figure 4.27 : User requests to change the application importance at run time

When the QoS Device receives a policy from the QoS Manager, it enforces the policy locally by setting up the tagging rules to mark all outgoing packets accordingly, Figure 4.28. The issued policy is also broadcasted to all QoS Devices in the network as a '*remote policy*' such that if any flow belonging to the application is originating from other QoS Devices it is also properly marked.

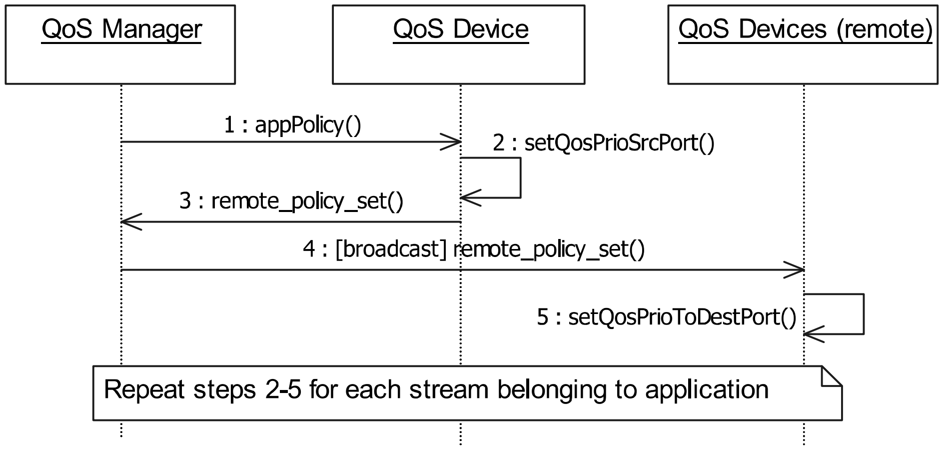


Figure 4.28 : QoS Device enforces a policy according to the QoS Manager's request

4.10 Demonstration Scenarios

The following is a set of basic usage scenarios that is provided to demonstrate the performance of the implemented approach. The system described in this chapter was implemented in our testbed wireless network. In this section, we present both simulation and testbed results. The simulation results are given to demonstrate the system performance with large number of different applications, which is more difficult to set up in the testbed network.

4.10.1 Simulation scenarios

The simulation results were obtained using the ns-2 network simulator[1], which is an open-source discrete event network simulator for networking research. The modified version of ns-2 with 802.11e extension[2] was used. The simulations results were also extensively described in [97].

[1] The Network Simulator ns-2, http://www.isi.edu/nsnam/ns/
[2] 802.11e (EDCF) extensions to ns-2, ftp://ftp-sop.inria.fr/rodeo/qni/ns-edcf.tar.gz

4.10.1.1 Scenario 1

The first scenario highlights the treatment of flows based on the level of preferences associated with them by the users. The *Audio Consumer* is listening to streaming mp3s (preferred flow). The *Surfer*, in some other room is listening to audio commentary of a football match (non-preferred flow) while having a text chat with his friend (preferred flow). Meanwhile *Background1* watches a streaming movie and *Background2* starts a voice chat with a friend. The only two preferred flows in this scenario, the *Surfer*'s interactive text and *Audio Consumer*'s streaming audio, take precedence over the remaining non-preferred flows as they have the highest importance to their users (Figure 4.29). The standard prioritization scheme has unconditionally assigned higher priority to the interactive voice flow, followed by streaming flows, all of which have been given identical service (Figure 4.30). The *Surfer*'s streaming audio has received the same treatment as the *Audio Consumer*'s streaming audio. Moreover, once the channel capacity had dropped below the total demand, the *Surfer*'s text-chat was completely choked out.

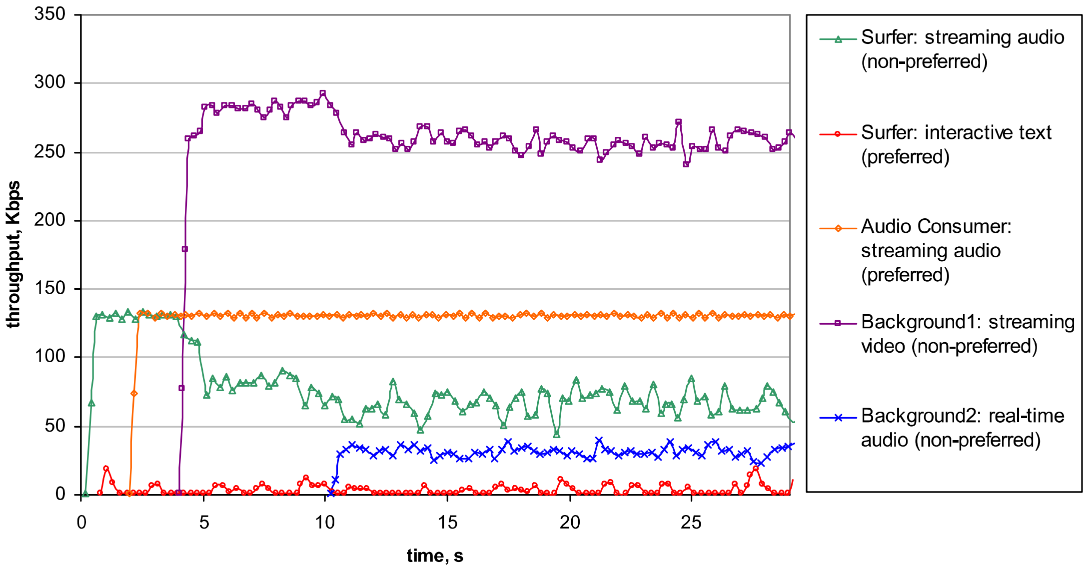


Figure 4.29: Effect of user preferences: precedence model

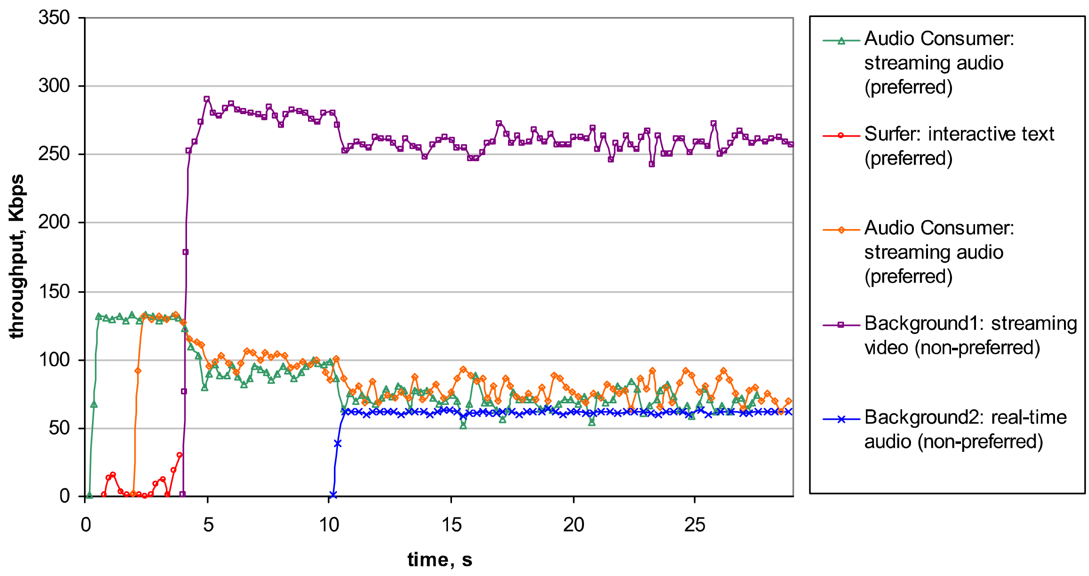


Figure 4.30: Effect of user preferences: standard prioritization scheme

4.10.1.2 Scenario 2

The second scenario gives an example of the effectiveness of the usability model. It features a gamer that uses some applications and then concurrently starts a gaming session. Since the gaming application has the greatest usability constraints, concurrently running applications are likely to conflict with it, and hence be downgraded. The *Gamer* is engaged in a text chat with his friends, while passively watching a streaming video broadcast of a tennis match. In the meantime *Background1* listens to streaming audio from an internet radio station. At some point the *Gamer* starts a gaming application while leaving his existing applications running. This triggers a conflict with streaming video on the basis of viewing, and with interactive text on the basis of operating. Since these applications are deemed to be hampered in their usability, and the user assumed to be engaged with his preferred application, they are downgraded to the level of unsupported (Figure 4.31). This causes some bandwidth to be freed for other flows, and is used by *Background1*'s streaming audio to stream at optimal rate. The downgraded flows will remain unsupported until the conflict is resolved. According to the standard prioritization scheme (Figure 4.32), interactive game would always be given the highest precedence (along with real-time audio/video) regardless of whether it is run by a *Gamer* or an *Audio Consumer*. Similarly, the interactive text flows, given the least priority, come to a halt as soon as the total bandwidth requirement exceeds the channel capacity. Both interactive text flows completely disappear from the bandwidth graph even before the game starts.

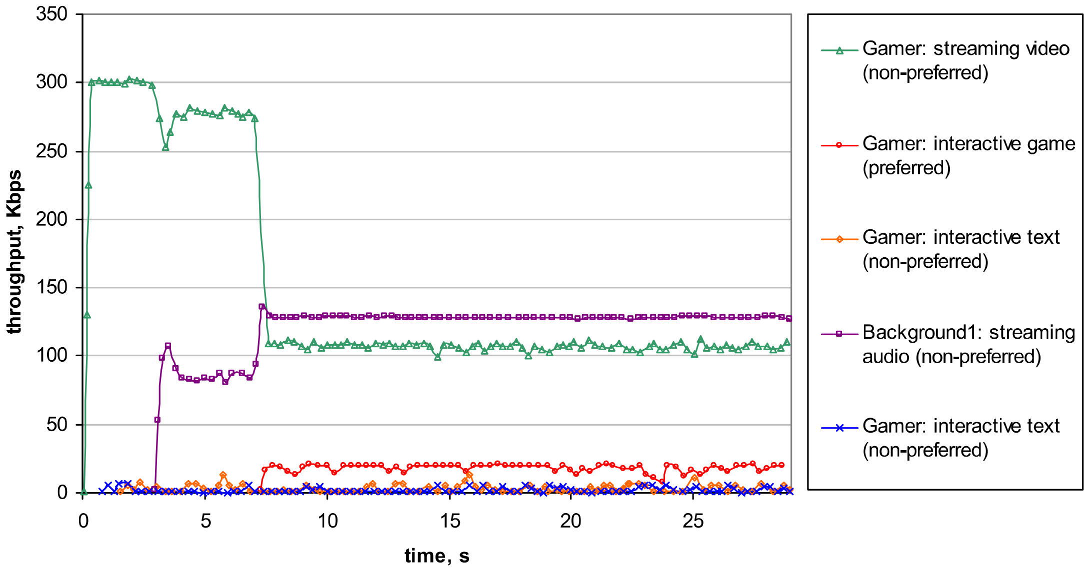


Figure 4.31: Example of usability rules: precedence model

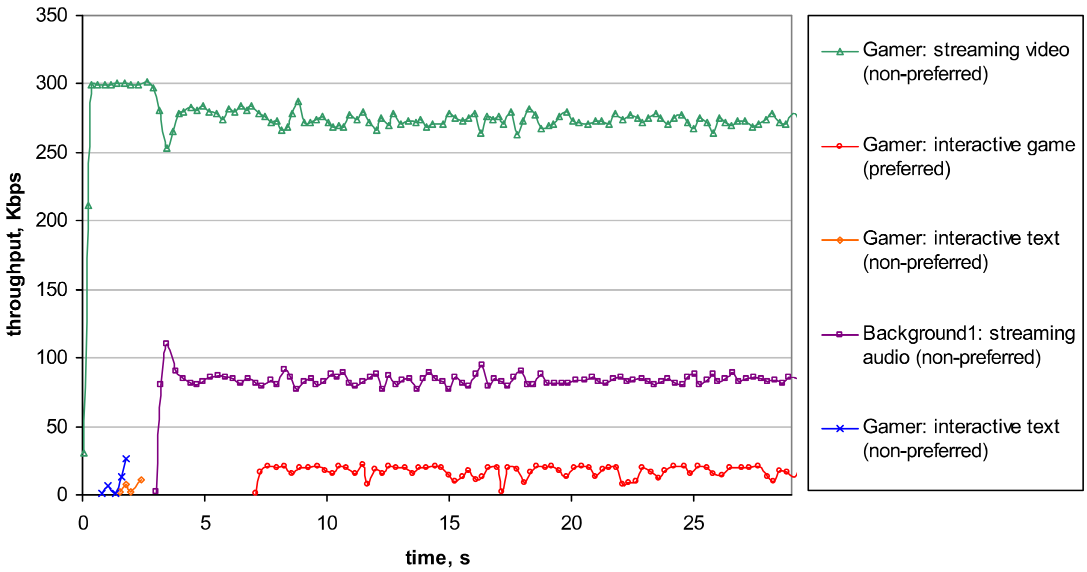


Figure 4.32: Example of usability rules: standard prioritization scheme

4.10.2 Testbed scenarios

For all experiments with the implemented architecture a local wireless network was used. The network consists of wireless clients based on Intel 2915abg cards and a Cisco access point Aironet 1130AG with WMM support. For traffic generation the *iperf* tool[1] was used. The implementation details can be found in Chapter 7. The system's implementation details and other demonstration scenarios can be also found in [98], [99].

4.10.2.1 Scenario 1

This scenario shows the difference in treatment of flows with and without user-oriented QoS prioritization. In the beginning, the QoS Device is not yet started and all three flows originating at this device share the bandwidth equally (Figure 4.33). After 10 seconds the QoS Device is initiated and policies for all running flows are requested from the QoS Manager. After the policies are enforced the flows continue to run according to their preference levels specified in profiles.

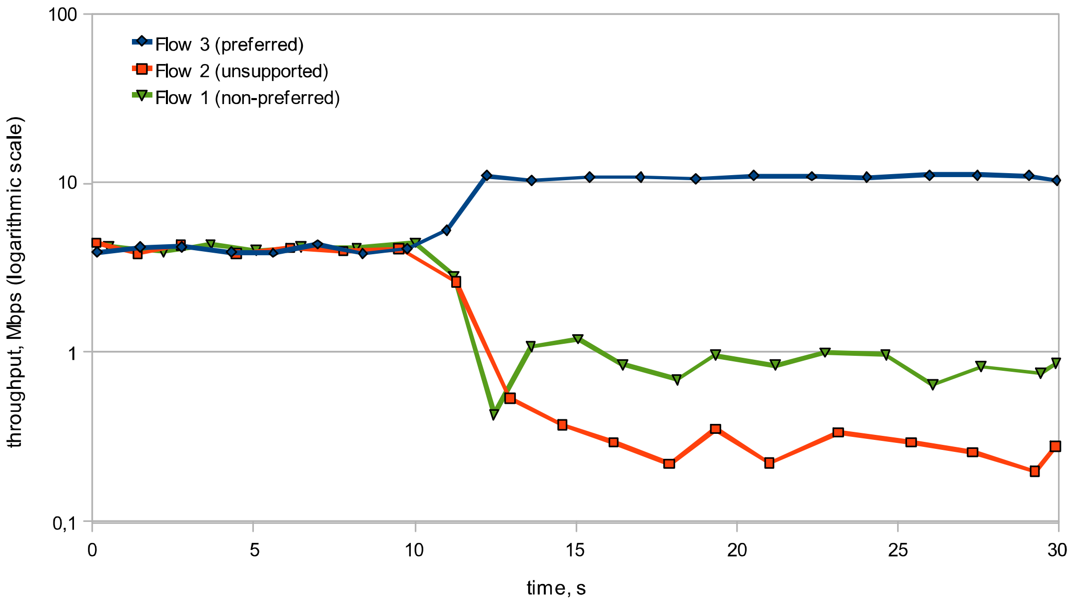


Figure 4.33: After policy enforcement all flows receive differentiated treatment

4.10.2.2 Scenario 2

This scenario demonstrates a usability conflict and how it is resolved (Figure 4.34). A user with a *Communicator* profile runs a streaming video flow (non-preferred). At 7s the user starts a real-time videoconference application (preferred). A conflict on the

[1] *iperf* homepage, http://iperf.sourceforge.net

basis of viewing is detected and the non-preferred flow is downgraded to unsupported. The preferred flow gains the bigger part of the available bandwidth.

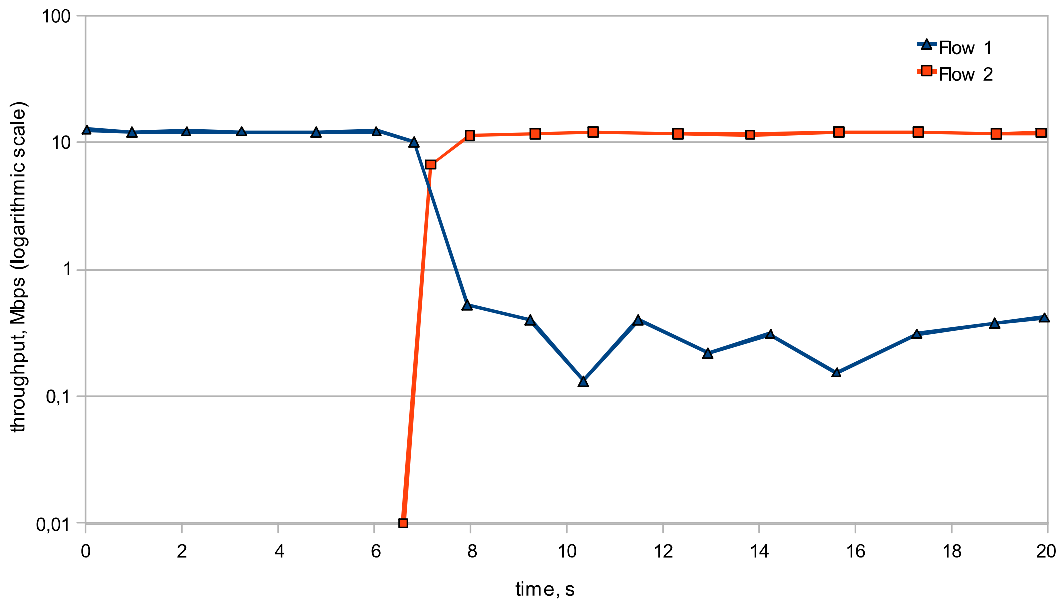


Figure 4.34: Non-preferred flow is downgraded when a conflict with the preferred flow is detected

4.10.2.3 Scenario 3

It can be configured in user policies that only one preferred application is allowed to run at a time. If a user is allowed to run several preferred applications at the highest precedence level simultaneously, the delivered level of quality might be not satisfied for all applications. The following scenario demonstrates such a policy and shows how the possible conflicts can be resolved. In this scenario (Figure 4.35) a background TCP flow is always running (unsupported, lowest priority) from a wireless node to the access point. A user with an "*Audio/Video Consumer*" profile is running a streaming audio application (preferred). After a while the user starts a streaming video flow that should also run as preferred according to the profile. However, due to the policy that two preferred flows are not allowed at the same time the streaming video flow is downgraded and started as unsupported competing equally for the bandwidth with the background flow. At the marked point the streaming audio application is cancelled and the streaming video application is automatically upgraded because the conflict is resolved.

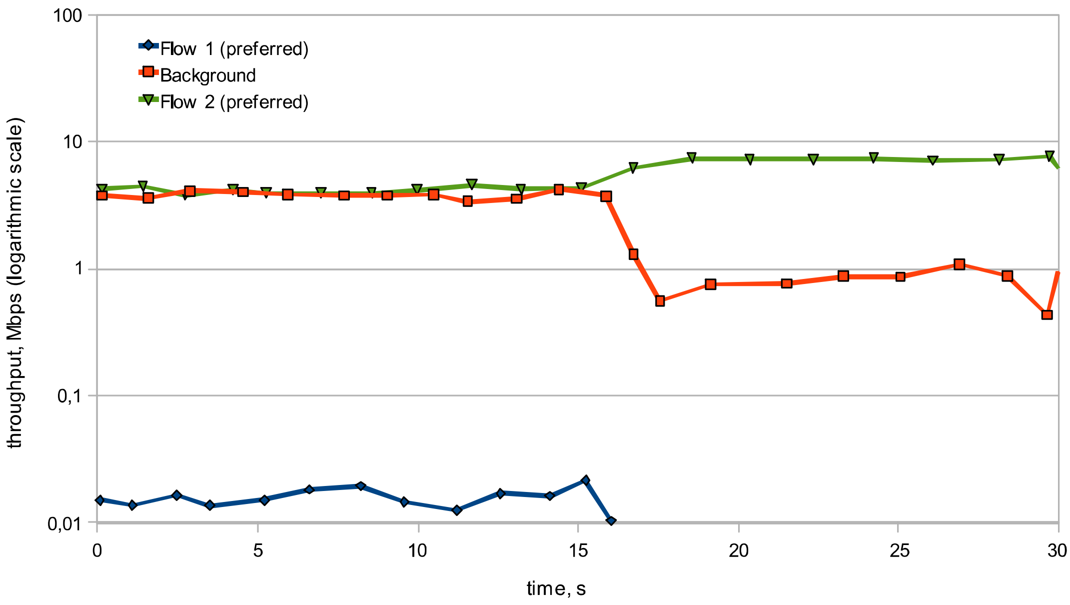


Figure 4.35: Only one preferred flow is allowed. Termination of the current preferred flow upgrades the other preferred flow previously run as unsupported

4.10.2.4 Scenario 4

This scenario demonstrates one of the policies with respect to mapping of the user profile to the precedence levels. If a user's preferred TCP flow runs at the highest precedence level it can hamper other users' preferred UDP flows due to the bandwidth consuming nature of the TCP flow (Figure 4.36). That is why a preferred TCP flow is not mapped to the highest precedence level. The preferred UDP-based flow uses the highest access category (AC) while the preferred TCP flow uses the second highest AC. Therefore the TCP flow can only grab the leftover bandwidth from the UDP preferred flow. This is well demonstrated in Figure 4.37 and Figure 4.38, which show correspondingly simulation and experimental results.

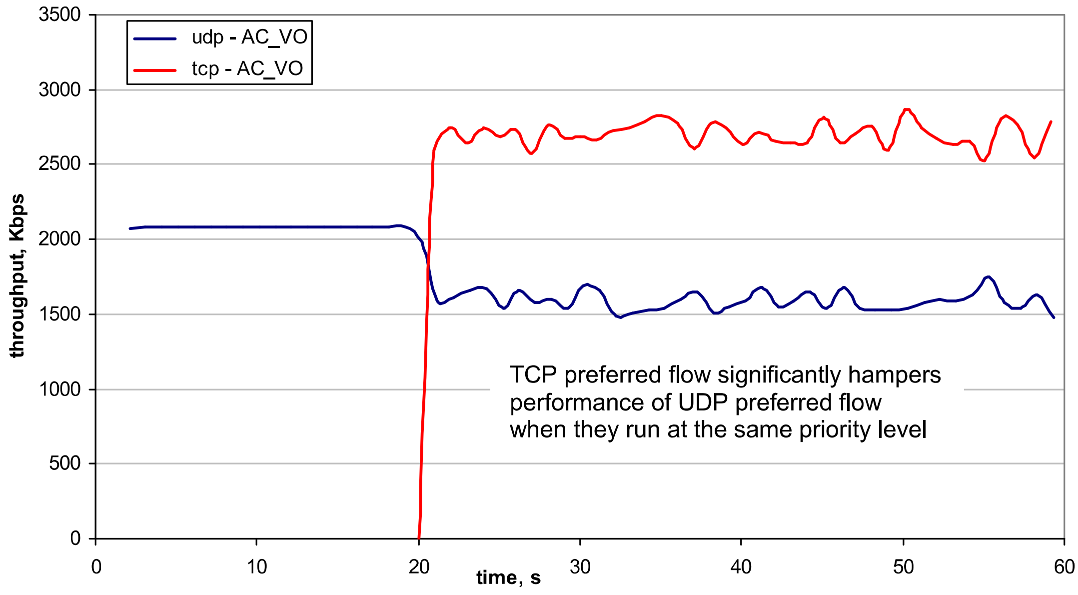


Figure 4.36: UDP and TCP flows running at the same priority level (simulation results)

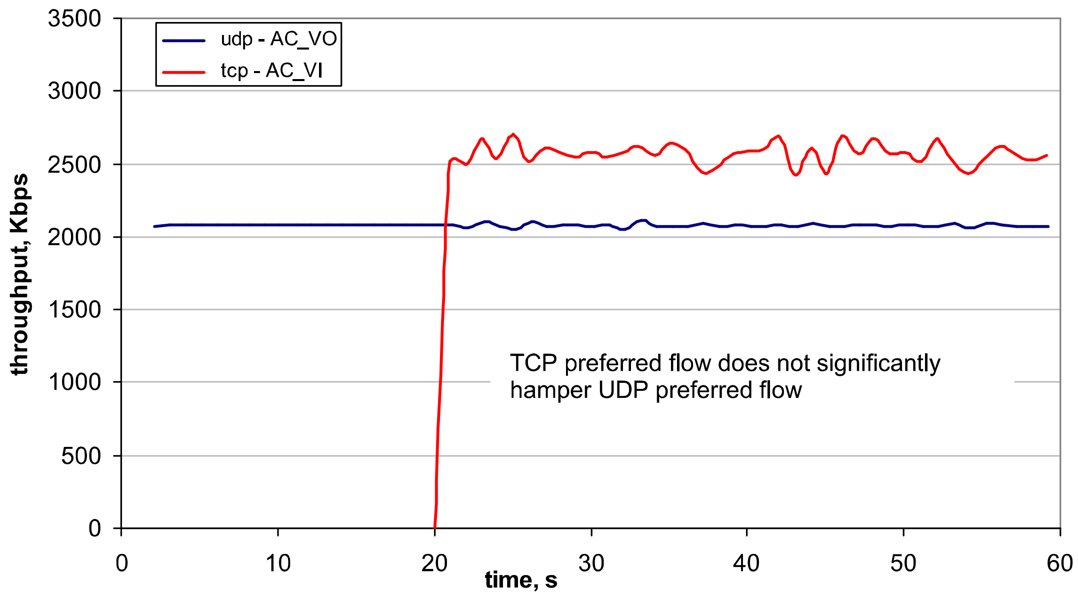


Figure 4.37: UDP flow running at the highest priority and TCP flow running at the second highest priority level (simulation results)

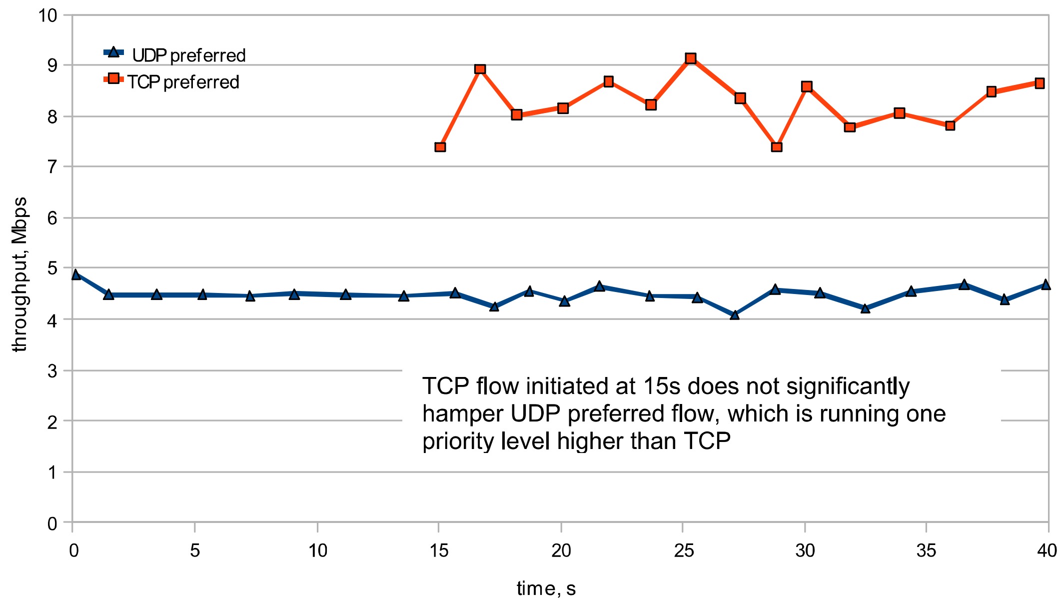


Figure 4.38: TCP-based preferred flow vs. UDP preferred flow (experimental results)

4.10.2.5 Scenario 5

This scenario demonstrates several policies in the multi-user environment. Figure 4.39 depicts the scenario split in several time intervals (*T1-T4*) used for better explanation below.

T1: User 1 runs two preferred applications. The UDP preferred flow (red) is running at the highest priority level and TCP preferred flow (blue) is running at the second highest priority level (explained in Scenario 4). It should be noted that if there is only one user on the network, the management system might allow a user to have several preferred flows running simultaneously. If there are several users on the network running preferred flows, only one preferred flow per user is normally allowed.

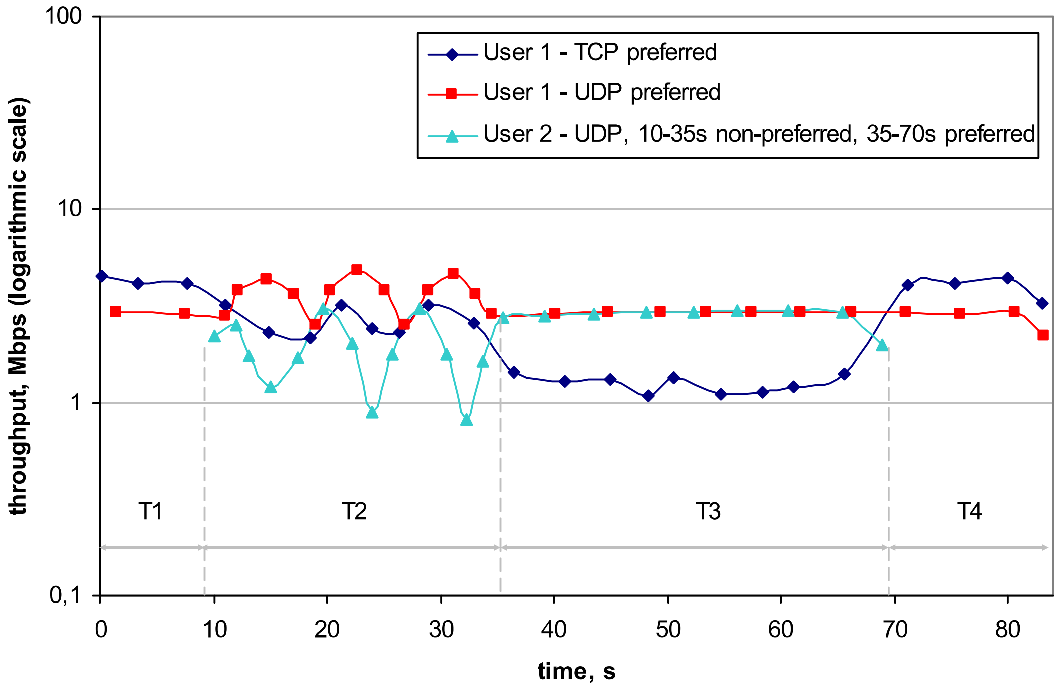


Figure 4.39: Example of user-centric policies in the multi-user environment

T2: User 2 starts a non-preferred UDP flow (cyan), which is started by the system as a best-effort flow. If the UDP flow is a video application, User 2 experiences bad video quality. It can be configured by the system administrator whether User 1 is still allowed to have two preferred flows when other users run non-preferred flows. In this scenario, User 1 is allowed to have multiple preferred flows unless other users do not have preferred flows running. Such configuration is also possible with taking into account user ranks. For example, User 1 is allowed to have multiple preferred flows running because he has a higher user rank than User 2.

T3: User 2 decides to change his preferences and makes the profile with the UDP flow (cyan) as preferred (either user's interests/activities change or user is not satisfied with the quality). The UDP flow (cyan) is upgraded to the highest priority level and runs as a preferred flow. As there are two users now running preferred flows, User 1 is not allowed any longer to have two preferred flows running simultaneously. According to the default intra-user LCFS policy (Last Come First Serve), the oldest started TCP-based preferred flow of User 1 (blue) is downgraded and continues running as a best-effort flow. Two preferred UDP flows (red and cyan) run at the highest priority level.

T4: User 2 stops his UDP flow (cyan). The previously downgraded TCP flow (blue) is automatically upgraded to its previous priority level.

4.11 Conclusion

Even though the interest in home networking is huge now, the subject of user-centric QoS is not well addressed. The most important standardization bodies relevant to home networking define at present only tagging mechanisms based entirely on traffic types. DLNA defines at the moment priority-based QoS that refers to 802.1D and WMM priorities, which is totally traffic-oriented. We believe that in the near future when broadcast and broadband services will widely penetrate home networks the traffic-oriented QoS approach will not be sufficient to satisfy all user requirements. The work presented in this chapter suggested that the overall user experience can be significantly improved by taking into account user preferences when managing flows on the network. The proposed approach classifies traffic according to user profiles ensuring a certain quality for preferred applications regardless of the traffic requirements. Additionally, the approach employs usability rules to take into account user behavior when managing the network. The described usage scenarios addressed typical situations for home networks and demonstrated how the approach can be applied to satisfy user specific requirements and network constraints.

5 Analytical model for 802.11e EDCA function

5.1 Introduction

The goal of this chapter is to present a simple analytical model for throughput estimations in 802.11e-based networks. This model can be useful for admission control tasks when there is a need to estimate how much bandwidth will be available for each station in the network at a certain priority level if a new request is admitted with a particular priority level.

The general objective is to calculate the achievable throughput per access category (AC) given a list of all ACs operating in the network along with their traffic loads. This will make it possible to predict what we will have if we admit a new stream on the network. Normally, it is not a trivial thing to do as adding a stream in one of the ACs, influences the traffic load in other ACs in a non-linear way. We developed a simple analytical model for the 802.11e EDCA function that gives a good match when compared with the experimental results.

In general, designing an analytical model for the EDCA function is a very complex task, which has been thoroughly addressed in the literature. Usually, analytical models are built upon various simplifications, approximations and assumptions. There have been numerous efforts to mathematically describe the EDCA behavior under the saturated [82], [83], [84], [85] and non-saturated mode [86], [87], [88]. Some models are designed for throughput analysis [89] and some for queuing delay analysis [90]. There are also different models developed for a specific traffic type, e.g. VoIP [91]. An extensive literature survey shows that there is no a single analytical model for EDCA, which considers all EDCA QoS parameters (CW, AIFS, TXOP) for any traffic load [86]. It can be also claimed that the experimental performance is close to theoretical expectations only in some ideal cases, which makes deployment of pure analytical methods in practice quite difficult. That is why we suggested in this work and implemented a post-admission control approach (presented in Chapter 6), which can be considered as a measurement-based adaptive admission control method and which can be more applicable in practice, especially in wireless networks. From our practical experience, we believe that in wireless networks the focus should be made on the measurement-based methods for bandwidth estimations. For precise theoretical estimations an analytical model should take into account not only all aspects of the 802.11e/WMM specification but also many external factors affecting the observed network performance in practice (variable nature of the wireless channel, hardware/firmware specifics, traffic patterns, network protocols, etc). Developing an analytical model that could take into account all these factors is a very challenging task. Keeping in mind all these problems, we believe that a very advanced analytical model, which could consider all aspects of the 802.11e/WMM specification (e.g. collisions, retransmissions) would not necessarily result in considerably better bandwidth evaluations in practice, comparing to a more simplified analytical model. Therefore, we think that for rough estimations a network management system can make use of a simple analytical model derived with a set of assumptions. However, for main management operations, measurement-based methods should be employed for network state estimations.

In this chapter we describe the operation of the Enhanced Distributed Channel Access (EDCA) function of 802.11e standard and we derive a simple analytical model for throughput estimations.

5.2 EDCA function overview

This section contains a general description of the EDCA function along with some illustrative state diagrams.

As was already discussed in Section 3.4.2.1, there are four transmission queues defined in the EDCA mechanism of the 802.11e standard [30]. Each transmission queue conveys traffic of the corresponding access category. The four access categories are designed with specific types of traffic in mind (AC_VO – voice, AC_VI – video, AC_BE – best effort, AC_BK – background traffic). To provide prioritization of traffic, each access category has a different chance to access the medium. In its basic form, the

EDCA channel access function can be represented as depicted in Figure 5.1. To obtain a transmission opportunity (TXOP) and transmit a packet, an access category has to wait first until medium is idle for a certain Arbitration Interframe Space (AIFS) time plus a certain number of time slots (backoff slots) randomly chosen from the Contention Window (CW) interval. The AIFS and CW intervals are different for each access category, which provides the differentiated access to the channel.

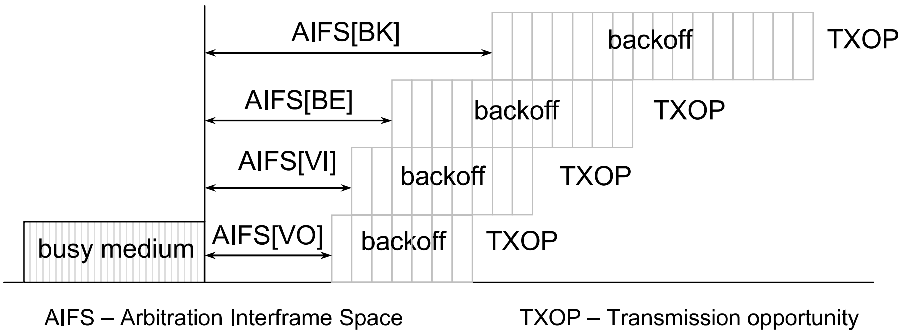


Figure 5.1: EDCA prioritized medium access

The detailed EDCA activity and statechart diagrams (derived from [30] and [40]) are depicted for reference in Figure 5.2 and Figure 5.3.

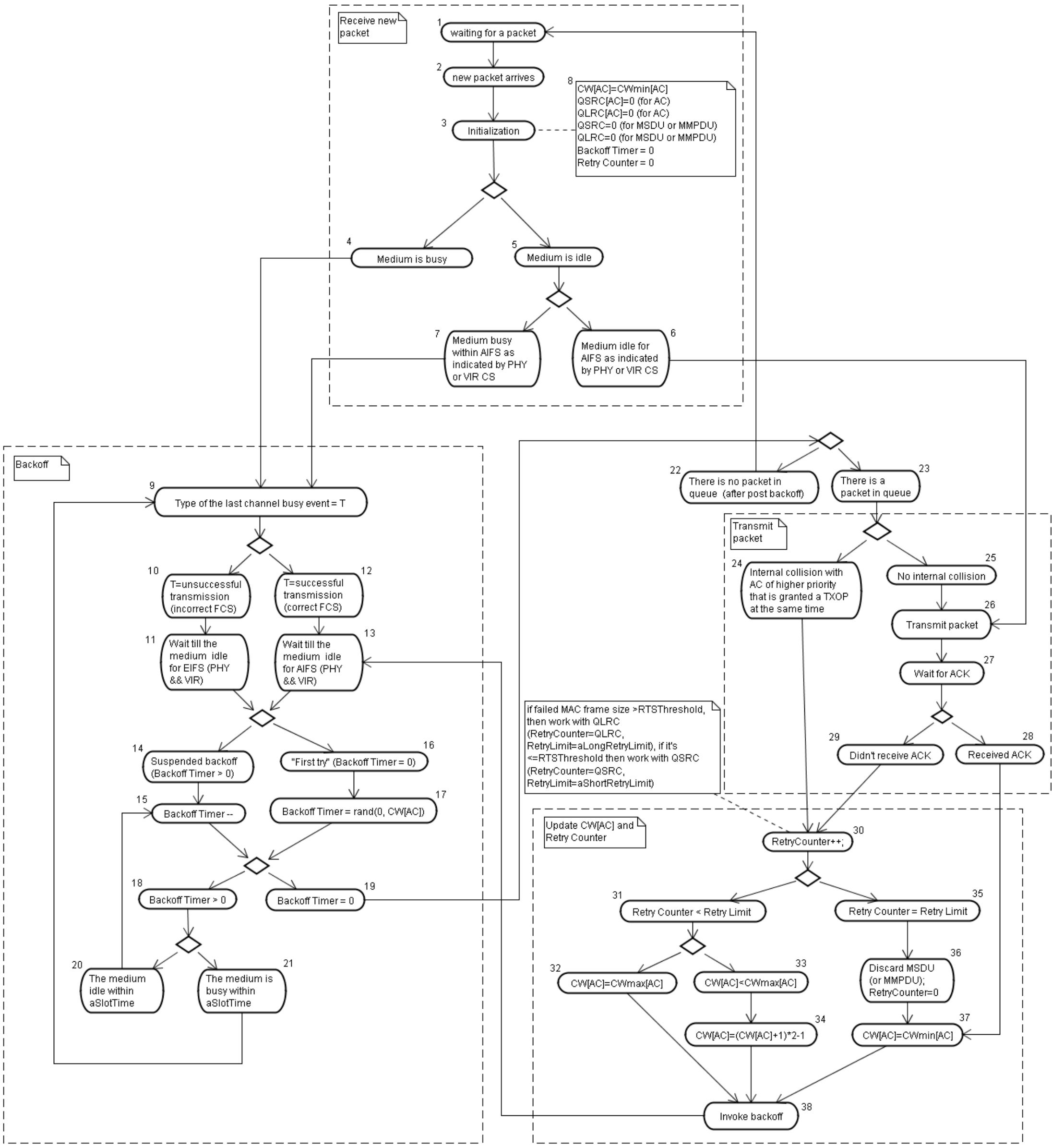


Figure 5.2: EDCA activity diagram

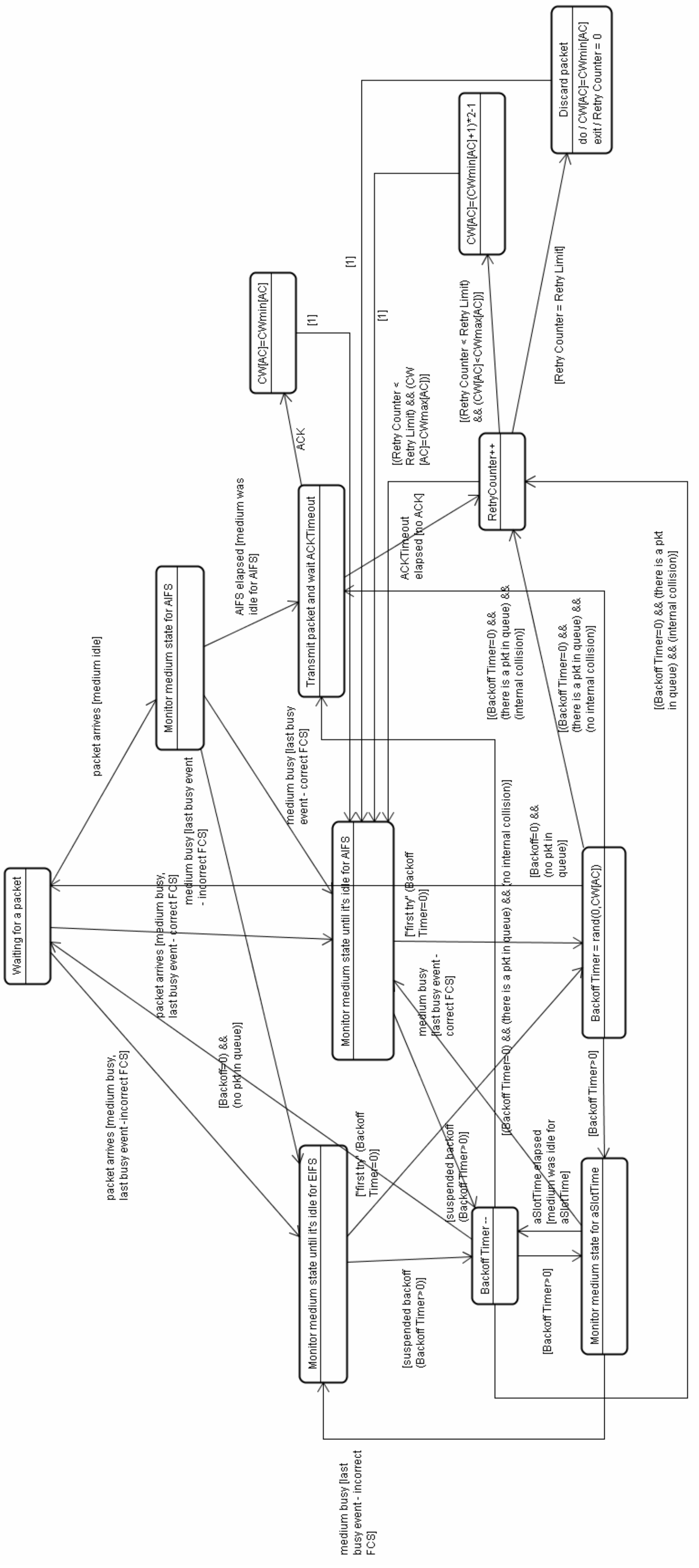


Figure 5.3: EDCA statechart diagram

From these diagrams we obtain a state diagram depicted in Figure 5.4. The state diagram represents a simplified discrete-time Markov process [81]. Each transition arrow is accompanied with a short event description and a pair of parameters in square brackets, which are the probability of transition and average time it takes to transit from the state.

The following assumptions have been made for the model presented in this document:

- Each station will successfully gain access to the channel after the first backoff attempt.
- Each sent packet will be successfully received and acknowledged (error-free channel).
- Only one packet is transmitted per TXOP.

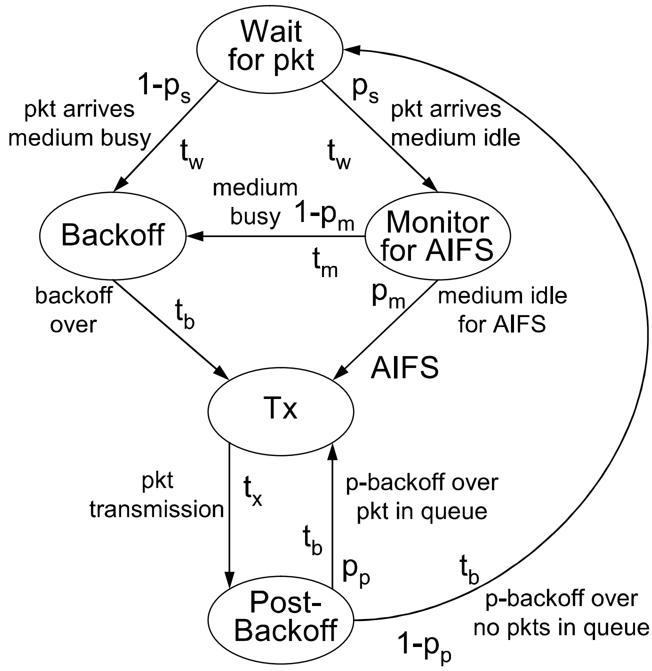


Figure 5.4: EDCA model state diagram

p_s - probability that medium is idle during one slot
t_w - average time to wait for a packet in queue
p_m - probability that medium is idle for AIFS time
t_m - average time to find medium busy when monitoring for AIFS
t_b - average time to backoff (same for postbackoff); this includes AIFS
p_p - probability that there is a packet in queue waiting for transmission
t_x - time to transmit a packet (send and receive acknowledgement)

This is a more detailed description of the states shown in Figure 5.4.

State	Description
Wait for pkt	After Post-Backoff the system spends on average t_w time in this state waiting until the next packet arrives.
Backoff	This state includes several internal states depicted in Figure 5.5.
Monitor for AIFS	If medium is idle for AIFS time, the system goes directly to Tx state, if not then the system goes to backoff, Figure 5.6.
Tx	Transmission state. This includes the time it takes to send a packet and receive an acknowledgment.
Post-Backoff	Technically it is the same state as Backoff, Figure 5.5.

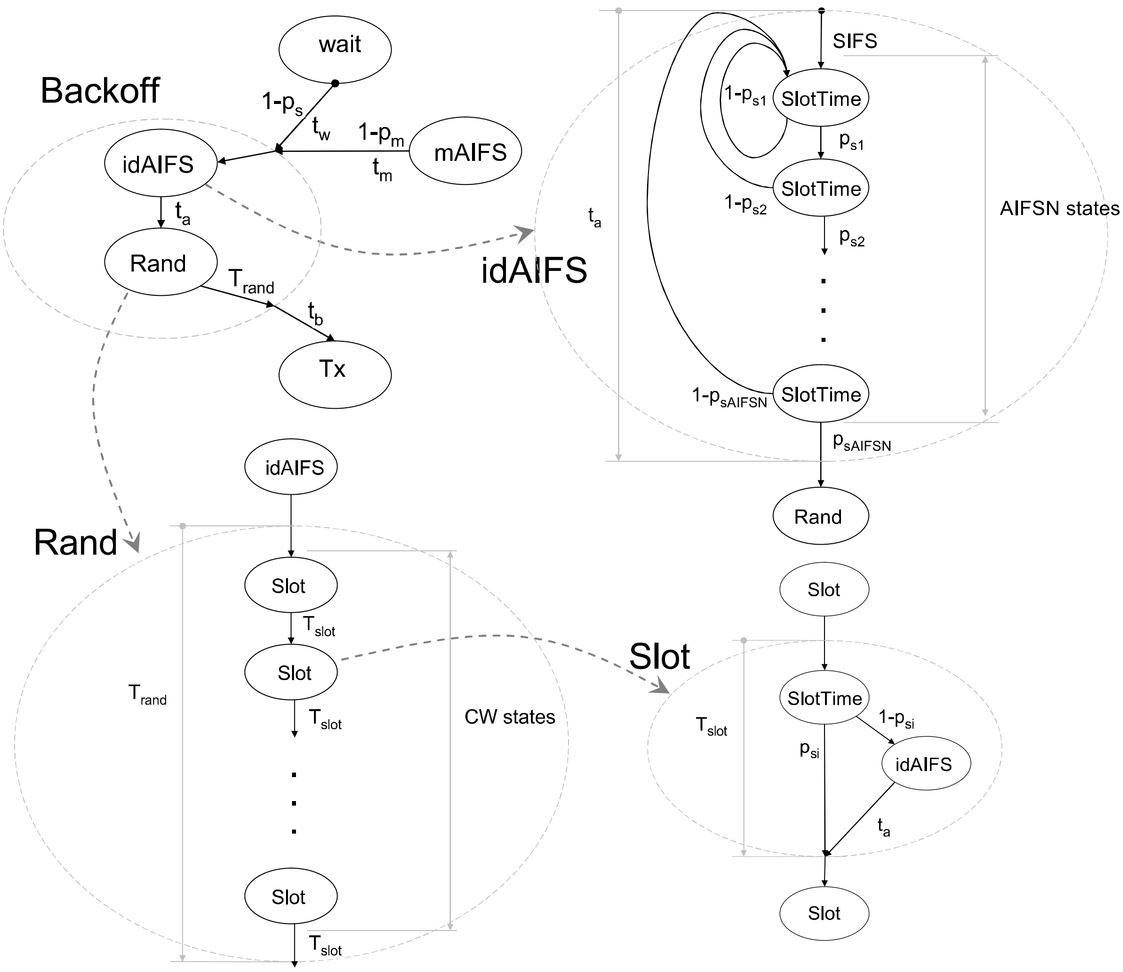


Figure 5.5: Backoff/Post-backoff and its internal states

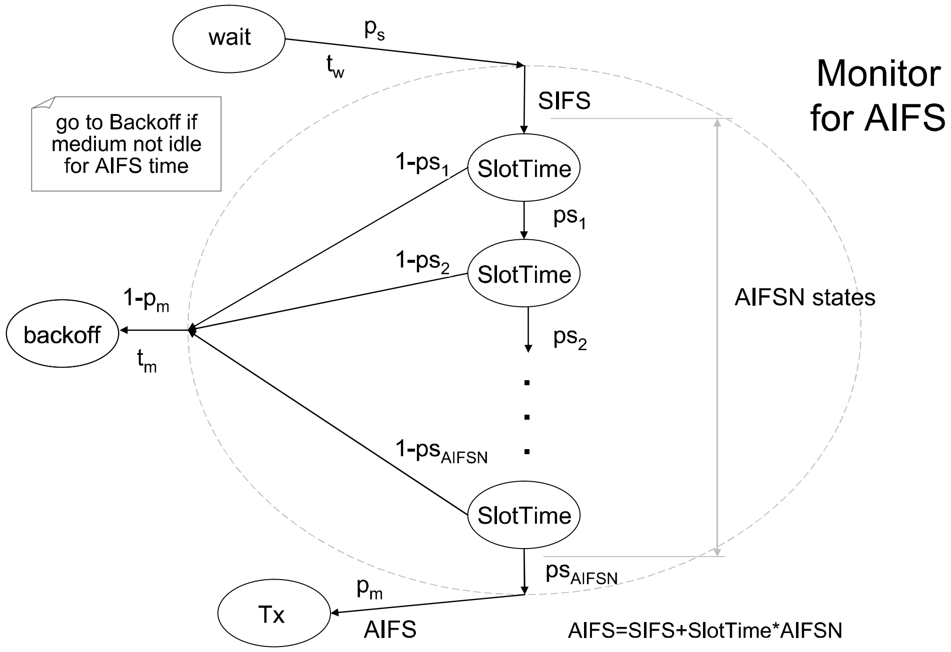


Figure 5.6: "Monitor for AIFS" state

Problem

To describe the EDCA process mathematically, one needs to find the hitting times (times it takes to go from one state to another) and limit probabilities (portion of time to be in each state). Given the hitting times and limit probabilities, we could answer all the possible questions (how long it takes on average to be in backoff, how much time the system spends in transmission state, how much data were transmitted and etc.). To find the hitting times and limit probabilities, we need to know all transition probabilities, i.e. probabilities to transit from one state to another. In other words, these are probabilities ps (as marked on the diagrams). The probability ps is the probability that the medium is idle for one SlotTime. The problem here is that this probability is time dependent. It is different for each SlotTime state depicted in diagrams in Figure 5.5 and Figure 5.6. Finding a probability distribution function for a medium to be idle for one SlotTime at a certain moment of time for each transmitting station is a very complicated task. That is why, we were looking for a more simplified approach, which is described in the next section.

5.3 Analytical model for throughput estimations

Here, we derive a simple model for throughput estimations.

If there is only one transmitting station (Figure 5.7) the maximum achievable throughput can be easily evaluated. The number of packets *n* that a station can send in a certain time interval *T*:

$$n = \frac{T}{t_s} = \frac{T}{Tx + AIFS + S \cdot k} \tag{1}$$

Where t_s is a packet service time, i.e. the time it takes for a packet to be sent (including backoff time) and be acknowledged. The average number of backoff slots randomly chosen from the CW interval is calculated as the following:

$$k = \frac{1}{2} CW_{\min}$$

CW_{min} is used here because due to our assumptions there are no retransmissions and therefore the *CW* interval equals always to CW_{min}. Note that *Tx* in Figure 5.7 is the time from the start of the packet transmission until the end of the acknowledgement transmission.

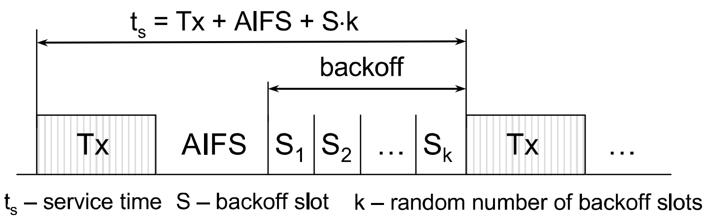


Figure 5.7: EDCA medium access for one station

Equation 1 can be expressed also as a rate or throughput *r* measured in packets per second:

$$r = \frac{n}{T} = \frac{1}{Tx + AIFS + S \cdot k} \quad [pkts/s]$$

If there are several stations, a station's backoff procedure may be suspended due to transmission from other stations (Figure 5.8). Whenever the medium is determined to be busy, the backoff timer does not decrement for that slot. The backoff procedure is resumed only after the medium has been sensed to be idle for the duration of AIFS.

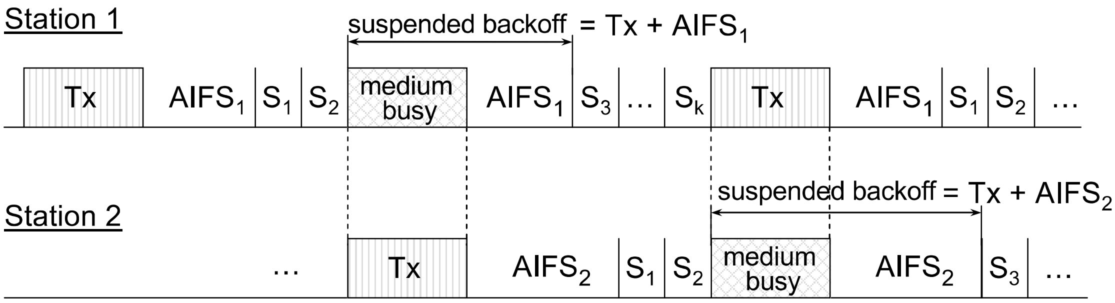


Figure 5.8: EDCA medium access for two stations

Each time when *Station 2* transmits a packet (Figure 5.8), *Station 1* is suspended for $(Tx+AIFS_1)$. (We consider a saturated case here, i.e. at each station there are always some packets waiting for transmission.) If *Station 2* transmits N_2 packets in time interval T then *Station 1* is suspended in overall for $(Tx+AIFS_1)\cdot N_2$ units of time. The number of packets that *Station 1* can send in time interval T is determined by the time when *Station 1* is not suspended, therefore:

$$N_1 = \frac{T-(Tx+AIFS_1)\cdot N_2}{t_{s1}} = \frac{T-(Tx+AIFS_1)\cdot N_2}{T/n_1} = \frac{n_1}{T}\left[T-(Tx+AIFS_1)\cdot N_2\right]$$

By dividing this equation by the time interval T, we express it in terms of the throughput:

$$R_1 = \frac{n_1}{T}\left[1-(Tx+AIFS_1)\cdot\frac{N_2}{T}\right] = r_1\left[1-(Tx+AIFS_1)\cdot R_2\right]$$

Lower-case letters in these equations (t_s, n, r) refer to the case when only one station is present. For example, r_1 is the maximum possible throughput for *Station 1*, which is possible when *Station 2* does not transmit data, i.e. when $R_2 = 0$.

If we consider a similar equation for *Station 2*, then we have a system of two equations:

$$\begin{cases} R_1 = r_1\left[1-(Tx+AIFS_1)\cdot R_2\right] \\ R_2 = r_2\left[1-(Tx+AIFS_2)\cdot R_1\right] \end{cases}$$

This is a system of linear equations that can be easily solved relatively to R_1 and R_2.

In more general case for m stations, a system of linear equations takes the following form:

$$\begin{cases} R_1 = r_1\left[1-(Tx+AIFS_1)\cdot(R_2+R_3+...+R_m)\right] \\ R_2 = r_2\left[1-(Tx+AIFS_2)\cdot(R_1+R_3+...+R_m)\right] \\ \qquad\qquad ... \\ R_m = r_m\left[1-(Tx+AIFS_m)\cdot(R_1+R_2+...+R_{m-1})\right] \end{cases} \qquad (2)$$

If a saturated case is considered, the system has to be solved for throughput values R_i satisfying the condition $R_i \geq 0$. If a non-saturated case is considered, the condition is $0 \leq R_i \leq D_i$, where D_i is the date rate generated at station i.

Figure 5.9 shows a comparison of analytical and experimental results for two Gigabyte 802.11abg GN-WI01HT stations with Atheros AR5413 chipsets operating in 802.11a 12 Mbps mode. The stations perform transmission of UDP packets with the size of 1024 bytes at a constant rate. One station uses the AC_VI access category and the other station uses the AC_VO access category. The analytical results in Figure 5.9 represent a solution of Equations 2 for AC_VI and AC_VO access categories. In Matlab we implemented a program to find throughput values for any number of stations given the traffic generated at each station.

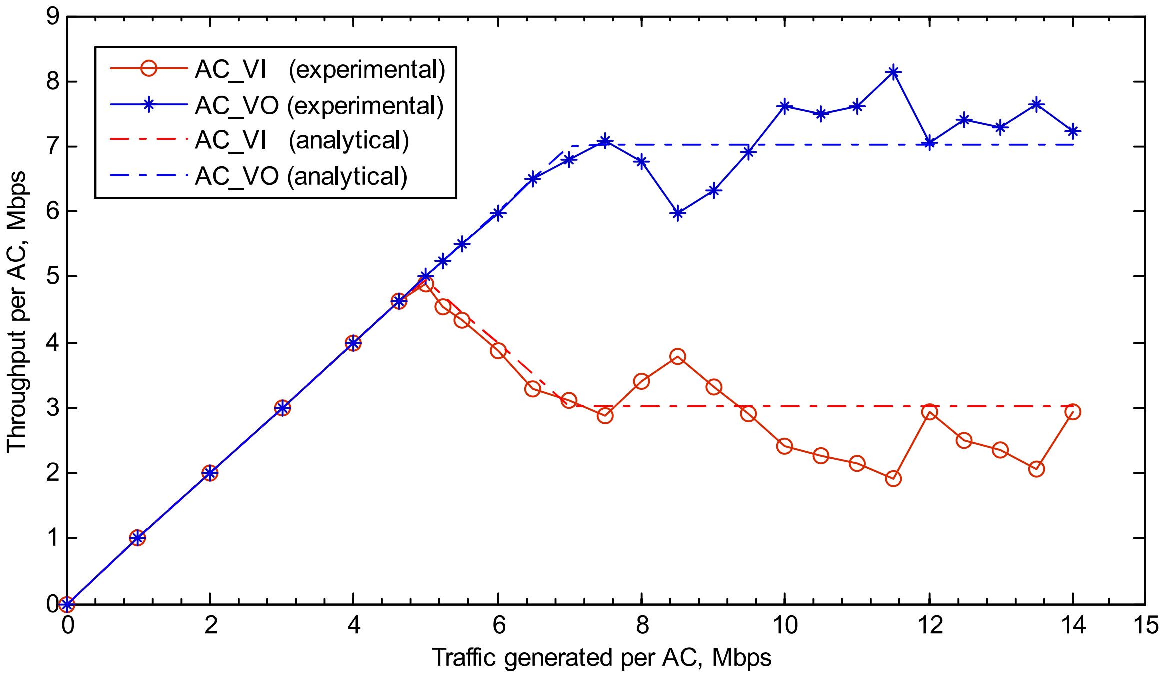


Figure 5.9: Comparison between analytical and experimental results for 802.11a 12Mpbs mode

5.4 Conclusion

As clearly seen from the graphs, our analytical model gives a good match when compared with the experimental results. However, the experimental performance is close to theoretical expectations only in some ideal cases, which makes deployment of pure analytical methods in practice quite difficult (even if a more sophisticated analytical model is used). The main factors that have a significant effect on the observed network performance are the following.

- Hardware and firmware implementation.

Different wireless cards provide different performance. This is especially true with respect to the implementation of the algorithm resolving internal virtual collisions. In a set of experiments with different wireless cards (Gigabyte 802.11abg, Intel 2915abg) we observed that if a station has several active transmission queues, the throughput results for each active access category can not be well explained theoretically based on the WMM specification [40]. It seems possible that vendors enhance sometimes wireless card functionalities with some proprietary features. An expectation that two arbitrary WMM-certified wireless cards from two different vendors provide same performance may not be always true.

- Network configuration and environment.

A slight change in network configuration, topology or wireless environment might significantly change the network performance. Due to the variable nature of wireless medium (e.g. interference in radio signals) and various system parameters (memory, CPU, operating system), two identical wireless clients can eventually provide completely different network performance.

- Network traffic.

The nature of data traffic flowing in the network has also a great effect on the network performance. A protocol in use (UDP, TCP) and data generation pattern (variable bitrate, constant bitrate, on-off, Poisson, etc.) play a big role in how the network resources are finally distributed among the clients.

Developing an analytical model that could take all these factors into account is a very complex task. A model, which could consider all aspects of 802.11e specification without considering these external factors would not necessarily result in considerably better estimations in practice than a simple analytical model derived with a set of assumptions. Therefore, we think that for rough estimations a network management system can make great use of a simple analytical model like the one described in this document (e.g. for basic admission control decisions). However, for main management operations, measurement-based adaptive methods for evaluating network state should be employed.

6 Admission control in wireless networks

6.1 Introduction

To address the problems of wireless networks, great efforts are currently being made in the research and industry communities. However, the only QoS mechanism broadly implemented so far in wireless adapters available on the market is prioritization of traffic known as Wi-Fi Multimedia (WMM) [28]. Unfortunately, WMM solves only some of the problems in wireless networks. Comparing to low priority traffic, high priority flows have more chances to get better service in terms of bandwidth, jitter and latency, but they still face many problems if the wireless channel is highly variable or the network is overloaded. The high traffic load results in degradation of services for high priority flows. For example, if the network is saturated with the high priority video traffic and the sum of transmission rates of all the flows is greater than the channel capacity, heavy channel contention occurs and QoS cannot be guaranteed for any flow. Therefore, it is very challenging to enhance today's wireless networks with an admission control mechanism, which could maintain the network in the non-saturated mode, thereby significantly improving the service for admitted traffic on the network.

The goal of this chapter is to describe an admission control approach that can be easily implemented in wireless home networks with WMM support. The design philosophy of the approach is a post-admission control. That is, all traffic is provided with the access to the network and admission control policies are enforced only if the traffic load exceeds a certain threshold. Possible enforcement policies can be configured differently and may include, for example, changing priority for some flows or terminating them. We show that this approach improves the total performance of the network as well as user experience.

6.2 Background

Admission control is the mechanism that makes the decision whether or not to allow a new service to join the network. This mechanism can ensure that existing services are not degraded and a new service is provided with QoS support. If there are not enough network resources to accommodate a new service, the admission control mechanism may either reject the service or admit it with the lower level of QoS than it is requested.

There are many options available for implementation of admission control in the network. The design choices are usually considered with respect to the entities and functionalities schematically depicted in Figure 6.1. Depending on implementation choices for each of the depicted components a different level of admission control complexity and performance can be achieved.

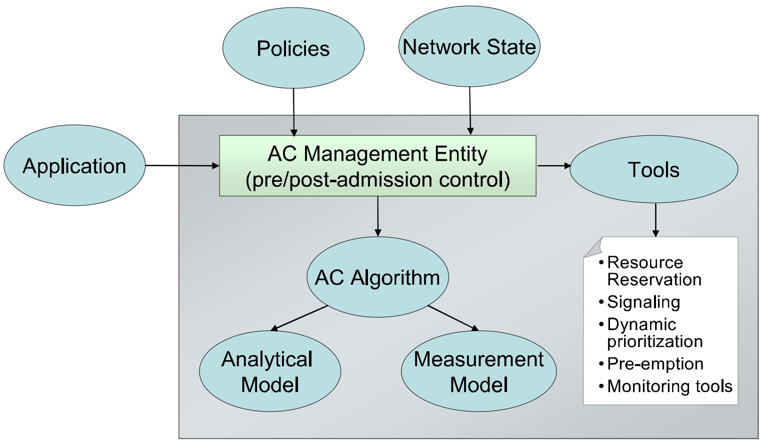


Figure 6.1: Admission control (AC) components

Based on whether admission control policies are enforced before or after a service is allowed to join the network, there are pre-admission and post-admission control approaches usually distinguished. In the former case, called *pre-admission control*, it is inspected before admitting the new services whether the network has enough resources to accommodate new requests. A typical use case of pre-admission control would be to prevent new Voice over IP (VoIP) sessions from joining the network if there are not enough available resources. Pre-admission control usually cooperates with a resource reservation signaling mechanism, which is used to signal traffic requirements and admission control decisions between network entities. Alternatively, *post-admission control* makes enforcement decisions after the new services have been provided with access to the network. In this case, every new service is allowed to join the network while being subject to future restrictions or cancellation if network resources decrease.

Post-admission control is easier to implement as it is not required that all services have to declare their QoS requirements and there is no need in an algorithm making provisional bandwidth estimations. However, post-admission control can be less effective in practice, as in this case some services can be disrupted during the time a new service joins the nearly saturated network and an admission control decision is taken. In this chapter, we present an implementation of a post-admission control approach that is considered as a complementary mechanism for the general QoS solution in wireless home networks. In practice, the pre-admission and post-admission control mechanisms are expected to be used together as they complement to each other.

6.3 Related work

Admission control is heavily discussed now in many Standard Developing Organizations (SDOs). Many believe that this is the only means to prevent overload of the network and a basis of any well thought through QoS solution. The SDOs such as UPnP, DVB and DLNA define standards with requirements and architectural solutions regarding admission control for home networks. UPnP has recently completed the work on QoS v.3 architecture that includes an admission control solution [35]. DVB has published high-level technical requirements with a QoS functional model containing admission control functionality [37]. DLNA has already defined functional QoS requirements with respect to admission control as well. The SDOs, however, do not specify how exactly admission control should be implemented at the low levels, for example in wireless networks. The standards and requirements are meant to provoke developers and service providers to work out different technical solutions for forthcoming home network technologies. That is why it is very timely and important to provide an admission control solution for wireless home networks.

In the research community the work on admission control in wireless networks is also of great interest now. The IEEE 802.11e specification defines optional admission control procedures for contention-based channel access (Section 3.4.2.3.3). This includes definitions of MAC management frame formats for signaling traffic specification parameters and admission control decisions between stations and an access point (AP). The defined 802.11e admission control procedures are also included in WMM specification [40]. However, admission control is not fully implemented in the currently available APs. It is quite a complex task to implement an algorithm that the AP could use for making admission control decisions. Unspecified in 802.11e, such an algorithm is a subject of work for many researchers.

The considered methods for making admission control decisions are usually classified as measurement-based and model-based methods. An extensive overview of such methods is given in [92]. Some methods [93] propose algorithms based on the signaling mechanism defined in 802.11e, and some require various MAC layer extensions [94]. All these methods can be considered as pre-admission control methods as they require that all services declare their QoS requirements before being admitted in the network.

Post-admission control methods (also called reactive or probe-based admission control methods) are usually measurement-based and simpler to implement. They typically require monitoring tools installed in the AP and/or wireless clients. Based on the measured transmission times or collision rates, the occupied and residual bandwidth can be derived [93]. If the occupied bandwidth exceeds a certain threshold, admission control decisions are enforced. Apart from the occupied bandwidth, other criteria can be used for monitoring and enforcing policy decisions (e.g. end-to-end delay). In [95], a post-admission control approach based on monitoring the traffic on the AP is considered. The authors perform packet loss and delay estimates for each 802.11e access category (AC) directly at the AP. They validate their approach with the VoIP traffic. When a threshold for delay is exceeded an appropriate action is taken (e.g. termination of a VoIP session). In comparison to this work, we base our post-admission control on monitoring the traffic on the wireless clients rather than on the AP. This gives greater chances for deployment of our solution in a typical modern wireless home network where an arbitrary WMM-certified AP can be used.

6.4 Network Performance criteria

When making a pre-admission control decision it is usually estimated whether the network has enough resources to accommodate a new request. In the case of a post-admission control it is generally evaluated whether the network performance is adequate with respect to specific criteria after admitting a new request. We consider traffic load and queuing delays for evaluating the network performance and making post-admission control decisions.

6.4.1 Traffic load

The network performance is critical when the channel is heavily loaded and transmission queues are saturated. Here, a saturated queue means that a queue has always a packet to transmit. To control the overall network load we consider the traffic load of each transmission queue.

There are four transmission queues at each station that supports WMM. Each transmission queue conveys traffic of the corresponding access category (AC) as it is defined in the Enhanced Distributed Channel Access (EDCA) mechanism of the 802.11e standard. The four ACs are designed with specific types of traffic in mind (AC_VO - voice, AC_VI -video, AC_BE - best effort, AC_BK – background traffic). To provide prioritization of traffic, each AC has a different chance to access the channel.

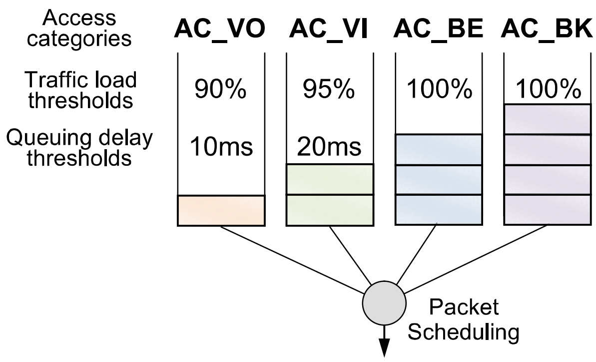


Figure 6.2: Transmission queues and corresponding thresholds

We perform the traffic load control on a per-queue basis to guarantee a certain performance for traffic belonging to each priority class or AC. A threshold-based approach is used with respect to each transmission queue. The goal is to keep the traffic load for each queue below a certain threshold. This is related to our post-admission control approach in the sense that if the threshold for a queue is exceeded then an appropriate action is taken. It is usually advised that the admission control is not applied to the best-effort and background traffic [30]. This is shown in Figure 6.2 where the transmission queues corresponding to AC_BE and AC_BK have 100% threshold (i.e. no admission control), whereas AC_VO and AC_VI have the traffic load thresholds set to 90% and 95% respectively. For example, if the traffic load for the AC_VO queue exceeds 90%, the network management system has to take a proper action to keep the load below 90% thereby preventing network overload.

6.4.1.1 Traffic load definition

The traffic load of a queue is defined here as a portion of time a transmission queue is busy, which is obtained in the following way. First, we measure the MAC layer service time for each packet, t_i. That is the time it takes for a packet to be sent and acknowledged (Figure 6.3).

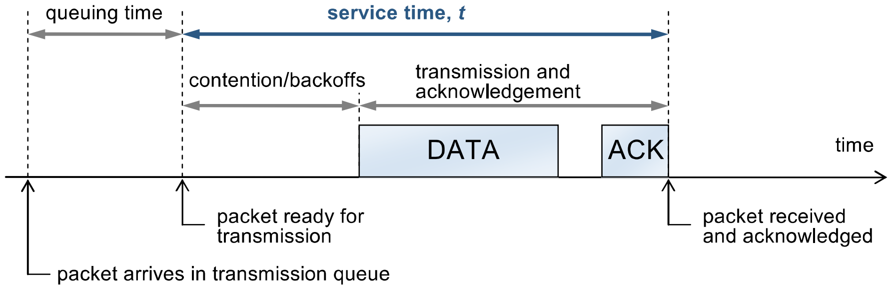


Figure 6.3: MAC layer service time

Then, we observe the number of packets N transmitted during the observation period T and calculate the traffic load of a queue:

$$\textit{Traffic Load} = \frac{1}{T}\sum_{i=1}^{N} t_i \cdot 100\%$$

In other words, the traffic load is the total time spent servicing the packets relative to a certain observation period.

All measurements at the MAC layer are performed with the help of our modifications of the wireless driver, which is described in detail in [96].

Since EDCA access categories have different probabilities of accessing the channel, their service times are also different. Figure 6.4 depicts the difference in service time per packet for different priority queues for 802.11g 12Mbps mode under light network load. The video queue (AC_VI) with the higher priority of accessing the media has the shorter service time per packet in comparison with the background (AC_BK) and best effort (AC_BE) queues.

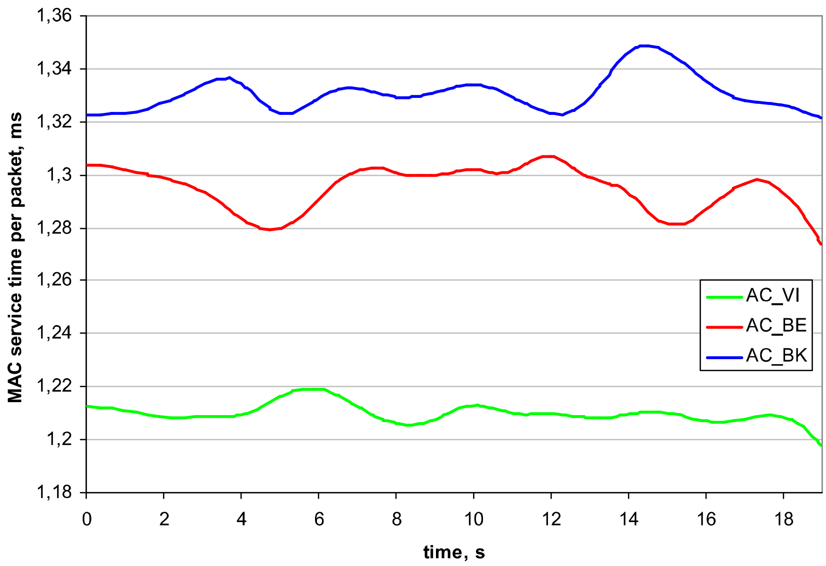


Figure 6.4: MAC service times per packet for different priority queues

6.4.1.2 Traffic load measurement example

In this section, we give an example of measuring the traffic load and service time for 802.11g mode with 11Mbps data rate. The measurements were done with the help of the modified 2915abg driver. Figure 6.5 shows the measured traffic load for the best-effort queue (AC_BE) for different generated data rates. It is seen that sending traffic at 1Mbps requires on average 13% of the whole time available at the MAC layer. That is, 13% of the time the stations competes for the channel, sends packets and waits for acknowledgments, and 87% of the time the station is idle. In these measurements the traffic load is linearly proportional to the generated data rate since the service time per packet (on average 1.56 ms) does not change (we have only one station with no collisions and no backoffs due to busy medium). That is why the 7Mbps data rate takes approximately 7·13%=91% of all resources at the MAC layer. It is seen that 9% of the free MAC layer resources is not enough for increasing the data rate up to 8Mbps. Indeed, by 100% utilization the maximum achievable throughput is 100/13 = 7.69Mbps and the 8Mbps stream starves from the lack of the available bandwidth. The maximum achievable throughput could also be calculated by dividing a packet size (1500 bytes) by the measured service time per packet: (1500*8)bits/1.56ms = 7.69Mbps.

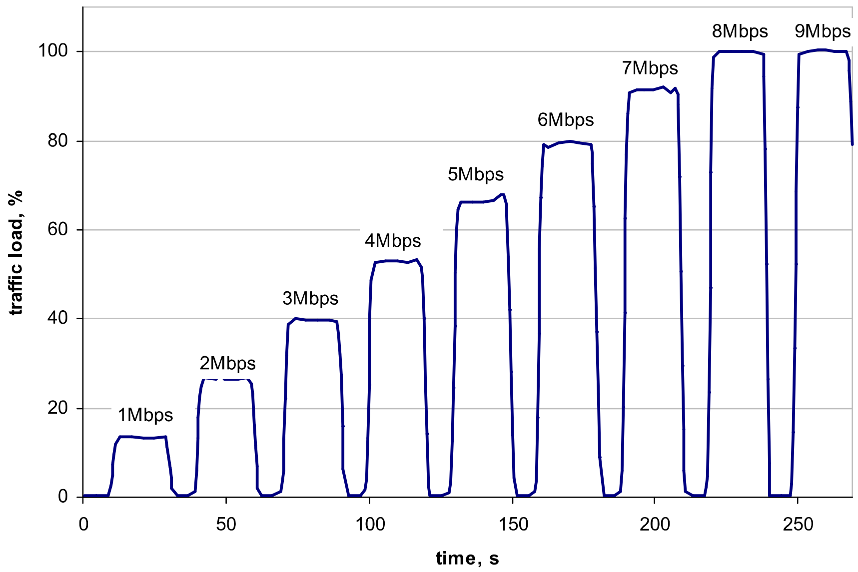


Figure 6.5: MAC service time for different traffic loads

The measured service time per packet (1.56ms) can also be justified theoretically. The total time to send a packet and receive an acknowledgment is determined as the following.

$$T = T_{DATA} + T_{SIFS} + T_{ACK} + T_{AIFS} + T_{POST-BACKOFF}$$

where,

$$T_{DATA} = T_{PREAMBLE} + T_{PHY\_HEADER} + T_{MPDU} = \frac{SIZE_{PREAMBLE}}{R_{preamble}} + \frac{SIZE_{PHY\_HEADER}}{R_{basic}} + \frac{SIZE_{MPDU}}{R_{data}} =$$
$$= \frac{8 \cdot 9}{1} + \frac{8 \cdot 6}{2} + \frac{8 \cdot 1500}{11} = 1186.9 \mu s$$

$$T_{SIFS} = 10 \mu s$$

$$T_{ACK} = T_{PREAMBLE} + T_{PHY\_HEADER} + \frac{ACK_{SIZE}}{R_{basic}} = 96 + \frac{8 \cdot 14}{2} = 152 \mu s$$

$$T_{AIFS} = AIFSN[AC\_BE] \cdot SlotTime + T_{SIFS} = 3 \cdot 9 + 10 = 37 \mu s$$
$$T_{POST-BACKOFF} = SlotTime \cdot \frac{CW_{\min}}{2} = 9 \cdot \frac{31}{2} = 139.5 \mu s$$

Thus, the successful transmission duration (service time) at the MAC layer is

$$T = T_{DATA} + T_{SIFS} + T_{ACK} + T_{AIFS} + T_{POST-BACKOFF} = 1186.9 + 10 + 152 + 37 + 139.5 \approx 1.53 ms$$

Therefore, the theoretical maximum achievable throughput at the MAC layer is

$$Througput_{\max} = \frac{SIZE_{MPDU}}{T} = \frac{8 \cdot 1500}{1.53ms} = 7.84Mbps$$

These theoretical values of service time and throughput are very close to the measured ones (1.56m/7.79Mbps). The difference is due to the fact that calculations were made assuming only successful transmissions.

This demonstrates an example of an admission control approach for a simple scenario when a decision of accepting a new flow has to be made. In practice, however, the estimation of available bandwidth is more complicated due to a number of access categories and stations competing for the channel simultaneously.

6.4.2 Queuing delays

For some applications it is also important to meet end-to-end delay requirements. We assume that from end-to-end delay requirements the constraints for queuing delays can be derived. In this case, a threshold-based approach can also be used with respect to queuing delays. Figure 6.2 shows an example of queuing delay thresholds set for AC_VO and AC_VI queues to 10 and 20 ms correspondingly. If the average queuing delay for the AC_VO queue exceeds 10 ms, the network management system can take a proper action to keep the average delay below 10 ms.

6.5 Network architecture

The proposed admission control solution is implemented in our user-centric QoS environment described in Chapter 4. This makes the admission control scheme be integrated with a variety of configurable policies satisfying different user preferences and network conditions. A typical network that we consider is depicted in Figure 6.6. The main functional components residing at various network nodes are QoS Device, QoS Policy Holder and QoS Manager.

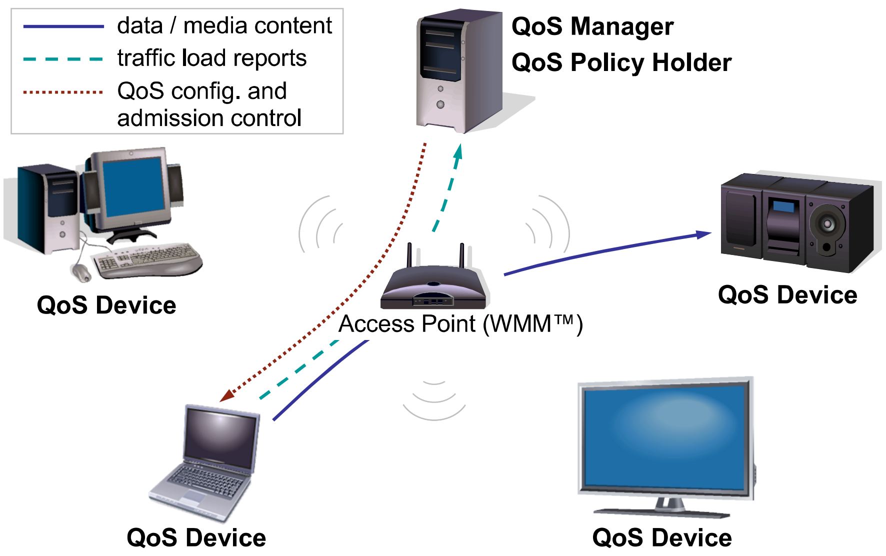


Figure 6.6: Wireless home network

6.5.1 QoS Device

All network nodes are represented as QoS Devices that are implemented on the basis of Intel 2915abg wireless network cards with WMM support. All packets originating at QoS Devices are classified according to user profiles and network policies. The classification is done by performing DSCP tagging on the outgoing packets as it was described in Sections 3.4.3 and 4.8.2. Each QoS Device implements a MAC layer monitor that provides information about actual traffic load and average queuing delays for all four transmission queues.

6.5.2 QoS Policy Holder

The QoS Policy Holder is represented by an SQL database for policy storage, which also contains admission control policies (queue thresholds, FCFS/LCFS policies, etc.) With the help of the QoS Tool a user (system administrator) can configure admission control polices (Chapter 7).

6.5.3 QoS Manager

The QoS Manager is the central management entity interconnecting all the components in the network. It receives information from QoS Devices about traffic load and queuing delay changes for all four transmission queues. With the help of the QoS Policy Holder, the QoS Manager makes admission control decisions and sends the corresponding commands to the QoS Devices (e.g. downgrade/upgrade/terminate application).

6.6 Testbed description

The wireless network under consideration consists of clients based on Intel 2915abg cards with WMM support implementing a subset of IEEE 802.11e. All clients run Linux Ubuntu OS. The open source driver for the network card ipw2200 was extended with some code to fulfill MAC layer monitoring related tasks [96]. A Cisco access point (AP) Aironet 1130AG was used in the network, but any AP Wi-Fi certified for WMM would work as well. For traffic generation the *mgen* tool[1] was used. Some scenarios were also tested with real unicast and multicast video traffic.

6.6.1 Driver level implementation

The MAC layer monitor residing in the user space collects the data supplied by the ipw2200 driver. The collected data are delivered to the user space using the */proc* file system that is used to provide file based communication with the kernel. Within the ipw2200 kernel component we created a file under the */proc* for delivering measurement data to the user space (Figure 6.7).

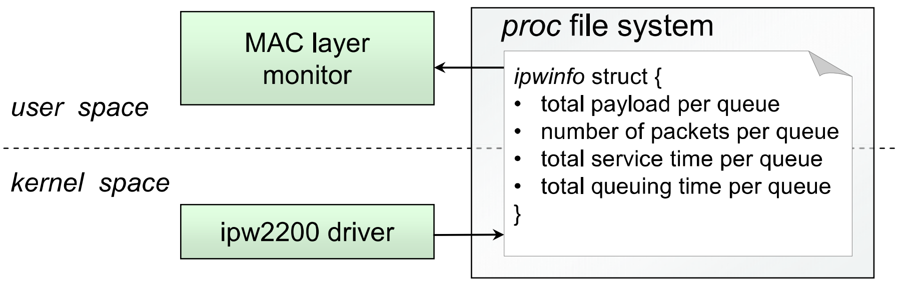


Figure 6.7: MAC layer monitor and proc file system entry

The data collected at the driver level (MAC layer service times, queuing times, etc.) are composed in the *ipwinfo* structure. This structure is eventually passed to the MAC layer monitor when it periodically reads the */proc* entry.

[1] The Multi-Generator (MGEN) website, http://cs.itd.nrl.navy.mil/work/mgen

6.7 *Theory of operation*

The following steps are numbered as in Figure 6.8.

1) Once a second the MAC layer monitor collects the traffic load statistics for all four transmission queues.

2) The collected statistics is analyzed and compared with the previously stored data. According to the current configuration if the noticed change in traffic load is more than 3% for any transmission queue the QoS Device sends a notice to the QoS Manager. Both increases and decreases of traffic load are reported. This lets the QoS Manager to always have an overall view of the network loading and capability.

3) With the help of the QoS Policy Holder the QoS Manager makes a decision of what has to be done if the traffic load of any transmission queue exceeds the threshold.

4) If a new policy decision is made the QoS Manager sends a corresponding command to one or several QoS Devices. Examples of possible decisions are given in the Section 6.9.3.

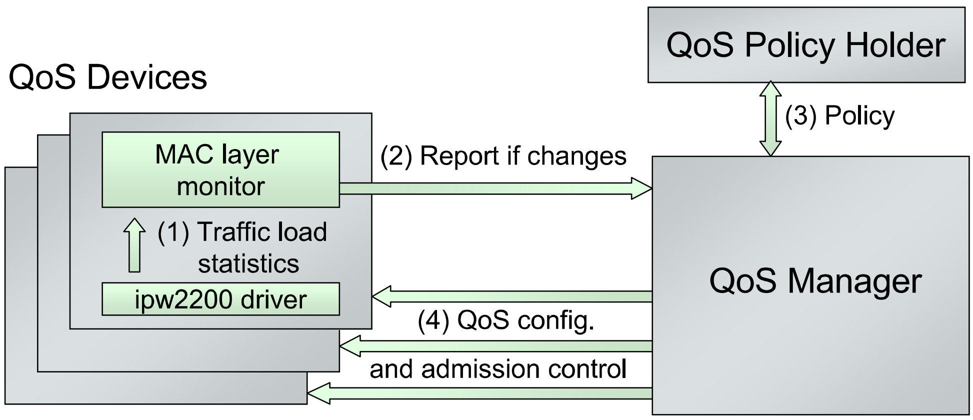


Figure 6.8: Post-admission control process

6.7.1 Message sequence diagrams

The message sequence diagrams illustrating the operation of the admission control process are given and explained below.

When the QoS Device detects a change in traffic load in one of its transmission queues, it sends a status message to the QoS Manager. Depending on the threshold values stored at the QoS Policy Holder, the QoS Manager concludes whether or not the transmission queue is overloaded. If traffic load is above the threshold, the QoS Manager asks the QoS Policy Holder for a policy and correspondingly downgrades (Figure 6.9) or terminates (Figure 6.10) one of the running applications.

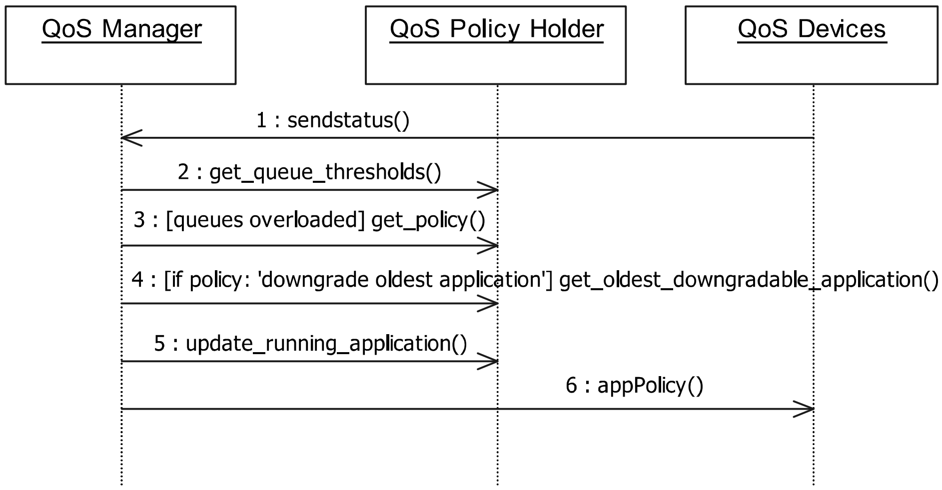


Figure 6.9: Downgrade one of the applications if queues overloaded

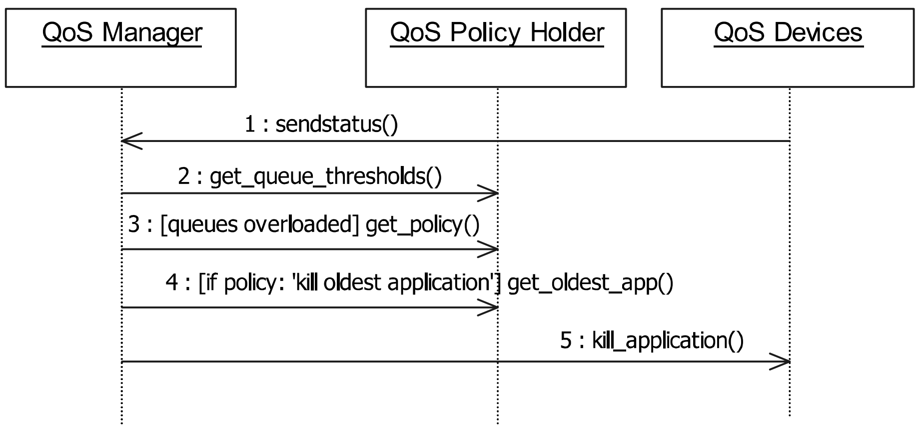


Figure 6.10: Terminate one of the applications if queues overloaded

If traffic load is below the threshold (Figure 6.11), the QoS Manager checks whether the traffic load has become low enough to upgrade one of the previously downgraded applications (the status message can contain information about increase and decrease in traffic load). The upgrade of applications is performed in the reverse order of downgrading.

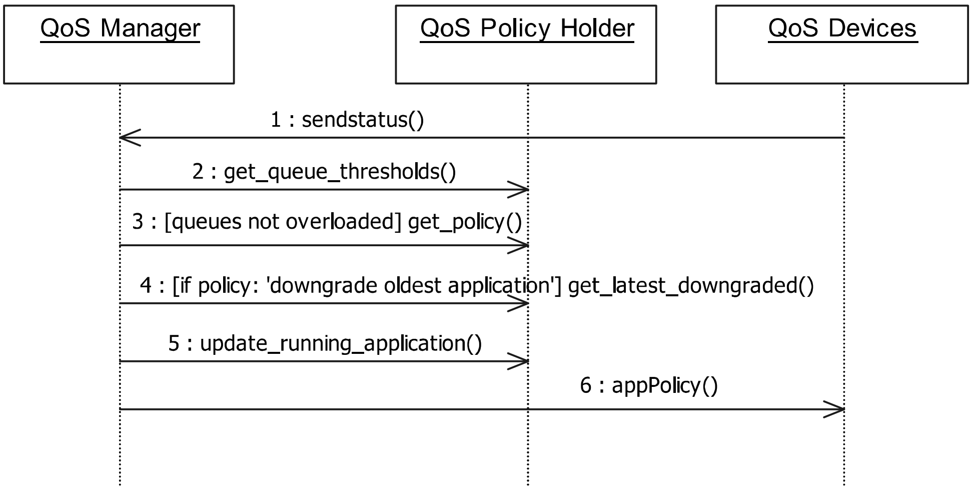


Figure 6.11: Upgrade one of the previously downgraded applications if queue load decreased

6.8 Computational complexity and network load estimation

With respect to the computational complexity and network load, we observed that the system provides acceptable performance. The following results were obtained for a saturated network consisting of three testbeds (Intel Pentium-4 CPU 3.0GHz, RAM 1GB) sending to each other video data through the access point. Figure 6.12 shows diagrams for three cases reflecting different load on the network:

1) "no system" – each testbed transmits and receives for playback an SD MPEG transport stream. The QoS system is not enabled. That is, there are no QoS Devices, QoS Manager and QoS Policy Holder started.

2) "3% bound on changes" – each time when QoS Devices detect the change in queue load for any access category for more than 3%, they send a status report to QoS Manager.

3) "1% bound on changes" – each time when QoS Devices detect the change in queue load for any access category for more than 1%, they send a status report to QoS Manager. This implies a bit higher CPU usage and higher overhead on the network control messages produced by the management system.

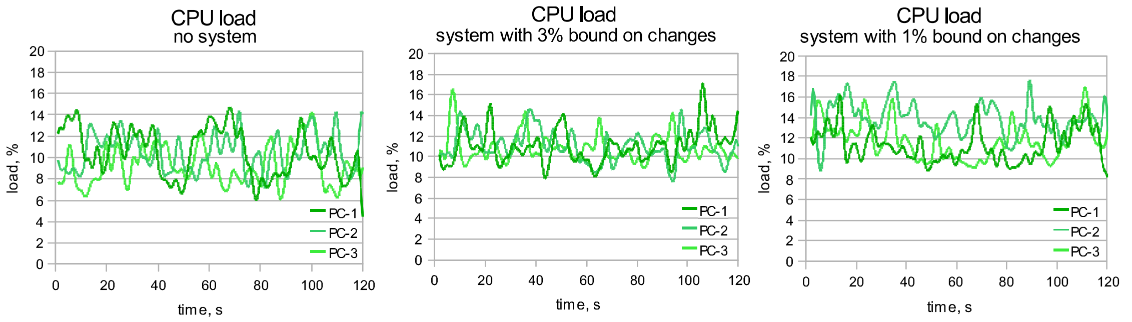


Figure 6.12: CPU load

Table 6-1 lists the average values for CPU load for these three cases for three testbeds. In the two last columns, there are also the values showing difference between CPU load when the QoS system is not enabled and when the system is enabled with 3% and 1% bounds. We observe that enabling the system on the network saturated with video traffic leads to the average CPU load increase of 2-3% at each testbed.

Table 6-1: Average values for CPU load, %

	no system	3% bound	1% bound	increase in CPU load for 3% bound	increase in CPU load for 1% bound
PC-1	10,48	11,02	11,29	0,54	0,81
PC-2	10,49	11,04	13,88	0,55	3,38
PC-3	9,28	10,85	11,78	1,57	2,53

The results for network load are summarized in Table 6-2. All network management data are always sent by QoS Devices through the AC_VO access categories. That is why the traffic load of AC_VO queues is given in the table. It shows directly the queue load produced by all network management traffic. The first column shows the queue load for the case when there is no admission control enabled. In this case the AC_VO traffic only includes some periodical exchange messages between QoS Manager and QoS Devices for maintaining connectivity. From the table, we observe that if all QoS Devices send status reports to the QoS Manager when the noticed change in traffic load is more than 1%, the resulting traffic load of AC_VO queues reaches 1-1.5% at each testbed. If QoS Devices send status reports only when traffic load changes for 3%, the traffic load of AC_VO queues decreases even to 0.5-0.8%. Therefore, the network overhead is not big even when we use 1% bound. 3% bound makes the network overhead even lower.

Table 6-2: Network load of management traffic in AC_VO queue (%)

	no AC	AC with 3% bound	AC with 1% bound
PC-1	0,11	0,36	0,47
PC-2	0,30	0,41	1,13
PC-3	0,13	0,76	1,35

Example for PC-3
When no admission control enabled, the network load of management traffic in AC_VO is 0,13%. When admission control is enabled and QoS Device at PC-3 sends notifications to QoS Manger by traffic load change of 1% at any queue, the network load of management traffic in AC_VO is increasing only up to 1,35%.

6.9 Admission control decisions

All admission control decisions are made and enforced within our user-centric QoS environment. Before giving examples of typical admission control policy decisions, we briefly describe some relevant features of the implemented environment.

6.9.1 Dynamic prioritization

The post-admission control approach is implemented together with the dynamic prioritization mechanism described in Chapter 4. First, this gives a possibility to mark the traffic according to current user preferences. Second, it allows the management system to dynamically change traffic priorities to respond to the post-admission control decisions (e.g. direct some high priority traffic to the low priority queue if network is heavily loaded).

6.9.2 Policy-based QoS

The behavior of the implemented home network is governed by a set of rules (policies) stored at the QoS Policy Holder. The policies describe how the management system should react to the changes happening in the user or network environment. All network management decisions including admission control decisions are made in accordance with the stored policies while taking into account user preferences and current network state. User preferences may include importance, which is a relative measure of priority that a user associates with a certain application or service (e.g. low, normal or high importance). A user importance level is mapped by the network management system to the 802.1D user priority according to the currently deployed policies and network state. Examples of the network state related parameters include traffic load and queue lengths for transmission queues.

6.9.3 Admission control policies

The admission control policies specify all the rules with respect to the admission control mechanism. These include definitions of the thresholds (for traffic load and queue length) and possible actions of what should be done when the thresholds are exceeded. The thresholds can be defined for each AC (Figure 6.2). If any of the thresholds is exceeded the following decisions (or combination of these) may be made:

- Send notification to the users of all involved applications.
- Downgrade one or several applications.
- Terminate one or several applications.

If the traffic load decreases and becomes lower than the threshold then the previously downgraded applications can be upgraded to the original level of priority.

A decision to downgrade or terminate any of the currently running applications depends on the deployed policy. If contending applications have different level of user importance then applications with the lower importance are downgraded or terminated. If contending applications have the same level of importance then the following policies are applied:

- First Come First Serve (FCFS). The last started application, which is in most cases considered as a cause of the queue overload, is downgraded or terminated. FCFS can be applied in case when competing applications belong to different users.
- Last Come First Serve (LCFS). The last started application is considered of higher importance to the user. One or several of the previously started applications can be downgraded or terminated. LCFS can be applied in case when competing applications belong to one user.

It is clear that terminating an application is not desirable from the user point of view and downgrading has preference. However, for some applications, downgrading may result in the complete degradation of quality and makes no much sense (e.g. voice or video application downgraded to the heavily loaded best-effort queue). According to the configuration policies, an application can be marked with a flag specifying whether or not it can be terminated or preempted to release resources for other applications. A non-preemptable (or non-preemptive) application may never be terminated. For example, it makes sense to downgrade an ftp-download application to the overloaded background queue rather than terminating it.

The activity diagram and pseudo-code of the admission control process that takes place at the QoS Manager are depicted in Figure 6.13 and Figure 6.14 respectively.

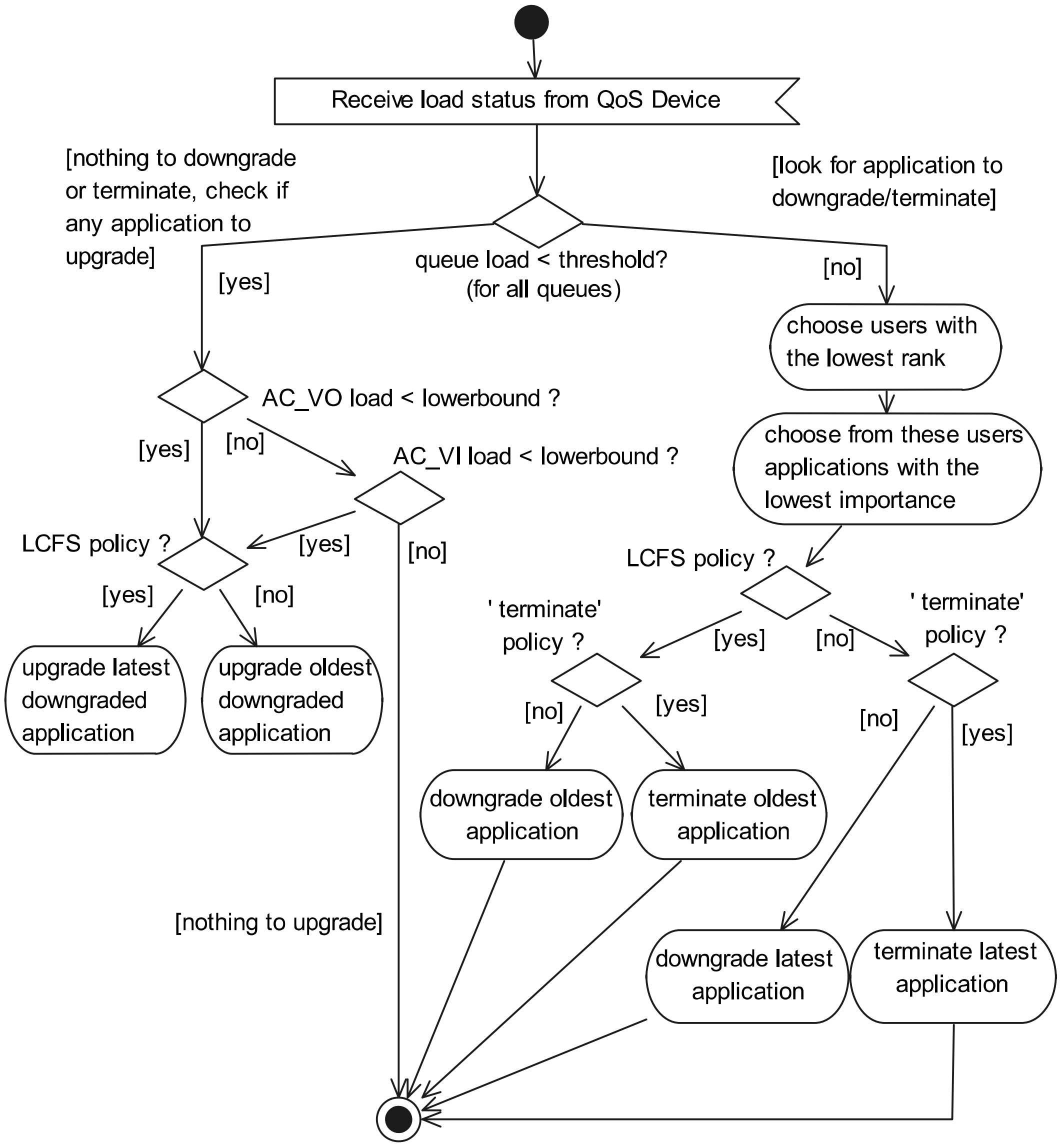


Figure 6.13: Activity diagram for admission control process at QoS Manager

```
// QoS Manager periodically receives queue load status from QoS Devices

if  queue load > threshold     // check this for all queues

     // find application to downgrade or terminate

    // get information from QoS PolicyHolder
    users = get_low_rank_users()      // get users with the lowest rank
    applications = get_downgradable_apps(users)  // get applications
                                            // with the lowest importance
    service_policy = get_service_policy()    // FCFS or LCFS?
    terminate_policy = get_terminate_policy() // downgrade or terminate?

    if  service_policy = 'LCFS'              // Last Come First Serve policy
          if  terminate_policy = 'true'
                 terminate_first_application(applications)
          else
         downgrade_first_application(applications)
          end
    else    //  service policy =  'FCFS' (First Come First Serve)
          if  terminate_policy = 'true'
       terminate_last_application(applications)
          else
         downgrade_last_application(applications)
          end
    end

else   // find application to upgrade

   if  (AC_VO load < lowerbound) or (AC_VI load < lowerbound)

           // get information from QoS PolicyHolder
          service_policy = get_service_policy()    // FCFS or LCFS?

          if  service_policy = 'LCFS'
                     upgrade_latest_downgraded_application()
          else
                     upgrade_oldest_downgraded_application()
          end
   end

end
```

Figure 6.14: Pseudo code for admission control process at QoS Manager

Apart from the application importance and service policies (FCFS/LCFS), other factors can be taken into account when making admission control decisions. We also consider user rights on the network. The applications belonging to the users with the lowest rank (e.g. guests) are downgraded first (Figure 6.13 and Figure 6.14). At the QoS Policy Holder it is also possible to configure other policies. For example, an AC_VI transmission queue can be allowed to be loaded above the threshold if there is no other traffic on the network or if there is only background traffic in AC_BK queues.

6.10 Demonstration scenarios

This section presents a set of basic usage scenarios to demonstrate the performance of the implemented post-admission control approach within our user-centric QoS environment. For all experiments a local 802.11a wireless network operating in the 12Mbps mode was used. The fixed data rate mode was used for demonstrational purpose only as it makes easier to follow the graphs. All streams are UDP streams generated with the help of the *mgen* tool[1]. All streams are set up between three wireless clients communicating through the access point (Figure 6.15). In our work, it is assumed that any type of traffic can be started in any access category depending on the level of service requested by the user. The AC_VO access category is used for network feedback and management messages only. The traffic load thresholds are set to 95%, 100% and 100% for AC_VI, AC_BE and AC_BK categories correspondingly. All stations have our QoS Device software running. *Station 1* has additionally the QoS Manager and QoS Policy Holder services installed.

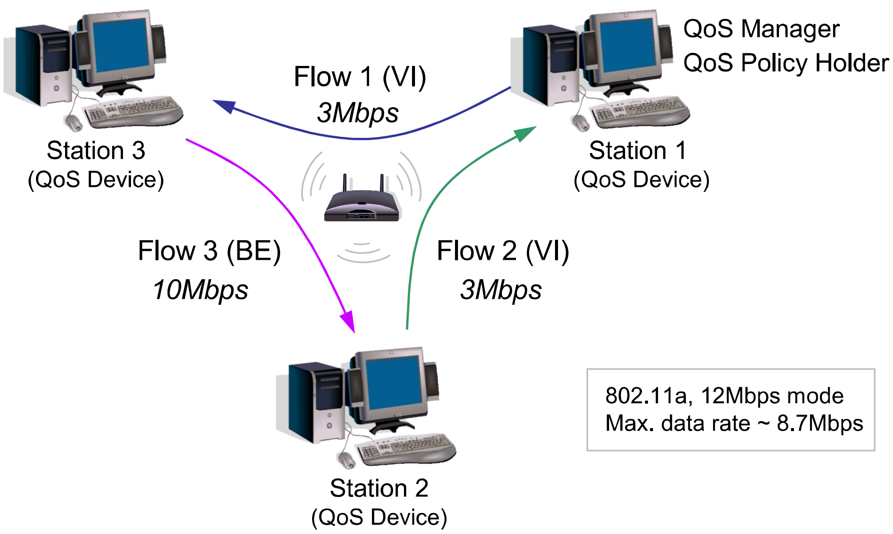


Figure 6.15: Experimental wireless network

All scenarios consider a case when the overall requested data throughput is greater than the network can provide. It is shown then how the proposed method is used to cope with the lack of bandwidth in the overloaded network.

There are two 3Mbps UDP flows started at *Station 1* and *Station 2* at different times. These two are supposed to be of high importance for the user with a video profile, which means here that the data are transmitted through the AC_VI access category (in this experiment the AC_VO access category is used for management messages only). As the stations communicate through the AP, each packet is transmitted twice and, therefore, the total throughput required is 6Mbps for each flow and 12Mbps for both flows together. Moreover, there is always a best-effort flow originating at *Station 3*. Considering that in the 802.11a 12Mbps mode the maximum achievable data rate at the UDP layer does not exceed 9Mbps, the network is heavily loaded when all three flows are set up.

Each scenario is provided with a throughput and load graph. The throughput graphs show the achieved throughput for all active access categories. The load graphs show the traffic load of all queues. It should be noted that in the described system all flows are started by default as best-effort flows, but shortly after the start the flows are classified by the QoS Manager according to the user profiles and active policies. That is why one might see on the graphs the traffic in two access categories when only one flow is started. The light shade of color is used to refer to the best-effort traffic in AC_BE and the dark shade of color refers to the traffic belonging to the same flow only in the AC_VI access category. The thick lines of the same color represent the measured data approximated with a smoothing spline.

6.10.1 No admission control

The first scenario shows the case when no any admission control rules applied. In Figure 6.16 it is seen that when *Flow 2* is started the two flows running in the AC_VI categories (*Flow 1* and *Flow 2*) have preference over the best-effort *Flow 3*, but compete with each other and experience lack of bandwidth. In Figure 6.17 it is seen that the AC_VI queues at *Station 1* and *2* are loaded for 100%.

[1] The Multi-Generator (MGEN) website. http://cs.itd.nrl.navy.mil/work/mgen

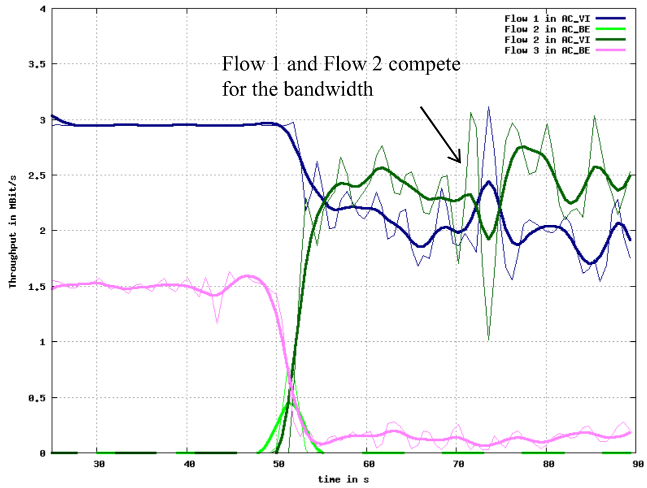


Figure 6.16: No admission control, throughput graph

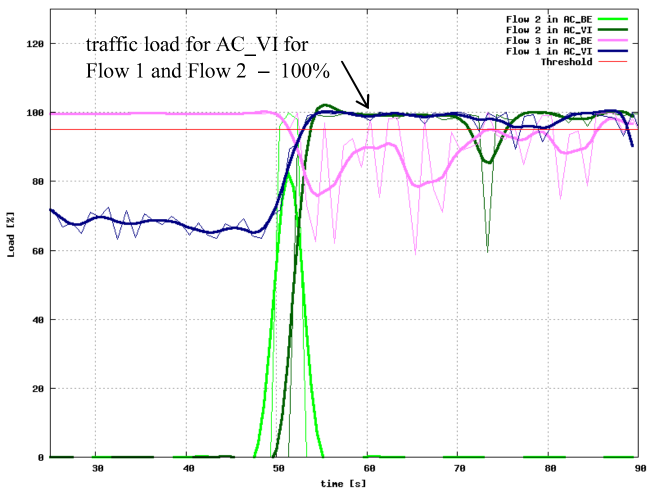


Figure 6.17: No admission control, load graph

6.10.2 Downgrading a flow (FCFS policy)

In this scenario the admission control rules are applied if there are AC_VI queues with the queue load exceeding the threshold of 95%. In Figure 6.18 and Figure 6.19 it is seen that when *Flow 2* is started the traffic load of the AC_VI queues at *Station 1* and *Station 2* exceeds the threshold. This is reported by the stations to the QoS Manager that makes an admission control decision. According to the active FCFS policy, the last started flow is downgraded to the AC_BE queue. Thus, *Flow 2* continues running as best-effort traffic releasing resources for *Flow 1*. It can be seen on the graphs that the time during which *Flow 1* experiences decrease in bandwidth is around 1-2 sec. If *Flow 1* is a video flow, the user experience can be improved with an appropriate buffer size for a video client.

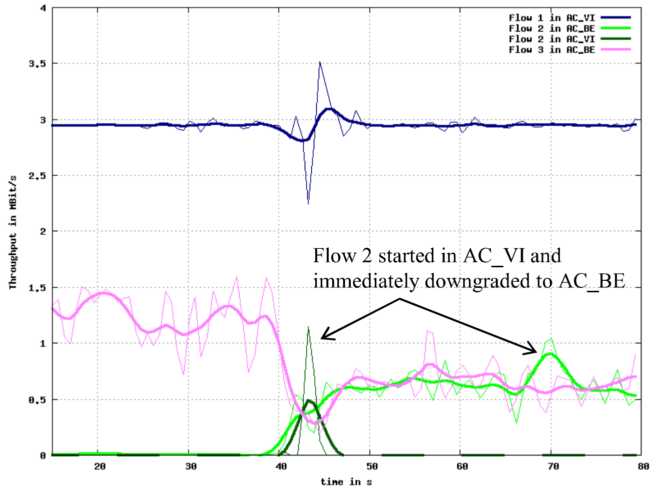


Figure 6.18: Downgrading a flow (FCFS policy), throughput graph

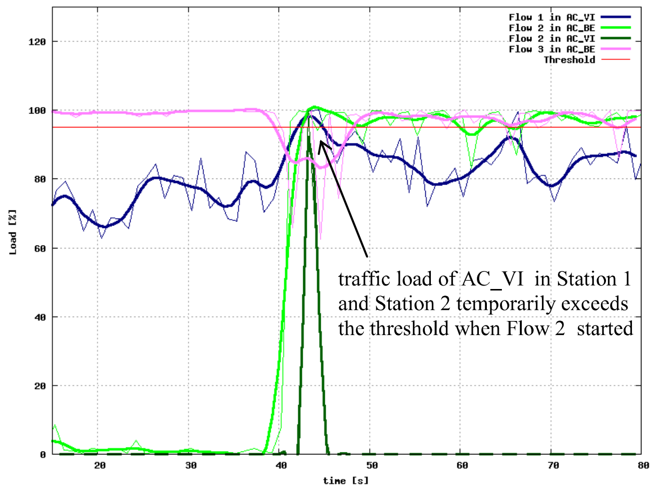


Figure 6.19: Downgrading a flow (FCFS policy), load graph

6.10.3 Downgrading a flow (LCFS policy)

This scenario is very similar to the previous one. It demonstrates also an enforcement of admission control rules leading to downgrading one of the flows. In this case the last started flow is considered more important according to the chosen LCFS policy. Figure 6.20 and Figure 6.21 show that the network becomes heavily loaded when *Flow 2* is started. The QoS Manager makes a decision to downgrade *Flow 1* according to the LCFS policy. It is seen that *Flow 1* continues running as best-effort traffic competing equally with *Flow 3* while *Flow 2* is provided with all the necessary bandwidth. The LCFS policy is normally used when competing applications belong to one user assuming that the application with which the user is currently working is more important. The LCFS policy is also used when applications belong to different users, but some users have more rights on the network.

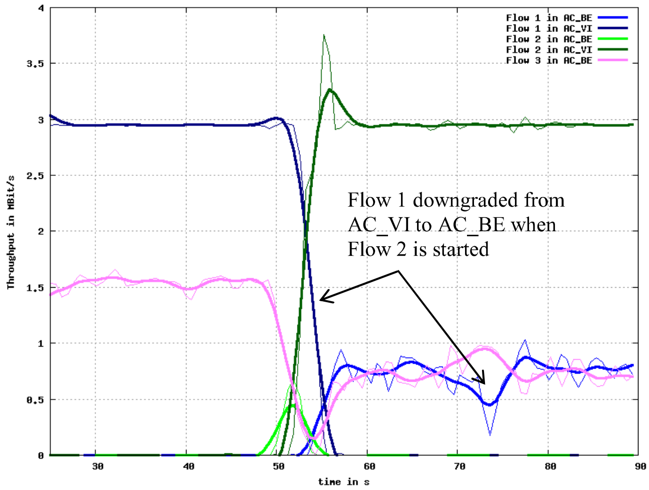


Figure 6.20: Downgrading a flow (LCFS policy), throughput graph

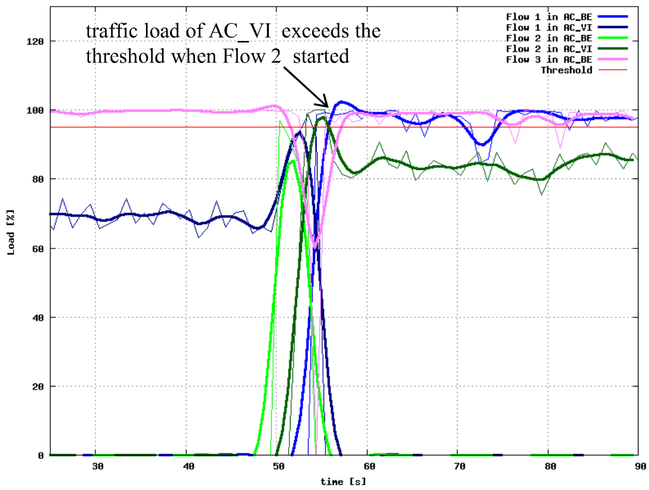


Figure 6.21: Downgrading a flow (LCFS policy), load graph

6.10.4 Upgrading a flow when resources released

A previously downgraded flow can be automatically upgraded if the available bandwidth in the network increases. Figure 6.22 and Figure 6.23 demonstrate two events: downgrading and upgrading a flow. First, *Flow 2* is downgraded to the best-effort queue when shortly after its start in the AC_VI queue it is determined that there are not enough resources in the network. However, when *Flow 1* is ended (e.g. by a user) the resources are released and *Flow 2* is automatically upgraded back to the AC_VI category according to the original user profile. A decision to upgrade the previously downgraded *Flow 2* is made by the QoS Manager after it has received a report from *Station 1* notifying about the traffic load decrease in its AC_VI queue.

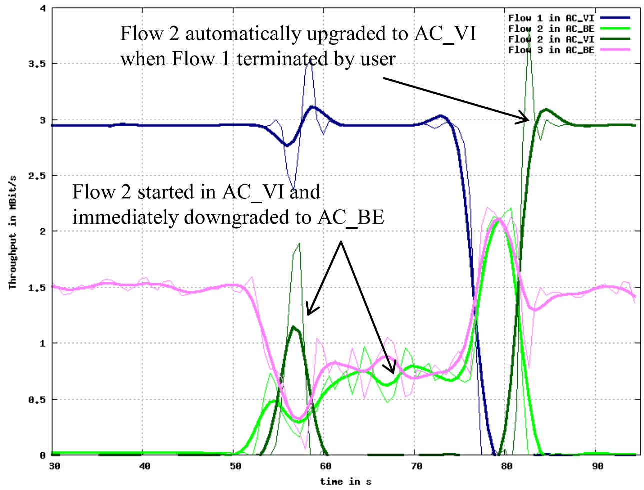


Figure 6.22: Upgrading a flow when resources released, throughput graph

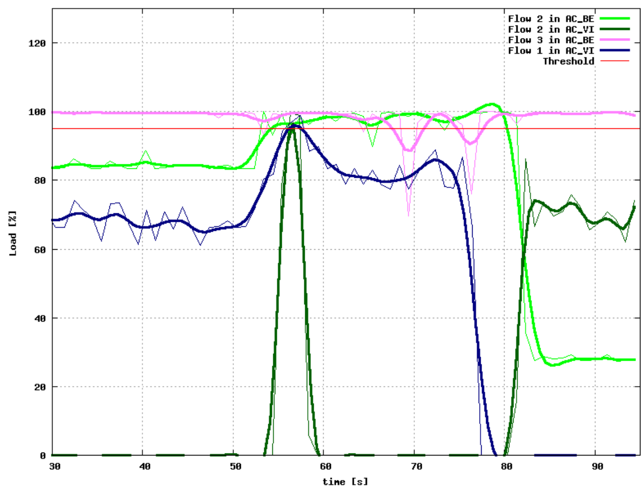


Figure 6.23: Upgrading a flow when resources released, load graph

6.10.5 Terminating a flow in the heavily loaded network

In this scenario a new flow gets terminated after it leads to the network overload (Figure 6.24, Figure 6.25). When *Flow 2* joins the network and starts running in AC_VI, the overall bandwidth demand considerably increases. The traffic load in the AC_VI queues exceeds the threshold of 95% and the QoS Manager makes a decision to terminate *Flow 2* (FCFS policy). *Flow 2* is terminated then with a corresponding notification sent to the user of *Station 2*. The user tries to start *Flow 2* again after some time, but as there are still not enough resources in the network the flow is terminated for a second time. If *Flow 1* is a video flow, the user perception can be improved with an appropriate buffer size for a video client to cope with the temporarily throughput variations experienced by *Flow 1* during the start and termination of *Flow 2*.

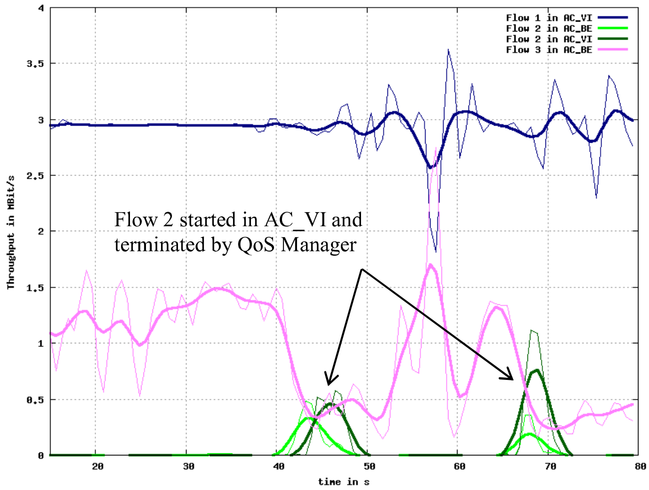


Figure 6.24: Terminating a flow in the heavily loaded network, throughput graph

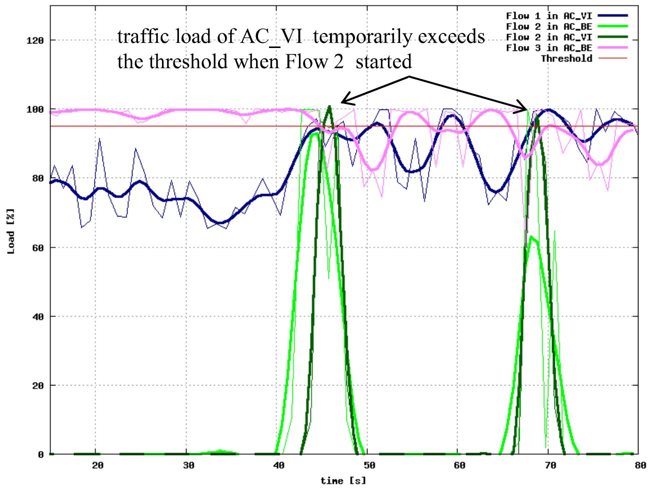


Figure 6.25: Terminating a flow in the heavily loaded network, load graph

6.11 Conclusion

The demonstration scenarios showed how the implemented post-admission control approach is applied to address the problems of network overload. If the start of a new application results in considerable increase of the traffic load, the application is terminated or downgraded to the lower priority level to maintain quality of service for other running services. It is important to note that for delay-tolerant applications such as video streaming and data transfers it can be required to configure the system such that the temporary traffic load increase does not affect user-perceived performance of the previously admitted applications. By means of correctly chosen buffer sizes and error correction mechanisms, video streaming applications can be enhanced to better cope with short-time throughput fluctuations when new bandwidth-demanding applications temporarily join the network.

To address the requirements of delay-sensitive applications such as voice and gaming, the QoS management system has to be extended also with a pre-admission control approach. For example, only a restricted number of applications can be allowed to run in the network with the highest priority, i.e. in the AC_VO access category. When shortly after the start a new flow is classified by the QoS Manager, it may not be allowed to run in AC_VO if the maximum number of allowed applications in AC_VO has been already reached. A pre-admission control approach, however, will not completely replace a post-admission approach. They are seen as complementary to each other. In wireless networks where available bitrate may change over the time it might be necessary to apply a post-admission control on the pre-admitted services (i.e. services allowed on the network by a pre-admission control mechanism).

In overall, the presented admission control approach provides good means for regulating the traffic load in the network. It is simple to implement and it can be easily deployed in any network with WMM support. We demonstrated how together with our previously implemented user-centric QoS environment the approach contributes to the overall user experience.

7 Implementation of the user-centric QoS approach

7.1 Introduction

The research approaches described in this thesis have been implemented in practice. The functionality of the system was tested in our testbed network. System implementation details are extensively described in [96] and [98]. The software, its usage and setup of some demonstration scenarios are also described in [99]. For general overview of how the system is intended to work in practice, we describe some implementation details and GUIs in this chapter.

The software packages include the following implementations.

- Precedence model and user-centric QoS management system.

  This software is available in terms of the implemented QoS services: QoS Device, QoS Manager and QoS Policy Holder. The services include implementation of the precedence model, protocols, message formats and objects for carrying the modeled policy data, policy enforcement decisions, SQL database requests, post-admission control related messaged and other requests between components of the management framework.

- GUI for user-centric QoS system.

  The QoS Tool is implemented as a GUI, with the help of which a user can modify user and network policies and perform configuration of the user profiles. A user can login with the QoS tool on any station in the network. A user can retrieve a list of available profiles stored on the QoS policy holder, choose one of the available profiles or make a new profile with preferred applications, and assign a certain importance level to the user profiles or applications.

- MAC layer monitor – wireless driver extensions for admission control.

  The wireless network under consideration consists of clients based on Intel 2915abg cards with WMM support implementing a subset of IEEE 802.11e. For implementation of our post-admission control method the open source driver for the 2915abg network card was extended with the code to fulfill MAC layer monitoring related tasks. The MAC layer monitor residing in the user space collects the transmission queue load statistics supplied by the driver. The collected data are delivered to the user space using the */proc* file system that is used to provide file based communication with the kernel.

The main implemented system's components and communication interfaces are shown in Figure 7.1. Apart from the implementation of the MAC layer monitor at the wireless driver level, all other components and interfaces were implemented with the help of the Qt Toolkit[1]. The detailed description of the major communication interfaces between components is given in Annex A.

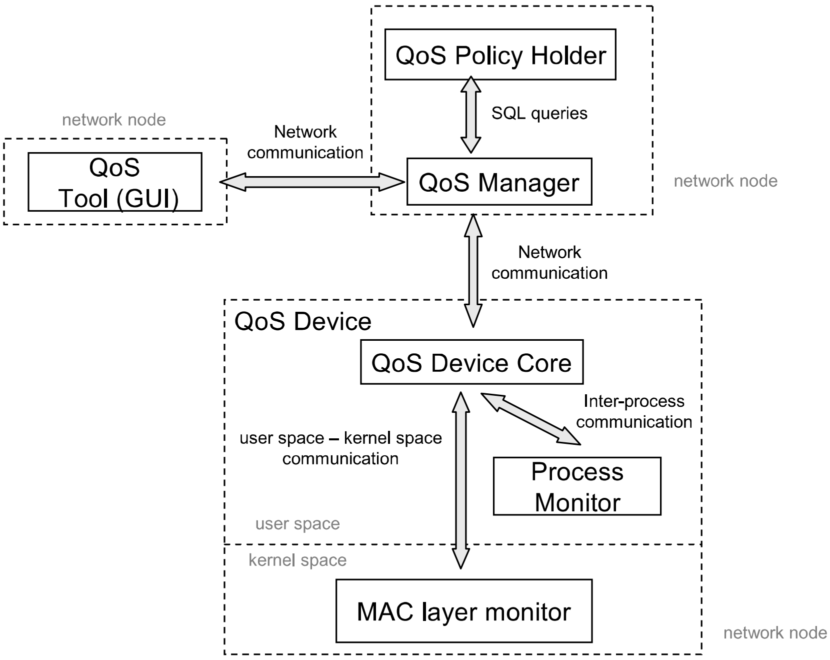


Figure 7.1: Implemented system's components and communication interfaces

From the user point of view, the key feature of the system is a convenient graphical interface (QoS Tool) allowing a user to easily manage the level of quality that the running applications and services receive in the network. User preferences specified as

[1] Qt Software Homepage, http://www.qtsoftware.com/

profiles determine the level of QoS assigned by the management system to the running applications. The management system includes the following services: QoS Device, QoS Manager and QoS Policy Holder. The services have to be installed in the network before a user can start using a QoS Tool.

7.1.1 System requirements

The system is implemented in the infrastructure wireless network with a WMM-certified Access Point (AP) and wireless clients. However, as the system's components can be distributed in the network, the system can be also easily installed in the ad-hoc wireless network with WMM-certified wireless clients.

For end-to-end system operation within the home network, all wireless clients have to have QoS Device services installed. The QoS Manager and QoS Policy Holder services can be installed on any node in the network. A user can start the QoS Tool from any node. The installation details are described in [99]. Some peculiarities with respect to the current implementation are given below.

Access Point

An arbitrary AP supporting WMM prioritization can be used. The QoS marking policies at the AP have to be configured such that the Differentiated Service Code Point (DSCP) marking is appropriately mapped to the corresponding Class of Service (COS) field. All packets entering the AP contain IP DSCP precedence information in the IP header Type of Service (TOS) field (set by the QoS Devices). Figure 7.2 illustrates an example of mapping rules that have to be configured at the AP. Without this mapping it is not guaranteed that the packets are forwarded by the AP with the requested by a user QoS level.

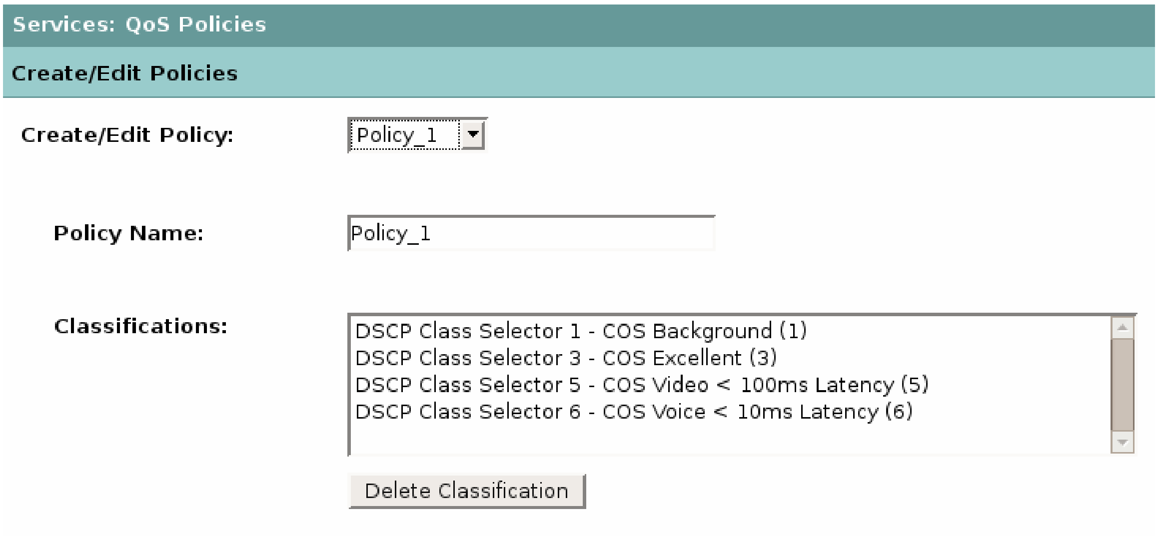


Figure 7.2: QoS Policies at the access point

The AP used in our testbed network is Cisco Aironet 1130AG.

Wireless clients

In our testbed network we used Intel 2915abg WMM-certified wireless cards enhanced with our MAC layer monitor (firmware version 3.0, ipw2200-fw-3.0.tgz, driver version 1.2.2, ipw2200-1.2.2.tgz[1]). Our software can be also used with any other wireless cards, but in that case, the admission control option cannot be supported by the system (due to the necessary extensions to the wireless driver). However, the main other features of the user-centric system would be available.

Operating system

The operating system used on clients and server is Linux, Ubuntu 7.10, kernel version 2.6.22-14-386. The QoS GUI Tool can be used in KDE or Gnome environment.

7.1.2 QoS Tool GUI

When we designed the graphical user interfaces for our system we followed the basic principles of the user-centered design approach stated in [55].

- Make it easy for a user to determine what actions are possible at any moment.

[1] ipw2200 driver, Home page, [Online]. Available: http://ipw2200.sourceforge.net

- Make things visible to the user, including the conceptual model of the system, the alternative actions, and the results of actions.

- Make it easy to evaluate the current state of the system.

- Follow natural mappings between user's intentions and the required actions; between user actions and the resulting effect; and between the information that is visible to the user and the interpretation of the system state.

These principles place the user at the center of the system and facilitate the user's task to manage the network as required.

The QoS Tool represents a GUI by the help of which a user is able to configure his preferences and enforce them in the network. When started, the QoS Tool is represented by a system tray for a quick user access, Figure 7.3.

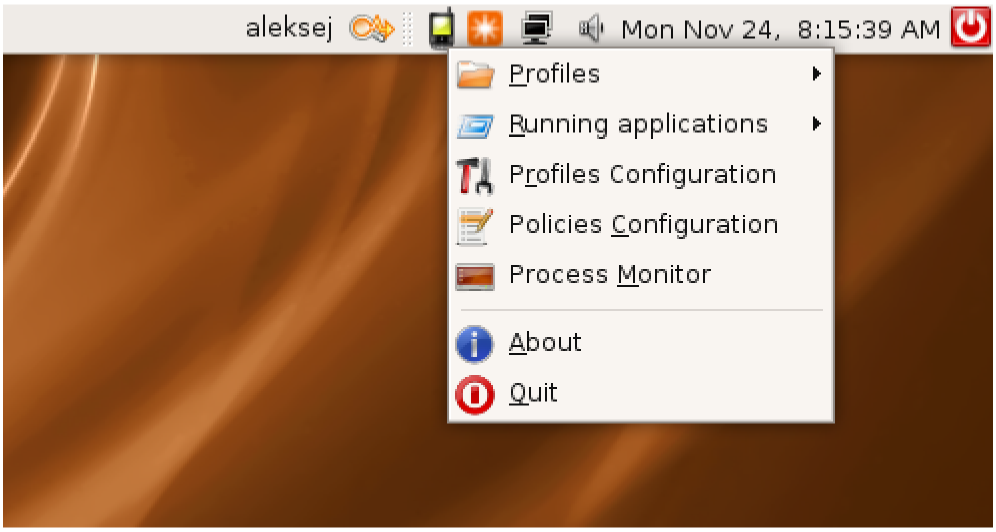


Figure 7.3: QoS Tool system tray menu

The QoS Tool allows a user to perform the following actions:

- Define profiles. Group various applications in different profiles.

- Assign importance levels to defined profiles. When an application is started it's started with the importance level defined in the corresponding profiles.

- Change importance levels of profiles at run time. When a profile's importance level is changed, all running applications belonging to this profile dynamically change their importance.

- Change importance levels of applications at run time. Regardless of the profiles configuration, the importance level can be changed for any application at its run time. In that case the importance levels of other applications from the same profile are not affected.

7.1.3 Profiles Configuration

Figure 7.4 shows a window for user profiles configurations which is accessible from a system tray menu (Figure 7.3). Each profile is assigned by the management system a particular importance level. The first profile in the list is considered as being most important for the user (preferred profile) and assigned to the highest importance level in the network (and so on, in order of appearance from top to bottom). When a user runs various applications, his preferred applications from the first profile will receive better services than other applications. A user can select one of the recommended profiles or create a new profile and populate it by his individual applications (Figure 7.5).

Figure 7.4: User profiles configuration

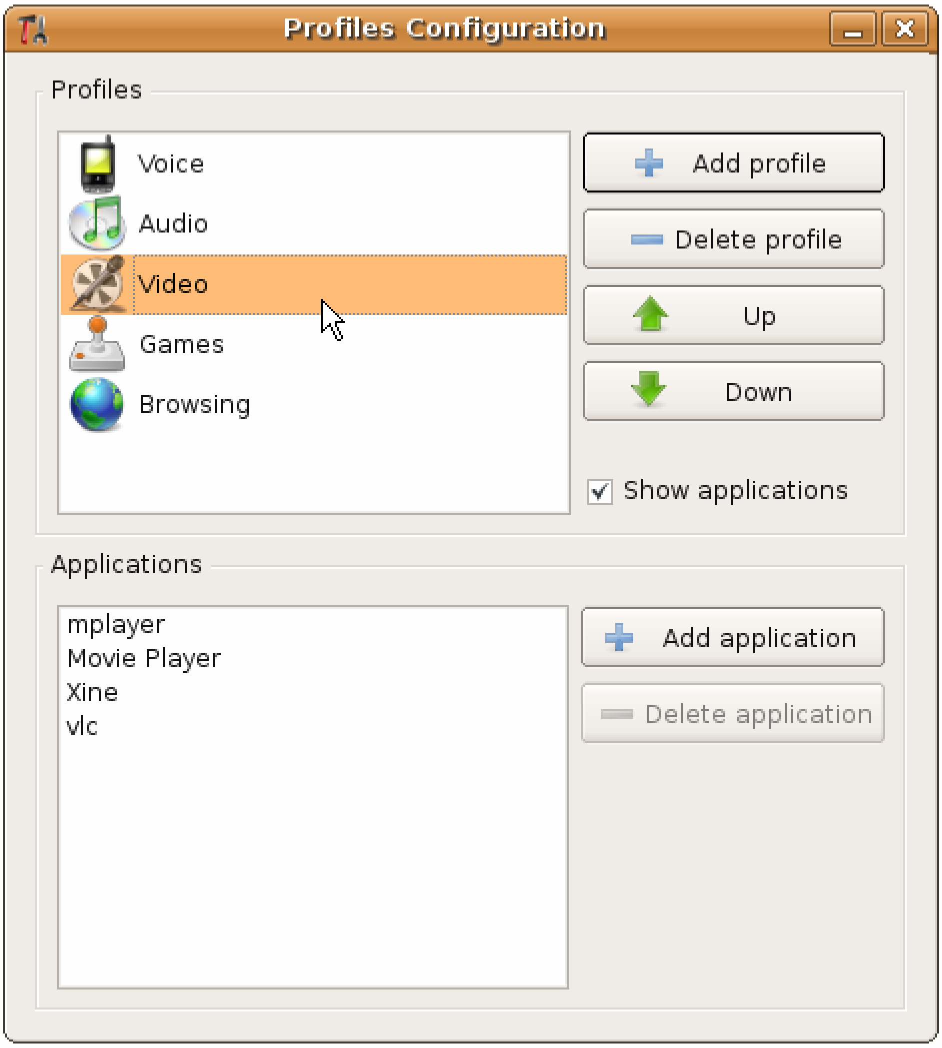


Figure 7.5: User profiles configuration with applications list

7.1.4 Changing profile importance level

The first profile in the list (Figure 7.4) has the highest importance level and is also referred to as preferred profile. Mapping of profiles to user importance levels can be performed differently and currently configured as following (Table 7-1).

Table 7-1: Mapping of profiles to importance levels

Profile number (from top to bottom)	**Importance**
1	Realtime
2	High
3	Normal
4..∞	Low

The icon of the currently preferred user profile is shown on the system tray, so that a user can always see his current settings (in Figure 7.3 icon of the "*Voice*" profile). Figure 7.6 depicts how a user can quickly change his preferred profile from "*Voice*" to "*Games*".

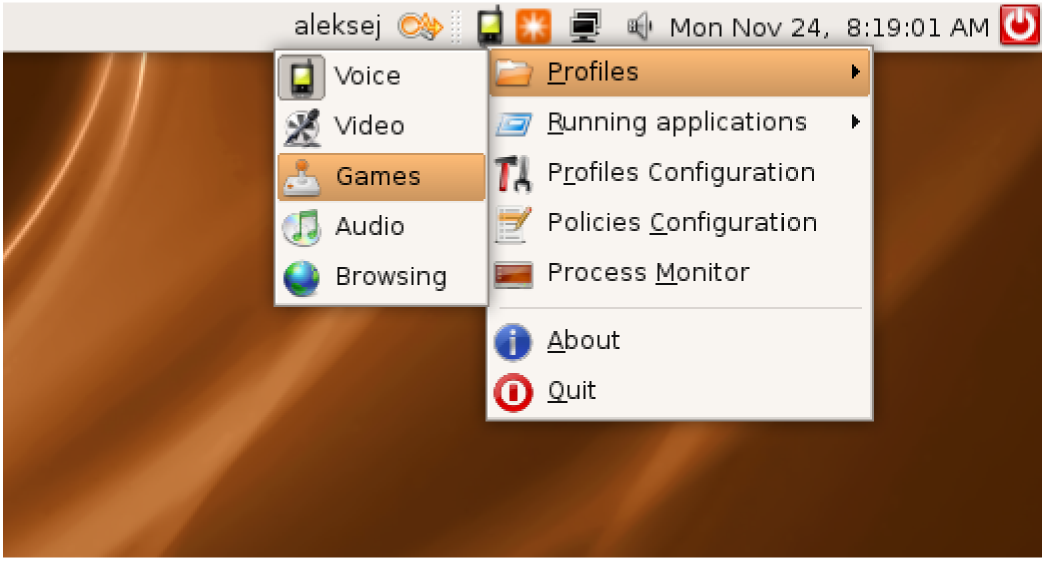


Figure 7.6: Quick change of profile importance level

7.1.5 Changing application importance level

A user can change an importance level for a profile or for each running application. How to quickly change an importance level for an application is shown in Figure 7.7. If a user assigns a new importance level to a running application and then terminates it, this is not stored in the settings and by the next launch the application will be automatically started with an importance level according to the user profile. It can be said that profiles contain the default user importance levels.

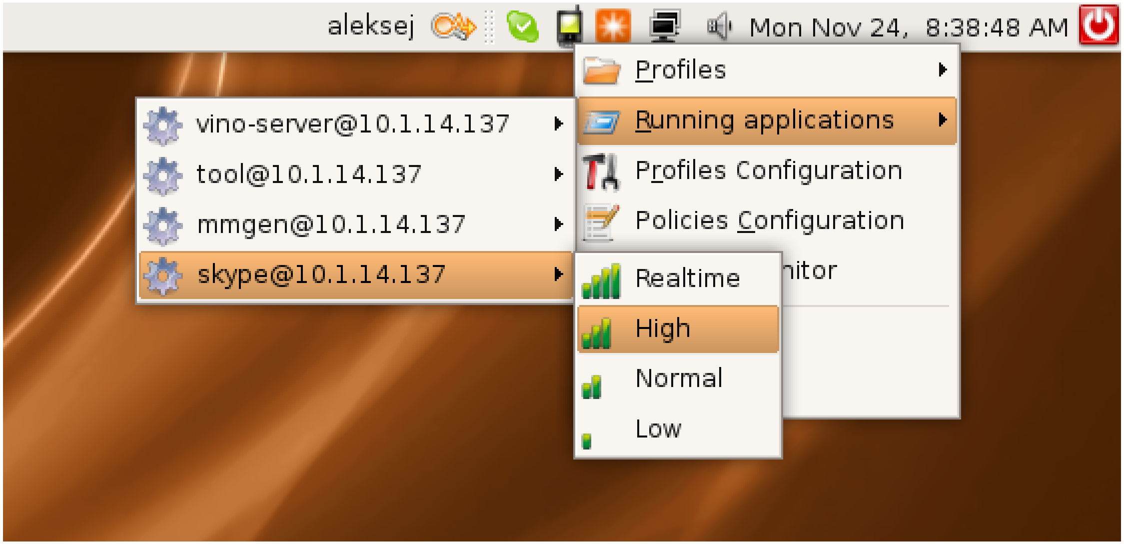


Figure 7.7: Quick change of application importance level

7.1.6 Configuring policies

There can be different policies configured in the network. The examples of some implemented policies are available in the *Policies Configuration* interface (Figure 7.8 and Figure 7.9) available from the main system tray.

7.1.6.1 User policies

Policy 1: Mapping of user profiles to importance levels.

A user can define many different profiles listed in the *Profiles Configuration* window (Figure 7.4). With *Policy 1* a user can specify what importance levels his profiles should have in the network and what importance level the unknown applications should be assigned (applications not defined in any profile).

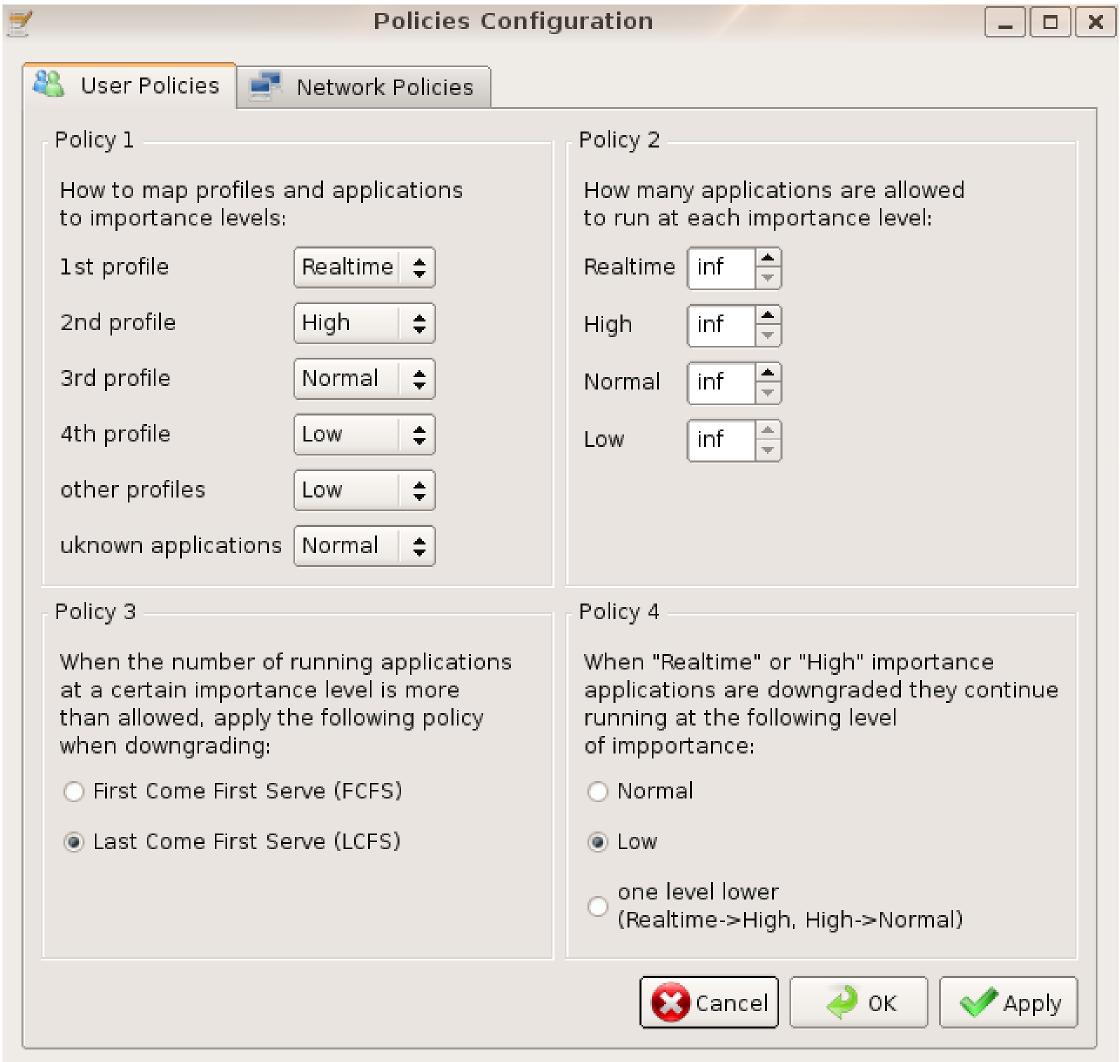


Figure 7.8: User policies

Policy 2: How many applications are allowed to run at each importance level.

Sometimes it makes sense to allow only one preferred application to run with the highest level of importance. This can be configured with *Policy 2*.

Policy 3: Downgrading rules.

When there is a usability conflict or when the number of applications allowed to run at the certain importance level exceeds the maximum number of applications specified in *Policy 2*, one of the current applications is downgraded according to *Policy 3*. First Come First Serve (FCFS) – the last application started is downgraded; Last Come First Serve (LCFS) – the oldest application started is downgraded.

Policy 4: Downgrading level

When one of the running applications is downgraded it is downgraded into the level of importance specified in Policy 4.

7.1.6.2 Network policies

The network policies (Figure 7.9) are supposed to be available to the user performing the management of the whole home network (e.g. home owner or system administrator) and access to them is secured with the password.

Policy 1: Mapping of user importance levels to WMM access categories.

This policy shows how user importance levels correspond to access categories. A system administrator may also restrict access to particular access categories. For example, if all levels are mapped to the best-effort queue (AC_BE) then no prioritized services are available to the user.

Policy 2: How many users are allowed to use each access category.

Policy 3: Defines users allowed to use each access category.

For example, it may be configured for a *Guest* user to use only best-effort services (AC_BE).

Policy 4: Ranking among users.

This policy helps to configure how conflicts should be resolved among the users. For example, when one of the applications has to be downgraded the users with lowest ranking will be affected first.

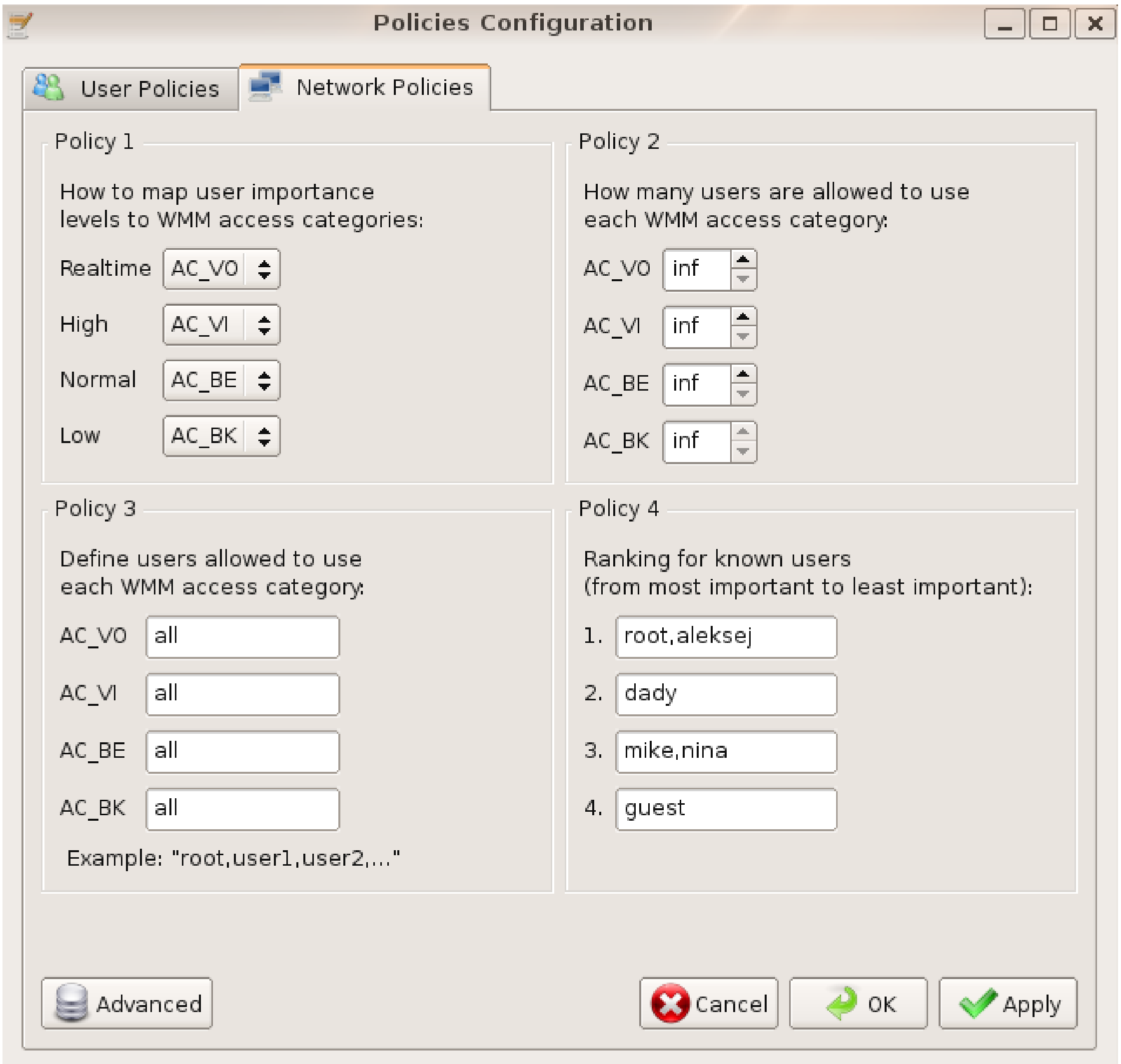


Figure 7.9: Network policies

With the "Advanced" button available from the *Network Policies* interface, one can start the QoS Policy Holder Browser for advanced database configurations (Figure 7.10). The browser is an SQL GUI client tool with the help of which it is possible to edit policies/tables stored at the MySQL server. This can be useful when configuring policies that are not available to the user through the graphical interfaces (e.g. usability rules, admission control policies).

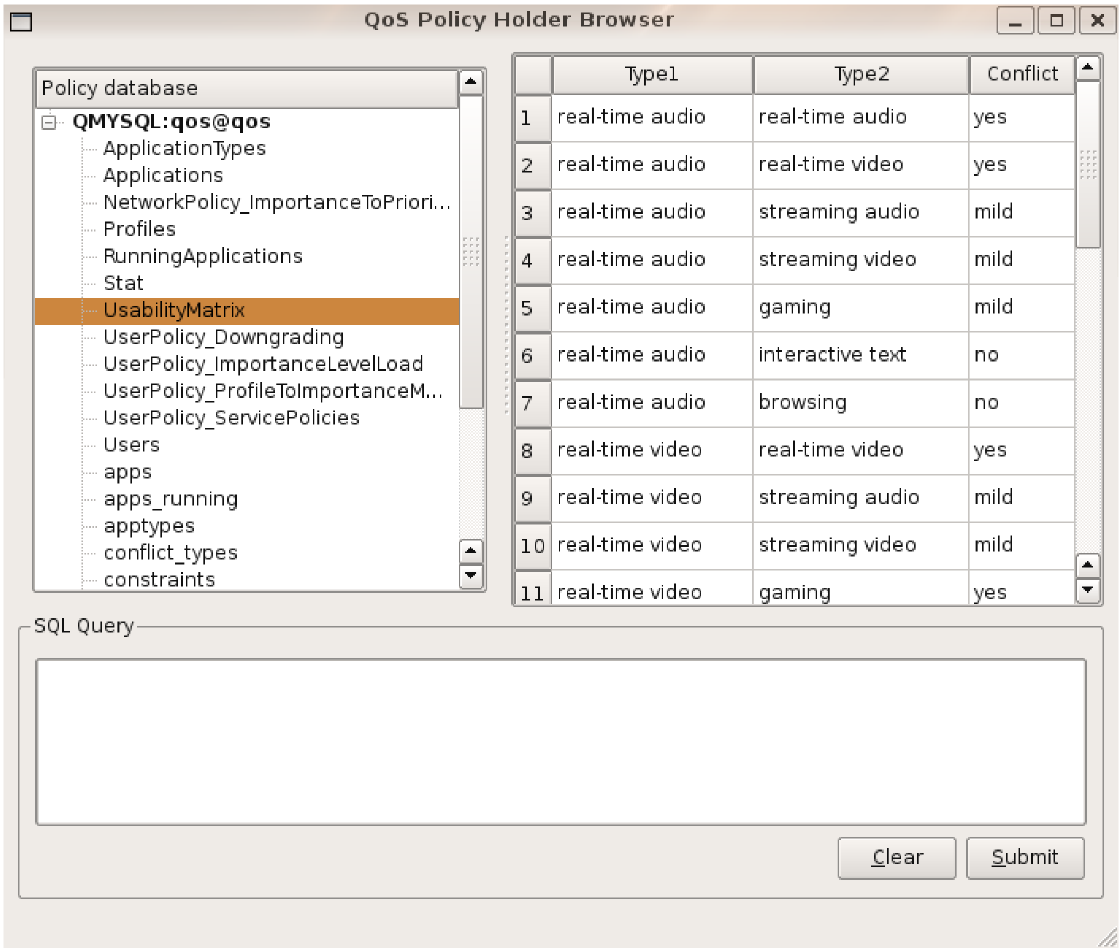


Figure 7.10: QoS Policy Holder Browser

7.1.7 Process Monitor

With the help of the process monitor (Figure 7.11) a user can see what applications are currently running in the network and with which importance and network priority levels. A user can also change the importance level of any running application and see if his request is accepted by the management system. It should be noted that due to various network policies not all user requests can be satisfied by the management system. In Figure 7.11 an importance level shows what level of quality a user wants to have, and a network priority level is what the management system finally assigns to the application.

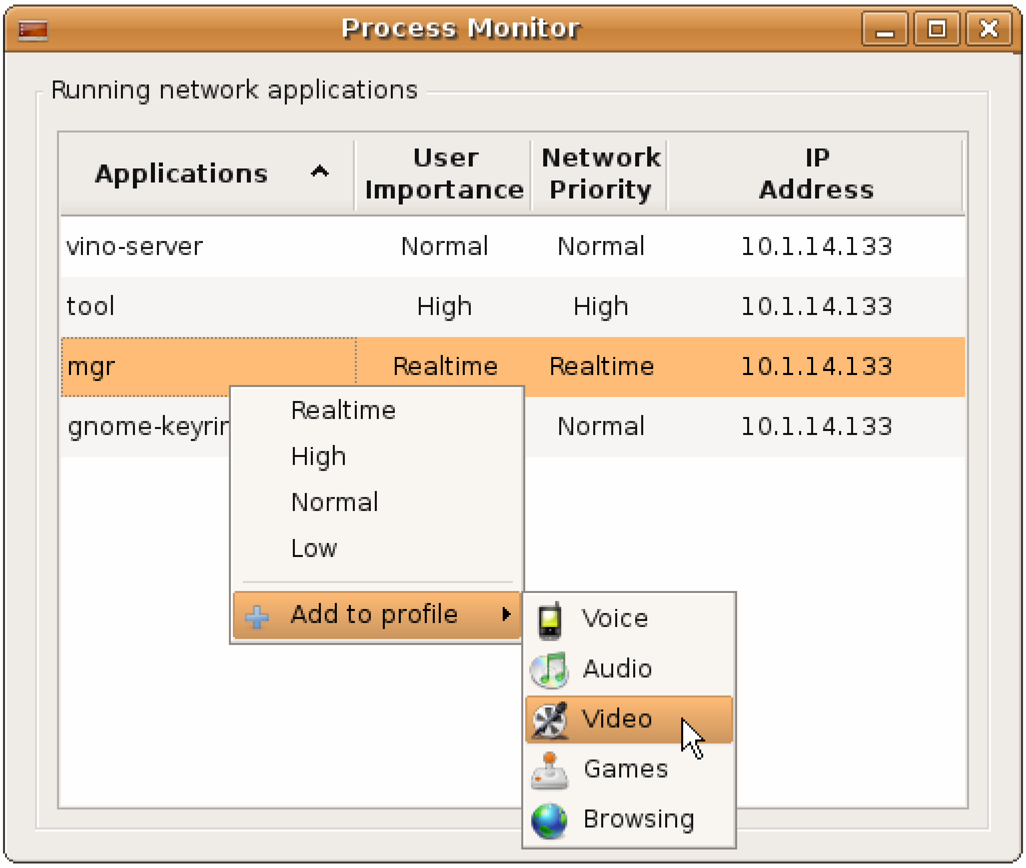


Figure 7.11: Process Monitor

7.2 Conclusion

The research approaches presented in this work have been implemented in our wireless testbed network in accordance with the basic principles of the user-centered design [55]. The implementation includes the main components and interfaces for our precedence model and user-centric QoS system, Graphical User Interfaces (GUIs) and post-admission control method described in Chapter 4 and Chapter 6. The implemented user-centric QoS system allows for system's operation as described in use cases in Chapter 4 (Section 4.4) and in demonstration scenarios in Chapter 4 (Section 4.10) and Chapter 6 (Section 6.10).

8 Conclusion

8.1 Summary and conclusions

The prime research objective of the thesis included a study and development of a QoS management approach for wireless home networks. Today, the home networking technologies are rapidly growing and various home entertainment solutions are evolving and competing (e.g. Intel Digital Home, AMD Live, Windows Media Center). Even though this offers consumers a simple way to access, share and enjoy their data throughout the networked home there is still a lack of QoS support affecting user experience especially in wireless networks. Many Standards Development Organizations (SDOs) are working now in collaboration on development of a unique QoS solution for home networks. The recently developed UPnP QoS architecture [35] and DVB QoS functional reference model [37] are examples of a great interest to this subject from many companies participating in the developments.

There is also a big interest now in designing the future media services in a user-centric manner. Many European projects are working now on the development of the new user-centric media solutions for future Internet [49]. The network and service providers work on deploying user-centric broadband solutions [54]. Some recent IETF drafts consider development of the user-centric QoS policy management for heterogeneous Internet environment [59], [60], [61]. Clearly, this rapidly growing user-centric role in relation to the internet services has a direct connection with the home network services, where users consume and distribute both internet and intranet services. Therefore, we believe that the future home networks have to be also designed in the user-centric manner. Enhancing a QoS home network solution with user-centric management tools can improve the user experience and make it more attractive for consumers.

A user-centric QoS management approach described in this thesis provides a management solution for wireless home networks based on user preferences. Unlike traditional QoS approaches that always give multimedia applications a pre-determined high priority due to their strict latency and loss requirements, the proposed approach classifies traffic according to user preferences, thus, ensuring a certain quality regardless of the application requirements. The application priorities are assigned according to user profiles and automatically updated in case of changes in the network or user environment. The implementation details and experimental results demonstrate a practical application of the described approach in wireless home networks. The thesis suggests that the introduced management approach will significantly contribute to the overall user experience in digital home

Furthermore, we also presented a post-admission control solution for wireless home networks. Many SDOs currently consider admission control as the only means to prevent overload of the network. The UPnP QoS architecture v.3 and DVB QoS functional reference model have included admission control into consideration. The SDOs, however, do not consider the peculiarities of the wireless networks. According to our experience, the admission control in wireless networks has to be measurement-based and adaptive to take into account the variable nature of the wireless media. In the proposed post-admission control approach, the admission control decisions are made with respect to the already running applications based on the current traffic load of the network. With the help of a dynamic prioritization mechanism coupled with the policy-based user-centric QoS solution, the presented post-admission control approach provides flexible regulation of traffic on the network and improves the overall user experience.

The main contributions of this thesis are summarized below.

- We defined the precedence model which includes the main principles describing how to dynamically manage the precedence levels of flows based on user preferences and user behavior. According to the precedence model, all applications and their respective network flows are managed in a special way pursuant to network policy rules. The policy rules are based on user profiles and user usability rules such that each flow is assigned a particular precedence level in accordance with user preferences. The precedence model defines how to map user preferences to network precedence levels and how to manage precedence levels when certain events happen in the user or network environment. Therefore, the model contributes to defining a solution for future home networks where users will play a crucial role in the overall network management. The precedence model was defined in Chapter 4.

- For implementation of the precedence model in home networks, we designed the architecture of a user-centric QoS management system for wireless home networks. The structural design of the architecture is partially based on the UPnP QoS architecture [35] that defines components and interfaces for policy-based QoS management in home networks. The UPnP QoS architecture does not, however, consider how to implement the QoS solution in wireless networks. Neither does it define any policy strategies with respect to how to manage particular traffic and QoS requests on the network. We extended this with functionalities and user-centric policy rules of the precedence model. We identified main components, interfaces and data models that are necessary to be deployed in the network for user-centric capabilities for enhancing QoS and user experience in future wireless home networks. The implementation details and experimental results presented in Section 4.10 demonstrated practical applications of the described approach in wireless home network.

- We developed a simple EDCA analytical model of the Enhanced Distributed Channel Access (EDCA) function for throughput estimations in 802.11e-based networks. The model can be used for admission control tasks when there is a need to estimate how much bandwidth will be available for each station in the network at a certain priority level if a new request is admitted with a particular priority level. The model allows for calculations of what we will have if we admit a new stream on the network. Normally, it is not a trivial thing to do as adding a stream in one of the 802.11e access categories, influences the traffic load in other access categories in a non-linear way. As it was demonstrated in Chapter 5, our analytical model gives a good match when compared with the experimental results.

- We developed a post-admission control approach for wireless home networks. In comparison with the pre-admission control method, the post-admission control approach makes admission control decisions after a new service has been admitted on the network. This is aimed at addressing the peculiarities of wireless networks. Due to the variable nature of the wireless medium the resources available to a service might change in the wireless network any time after the service has been admitted. This might lead to network contention and degradation of all services on the network. That is why we proposed a measurement-based adaptive post-admission control method that can be very practical in wireless networks. In our approach the enforcement decisions (e.g. downgrading or terminating a service) are made after the new services have been provided with access to the network and only in case if the traffic load in transmission queues exceeds a certain threshold. As it was described in Chapter 6, such approach allows us to continuously keep the network in the non-saturated case and considerably improve network performance for already admitted services.

- The user-centric QoS management system described in this thesis has been implemented in practice. This includes implementation of the precedence model and all system's components defined in Chapter 4, GUIs for the QoS Tool and post-admission control method including implementation of the MAC layer monitor for the 2915abg wireless card's driver. The system have been installed and tested in our wireless testbed network. Moreover, the implemented user-centric QoS management system was successfully demonstrated at the Networked and Electronic Media (NEM) Summit[1] in 2008 (European Technology Platform).
- The core results of this work were also published in several IEEE symposiums and workshops held in 2007-2008 and also accepted for publication in the IEEE Transactions on Broadcasting Journal in 2009.

To summarize, it should be noted that even though home networking technologies are rapidly growing today, the wireless networks still suffer with regard to the QoS problems. Since user-centric role is currently considerably increasing when consuming and distributing the modern digital services, we believe that the QoS problems in wireless home networks have to be addressed in the user-centric manner. This thesis suggests that the introduced user-centric QoS management approach will significantly contribute to the overall user experience in digital home.

8.2 Directions for future work

There are several research directions that can be explored for possible extensions of our work.

- The presented user-centric QoS management system provides valuable means for enhancing user experience in the wireless home networks. The proposed precedence model along with the policy-based QoS allows for QoS management

[1] Networked and Electronic Media (NEM) Summit 2008, http://www.nem-summit.eu

according to user preferences. However, the delivered quality of services strongly depends on the QoS mechanisms provided by the home network (e.g. Layer 2 QoS technology). Currently, our system is implemented in the wireless network with WMM support providing prioritized services only. Keeping in mind the limitations of prioritized services (no guarantees, bad performance in saturated state), we have extended our system with a post-admission control mechanism. Even though this considerably improves the user experience, it does not solve all QoS problems over wireless. For example, the quality of a video stream can be strongly affected when the channel state has worsened and available bandwidth has decreased due to the increased noise or interference. The use of various FEC techniques [25], [26] and video transcoding [21], [22] or SVC techniques [23], [24] would be beneficial in this case. Therefore, for future research it would be very useful to consider various QoS mechanisms at different network levels for using them together with our user-centric QoS management system for truly beneficial user experience.

- In practice, the presented post-admission control approach can be used together with a pre-admission control approach as they complement to each other. A good continuation of this work would be an extension of the system with a pre-admission control approach based on the analytical and/or measured-based methods.

- Our policy-based QoS system provides the tools for adaptive management of the precedence levels, however, the policy rules themselves are static. That is the management system can be configured by a user or system administrator, but it cannot learn from the gained experience and from user activities. Observing the user and learning from his usage habits would be a valuable extension to our work.

- The software implementation of our user-centric QoS management system can be considered as middleware that is independent of the lower layers and which can be installed in any network with WMM support. However, for the post-admission control functionality it is required that a wireless driver is able to deliver the MAC layer network statistics such as transmission queue loads and queuing times. This makes the wide-spread usage of the system with the post-admission control difficult, since it depends on a particular wireless driver implementation. The implementation and system's deployment can be much easier if hardware (i.e. wireless cards) and drivers support unique interfaces for reporting transmission queue load and queuing time statistics. It would be very advantageous to explore how to solve this interoperability issue in future, which could attract both developers and consumers.

- Although we have considered the user-centric QoS management system for wireless networks, the scope of this work can be broadened and the main ideas of this work can be also applied to wireline networks. Taking into account a great interest in home networking today, it would be very valuable to consider the further integration and usage of our system with the evolving UPnP, DVB and DLNA technologies and consider possible contributions for the relevant Standards Developing Organizations (SDOs).

9 Publications arising from this work

The core results of our work were published in several IEEE conferences held in 2007-2008 and also accepted for publication in one of the IEEE journals in 2009.

- Spenst, A.; Andler K.; Herfet Th.: “Implementation of a Post-Admission Control Approach in Wireless Home Networks”, IEEE Transactions on Broadcasting Journal, June 2009.

- Spenst, A.; Herfet, Th.: "An Admission Control Approach for 802.11e-based Wireless Networks", NEM-Summit "Towards Future Media Internet", St. Malo, October 2008.

- Spenst, A.; Herfet, Th., Miroll, J.: "An Implementation of the User-Centric QoS Management Approach in Wireless Home Networks", IEEE International Symposium on Wireless Communication Systems(ICWCS 2007), Trondheim, Norway, October 16th-19th, 2007.

- Spenst, A.; Herfet, Th.: "A User-Centric QoS Management Approach for Digital Home", 9th IEEE International Workshop on Multimedia Signal Processing (MMSP 2007), Crete, Greek, October 1st-3rd, 2007.

- Spenst, A.; Herfet, Th.: "A user-centric QoS model for wireless home networks", 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2007), Athens, Greece, September 3rd-7th, 2007.

10 Annex A. UML Diagrams and interface specifications

This annex illustrates the message sequence diagrams for the main system's operations along with the description of the communication interfaces. The description of the message sequence diagrams is given in Section 4.9.1 (basic operation) and Section 6.7.1 (admission control).

10.1 *Message sequence diagrams and interfaces. Basic operation*

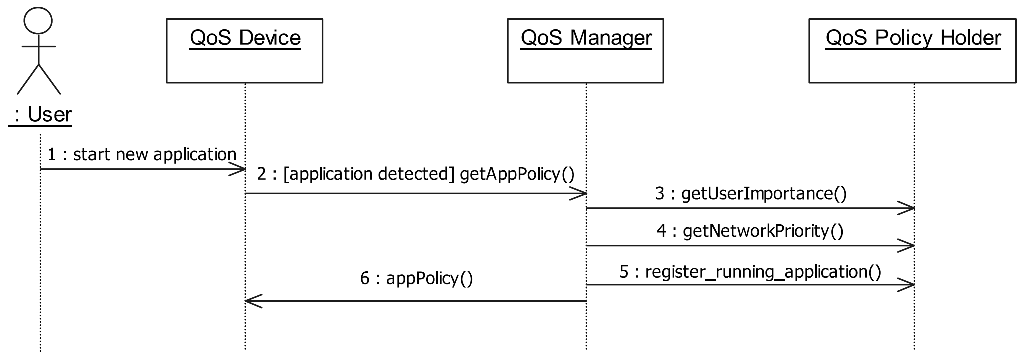


Figure 10.1: QoS device requests a policy for each new application

Arguments for *getAppPolicy()*

Message type: QM_UAPP_REQ

Table 10-1: Arguments for *getAppPolicy()*

Argument	Direction	Type	Description
username	IN	string	user name
appname	IN	string	application name
protocol	IN	string	application protocol

Arguments for *getUserImportance()*

Table 10-2: Arguments for *getUserImportance()*

Argument	Direction	Type	Description
username	IN	string	user name
profile_num	IN	int	profile number (Table 10-3)
user_importance	OUT	int	user importance

Table 10-3: Mapping user profiles to importance and precedence levels

Profile number (from top to bottom)	Importance level	User importance number
1	Realtime	6
2	High	5
3	Normal	3
4..∞	Low	1

Profiles are numbered from top to bottom as user sees them in the list of profiles.

Arguments for *getNetworkPriority()*

Table 10-4: Arguments for *getNetworkPriority()*

Argument	Direction	Type	Description
username	IN	string	user name
user_importance	IN	int	user importance
protocol	IN	string	application protocol
appname	IN	string	application name
address	IN	string	IP address of corresponding QoS Device
network_priority	OUT	int	network priority (ToS)

Arguments for *register_running_application()*

Table 10-5: Arguments for *register_running_application()*

Argument	Direction	Type	Description
address	IN	string	IP address of corresponding QoS Device
appname	IN	string	application name
protocol	IN	string	application protocol
user_importance	IN	int	user importance
network_priority	IN	int	network priority (ToS)
username	IN	string	user name

Arguments for *appPolicy()*

See Table 10-25.

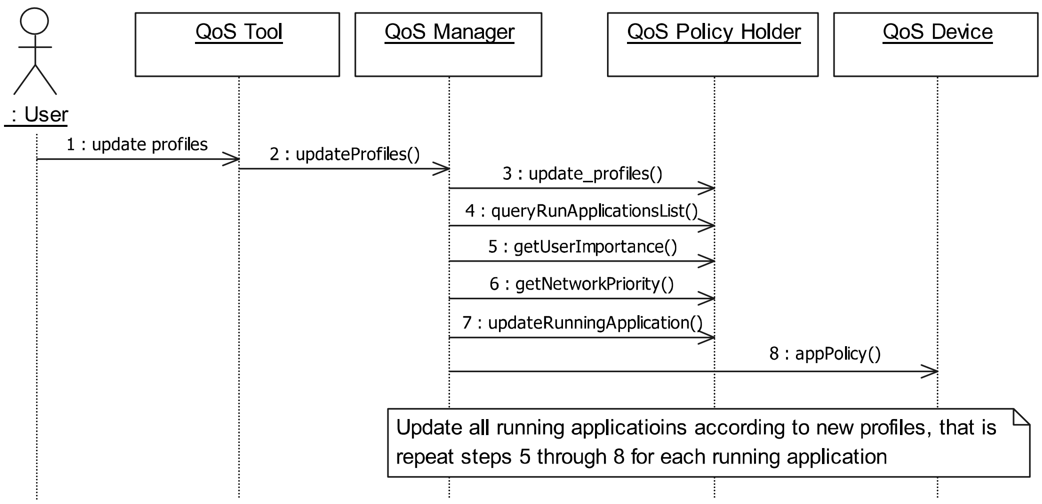


Figure 10.2: QoS Manager updates system performance according to user preferences

Arguments for *updateProfiles()* and *update_profiles()*

Message type: QM_PROF_UPDATE

Table 10-6: Arguments for *updateProfiles()* and *update_profiles()*

Argument	Direction	Type	Description
username	IN	string	user name
profile	IN	string[]	array of user profiles (Table 10-7)

Table 10-7: Structure *profile*

Argument	Type	Description
profile_num	int	profile number (Table 10-3)
profile_name	string	profile name
icon	int	profile icon index
application	string[]	array of application names

Arguments for *queryRunApplicatioinsList()*

Table 10-8: Arguments for *queryRunApplicationsList()*

Argument	Direction	Type	Description
username	IN	string	user name
application	OUT	string[]	array of running applications (Table 10-9)

Table 10-9: Structure *application*

Argument	Type	Description
appname	string	application name
user_importance	int	user importance
network_priority	int	network priority (ToS)
address	string	IP address of corresponding QoS Device
app_downgraded	bool	'application downgraded' flag (Table 10-10)
protocol	string	application protocol

Table 10-10: Valid values for *'application downgraded'* flag

Value	Description
0	application is running with the initially assigned network priority
1	application has been downgraded, i.e. now candidate for upgrading

Arguments for *getUserImportance()*

See Table 10-2.

Arguments for *getNetworkPriority()*

See Table 10-4.

Arguments for *updateRunningApplication()*

Table 10-11: Arguments for *updateRunningApplication()*

Argument	Direction	Type	Description
address	IN	string	IP address of corresponding QoS Device
appname	IN	string	application name
user_importance	IN	int	user importance
network_priority	IN	int	network priority (ToS)
username	IN	string	user name

Arguments for *appPolicy()*

See Table 10-25.

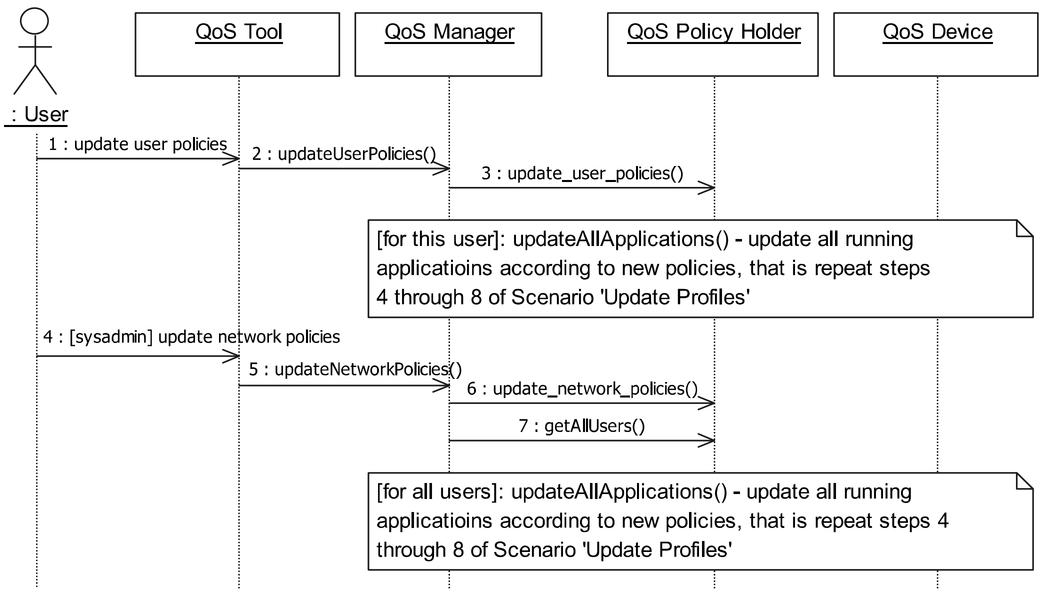


Figure 10.3: QoS Manager updates system performance when user or network policies change

Arguments for *updateUserPolicies()* and *update_user_policies()*

Message type: QM_USERPOL_UPDATE

Table 10-12: Arguments for *updateUserPolicies()* and *update_user_policies()*

Argument	Direction	Type	Description
username	IN	string	user name
user policy 1	IN	string[]	array of user policy 1 (Table 10-13)
user policy 2	IN	string[]	array of user policy 2 (Table 10-14)
user policy 3	IN	string[]	array of user policy 3 (Table 10-15)
user policy 4	IN	string[]	array of user policy 4 (Table 10-16)

Table 10-13: Structure of *user policy 1*: how to map profiles and applications to importance levels

Argument	Type	Default	Description
1st profile	string	Realtime	user importance level for 1st profile
2nd profile	string	High	user importance level for 2nd profile
3rd profile	string	Normal	user importance level for 3rd profile
4th profile	string	Low	user importance level for 4th profile
other profiles	string	Low	user importance level for all other profiles
unknown applications	string	Normal	user importance level for unknown applications

Table 10-14: Structure of *user policy 2*: how many applications are allowed to run at each importance level

Argument	Type	Default	Description
Realtime	int	infinite	maximum number of applications allowed at 'Realtime' level
High	int	infinite	maximum number of applications allowed at 'High' level
Normal	int	infinite	maximum number of applications allowed at 'Normal' level
Low	int	infinite	maximum number of applications allowed at 'Low' level

Table 10-15: Structure of *user policy 3*: when the number of running applications at a certain importance level is more than allowed, apply the following policy when downgrading

Argument	Type	Values	Default	Description
service policy	string	'fcfs', 'lcfs'	lcfs	service policy, i.e. First Come First Serve (fcfs) or Last Come First Serve (lcfs)

Table 10-16: Structure of *user policy 4*: when "Realtime" or "High" importance applications are downgraded they continue running at the following level of importance

Argument	Type	Values	Default	Description
importance level	string	'Normal', 'Low', 'one level lower'	Low	at which level applications are downgraded

Arguments for *updateNetworkPolicies()* and *update_network_policies()*

Message type: QM_NETWORKPOL_UPDATE

Table 10-17: Arguments for *updateNetworkPolicies()* and *update_network_policies()*

Argument	Direction	Type	Description
network policy 1	IN	string[]	array of network policy 1 (Table 10-18)
network policy 2	IN	string[]	array of network policy 2 (Table 10-19)
network policy 3	IN	string[]	array of network policy 3 (Table 10-20)
network policy 4	IN	string[]	array of network policy 4 (Table 10-21)

Table 10-18: Structure of *network policy 1*: how to map user importance levels to WMM access categories

Argument	Type	Default	Description
Realtime	string	AC_VO	access category corresponding to “Realtime” level
High	string	AC_VI	access category corresponding to “High” level
Normal	string	AC_BE	access category corresponding to “Normal” level
Low	string	AC_BK	access category corresponding to “Low” level

Table 10-19: Structure of *network policy 2*: how many users are allowed to use each WMM access category

Argument	Type	Default	Description
AC_VO	int	infinite	maximum number of users allowed to use AC_VO
AC_VI	int	infinite	maximum number of users allowed to use AC_VI
AC_BE	int	infinite	maximum number of users allowed to use AC_BE
AC_BK	int	infinite	maximum number of users allowed to use AC_BK

Table 10-20: Structure of *network policy 3*: define users allowed to use not all WMM access categories

Argument	Type	Default	Description
AC_VO	string	all	list of users allowed to use AC_VO
AC_VI	string	all	list of users allowed to use AC_VI
AC_BE	string	all	list of users allowed to use AC_BE
AC_BK	string	all	list of users allowed to use AC_BK

Table 10-21: Structure of *network policy 4*: ranking for known users (from most important to least important)

Argument	Type	Default	Description
rank 1	string	root	list of users with rank 1
rank 2	string	dhcl	list of users with rank 2
rank 3	string	-----	list of users with rank 3
rank 4	string	guest	list of users with rank 4

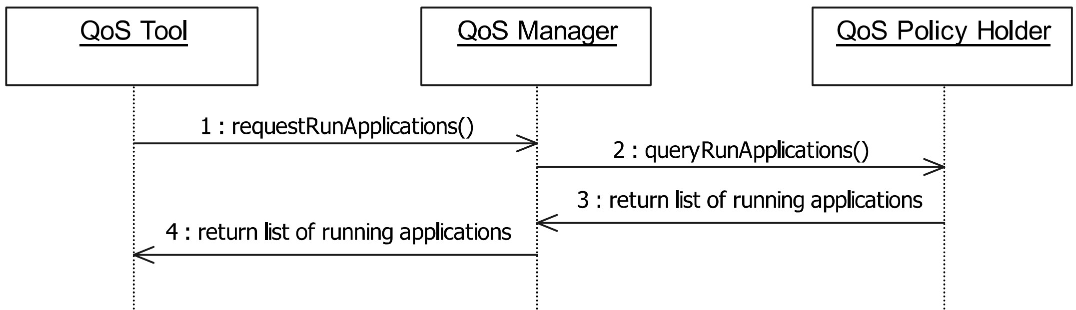


Figure 10.4: QoS Tool requests periodically information about running applications

Arguments for *requestRunApplications()* and *queryRunApplications()*

Message type: QM_APP_REQ for request and QM_APP_RES for return messages

Table 10-22: Arguments for *requestRunApplications()* and *queryRunApplications()*

Argument	Direction	Type	Description
username	IN	string	user name
application	OUT	string[]	structure of running applications (Table 10-23)

Table 10-23: Structure *application*

Argument	Type	Description
appname	string	application name
user_importance	int	user importance
network_priority	int	network priority (IP TOS)
address	string	IP address of corresponding QoS Device

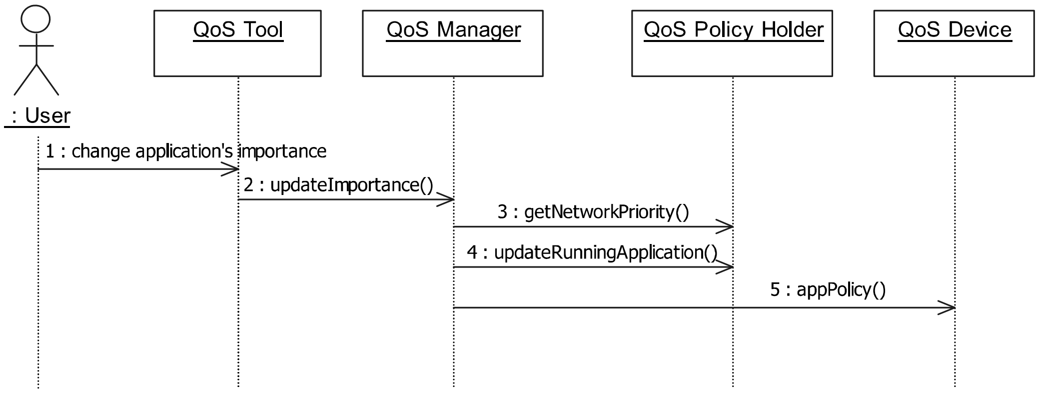


Figure 10.5: QoS Tool can request to change the importance for one application

Arguments for *updateImportance()*

Message type: QM_CHG_IMP

Table 10-24: Arguments for *updateImportance()*

Argument	Type	Description
username	string	user name
appname	string	application name
user_importance	int	user importance
address	string	IP address of corresponding QoS Device

Arguments for *getNetworkPriority()*

See Table 10-4.

Arguments for *updateRunningApplication()*

See Table 10-11.

Arguments for *appPolicy()*

See Table 10-25.

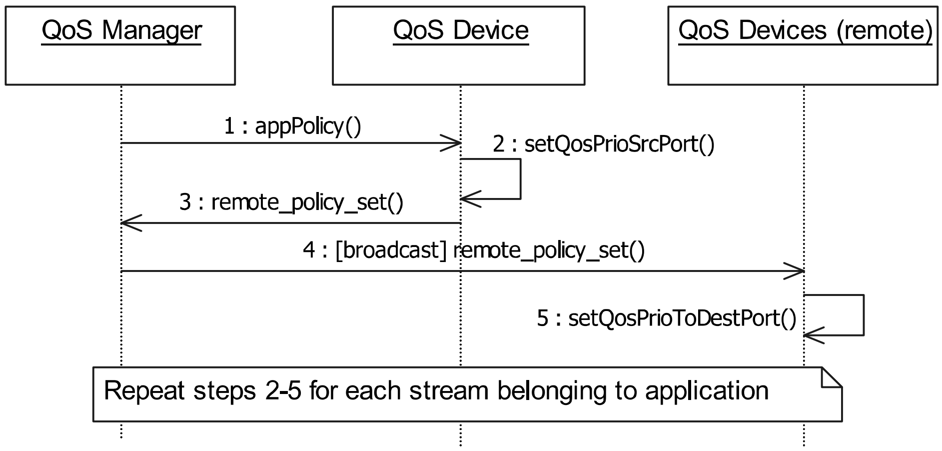


Figure 10.6: QoS Device enforces a policy according to the QoS Manager's request

Table 10-25: Arguments for *appPolicy()*

Argument	Direction	Type	Description
username	IN	string	user name
appname	IN	string	structure of running applications (Table 10-23)
protocol	IN	string	application protocol
network_priority	IN	int	network priority (IP TOS)

Table 10-26: Arguments for *setQosPrioSrcPort()*

Argument	Direction	Type	Description
protocol	IN	string	application protocol
source_port	IN	int	source port
network_priority	IN	int	network priority (IP TOS)

Table 10-27: Arguments for *remote_policy_set()*

Argument	Direction	Type	Description
protocol	IN	string	application protocol
address	IN	string	IP address of corresponding QoS Device
destination_port	IN	int	destination port
network_priority	IN	int	network priority (ToS)

Table 10-28: Arguments for *setQosPrioToDestPort()*

Argument	Direction	Type	Description
protocol	IN	string	application protocol
address	IN	string	destination IP address
destination_port	IN	int	destination port
network_priority	IN	int	network priority (ToS)

10.2 Message sequence diagrams and interfaces. Admission control operation

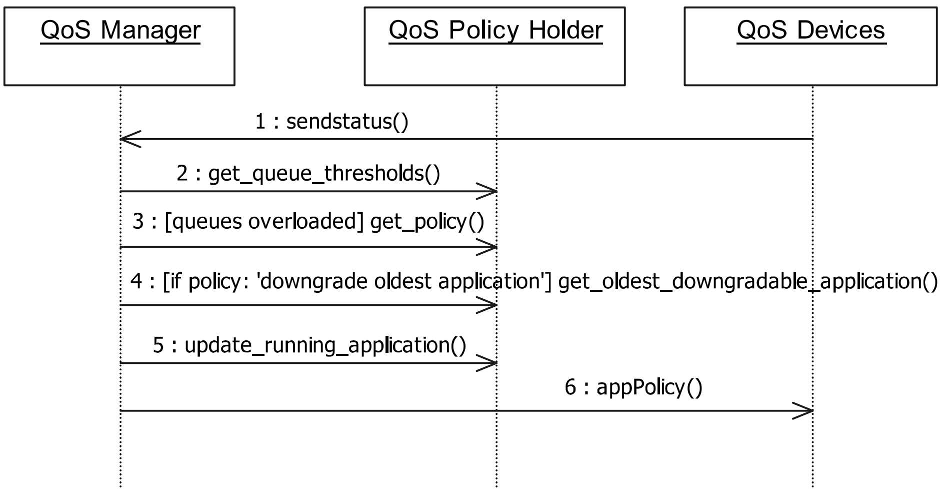


Figure 10.7: Downgrade one of the applications if queues overloaded

Arguments for *sendstatus()*

Message type: QM_STATUS

Table 10-29: Arguments for *sendstatus()*

Argument	Direction	Type	Description
LOADBE	IN	float	traffic load in AC_BE, %
LOADBK	IN	float	traffic load in AC_BK, %
LOADVI	IN	float	traffic load in AC_VI, %
LOADVO	IN	float	traffic load in AC_VO, %
QUEUINGTIMEBE	IN	float	queuing time in AC_BE, μs
QUEUINGTIMEBK	IN	float	queuing time in AC_BK, μs
QUEUINGTIMEVI	IN	float	queuing time in AC_VI, μs
QUEUINGTIMEVO	IN	float	queuing time in AC_VO, μs

Arguments for *get_queue_thresholds()*

Table 10-30: Arguments for *get_queue_thresholds()*

Argument	Direction	Type	Description
TRESHBE	OUT	float	traffic load threshold for AC_BE, %
TRESHBK	OUT	float	traffic load threshold for AC_BK, %
TRESHVI	OUT	float	traffic load threshold for AC_VI, %
TRESHVO	OUT	float	traffic load threshold for AC_VO, %
lowerbound	OUT	float	traffic load threshold for upgrading

If traffic load is less than *lowerbound*, upgrade is possible.

Arguments for *get_policy()*

Table 10-31: Arguments for *get_policy()*

Argument	Direction	Type	Description
policy	OUT	int	active admission control policy (Table 10-32)
terminate	OUT	bool	terminate application flag (Table 10-33)

Table 10-32: Valid values for *policy* argument

Value	Policy	Description
0	NO_ADMISSION_CONTROL	admission control is disabled
1	KILL_LATEST_APP	terminate latest application (FCFS policy)
2	KILL_OLDEST_APP	terminate oldest application (LCFS policy)
5	DOWN_LATEST_APP	downgrade latest application (FCFS policy)
6	DOWN_OLDEST_APP	downgrade oldest application (FCFS policy)

Table 10-33: Valid values for *terminate* flag

Value	Description
0	do not terminate application, only make warning about traffic overload
1	terminate application

Arguments for *get_oldest_downgradable_application()* and *get_latest_downgradable_application()*

Table 10-34: Arguments for *get_oldest_downgradable_application()* and *get_latest_downgradable_application()*

Argument	Direction	Type	Description
address	OUT	string	IP address of corresponding QoS Device
appname	OUT	string	application name
username	OUT	string	name of user running application
protocol	OUT	string	application protocol

Arguments for *update_running_application()*

Table 10-35: Arguments for *update_running_application()*

Argument	Direction	Type	Description
address	IN	string	IP address of corresponding QoS Device
appname	IN	string	application name
AC	IN	int	new precedence level (access category) for application

Arguments for *appPolicy()*

See Table 10-25.

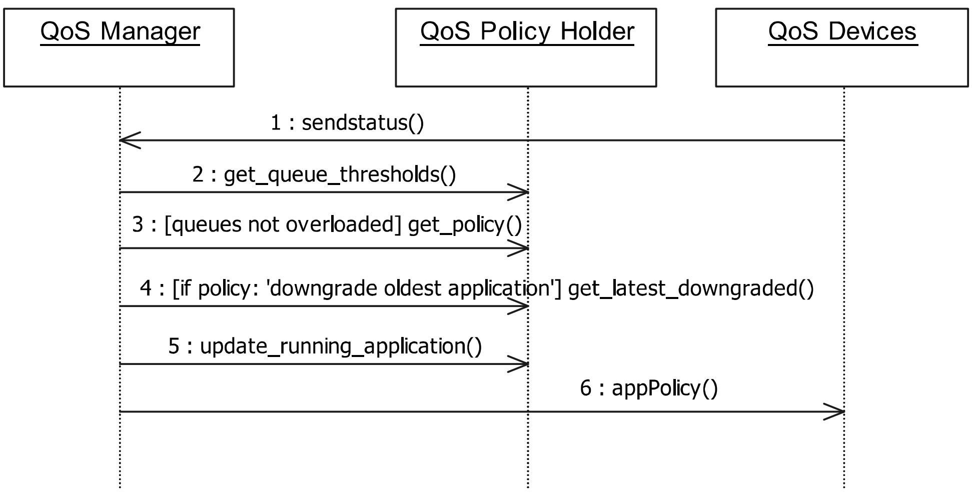


Figure 10.8: Upgrade one of the previously downgraded applications if queue load decreased

Arguments for *sendstatus()*

See

Table 10-29.

Arguments for *get_queue_thresholds()*

See Table 10-30.

Arguments for *get_policy()*

See Table 10-31.

Arguments for *get_latest_downgraded()* and *get_oldest_downgraded()*

Table 10-36: Arguments for *get_latest_downgraded()* and *get_oldest_downgraded()*

Argument	Direction	Type	Description
address	OUT	string	IP address of corresponding QoS Device
appname	OUT	string	application name
username	OUT	string	name of user running application
protocol	OUT	string	application protocol

Arguments for *update_running_application()*

See Table 10-35.

Arguments for *appPolicy()*

See Table 10-25.

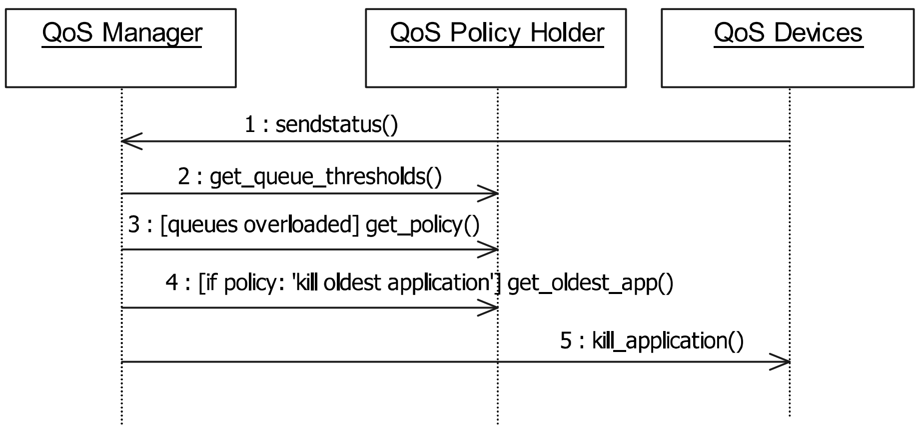


Figure 10.9: Terminate one of the applications if queues overloaded

Arguments for *sendstatus()*

See

Table 10-29.

Arguments for *get_queue_thresholds()*

See Table 10-30.

Arguments for *get_policy()*

See Table 10-31.

Arguments for *get_oldest_app()* and *get_latest_app()*

Table 10-37: Arguments for *get_oldest_application()* and *get_latest_application()*

Argument	Direction	Type	Description
address	OUT	string	IP address of corresponding QoS Device
appname	OUT	string	application name
protocol	OUT	string	application protocol

Arguments for *kill_application()*

Table 10-38: Arguments for *kill_application()*

Argument	Direction	Type	Description
appname	IN	string	application name

11 Annex B. Class Diagrams

In the figures below the class diagram only for the main system's components are depicted (QoS Tool, QoS Manager, QoS Policy Holder, QoS Device).

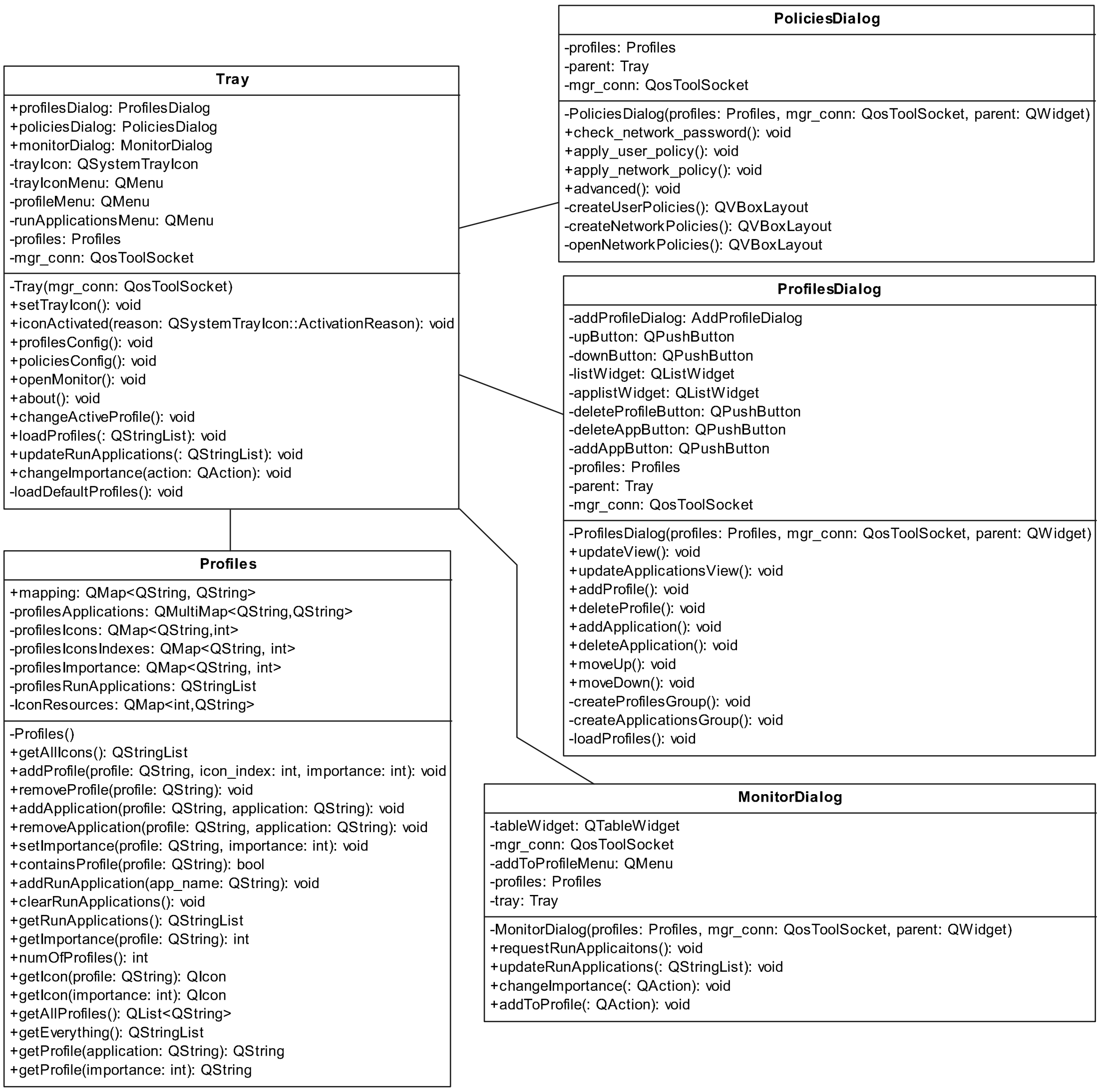


Figure 11.1: Class diagram for QoS Tool

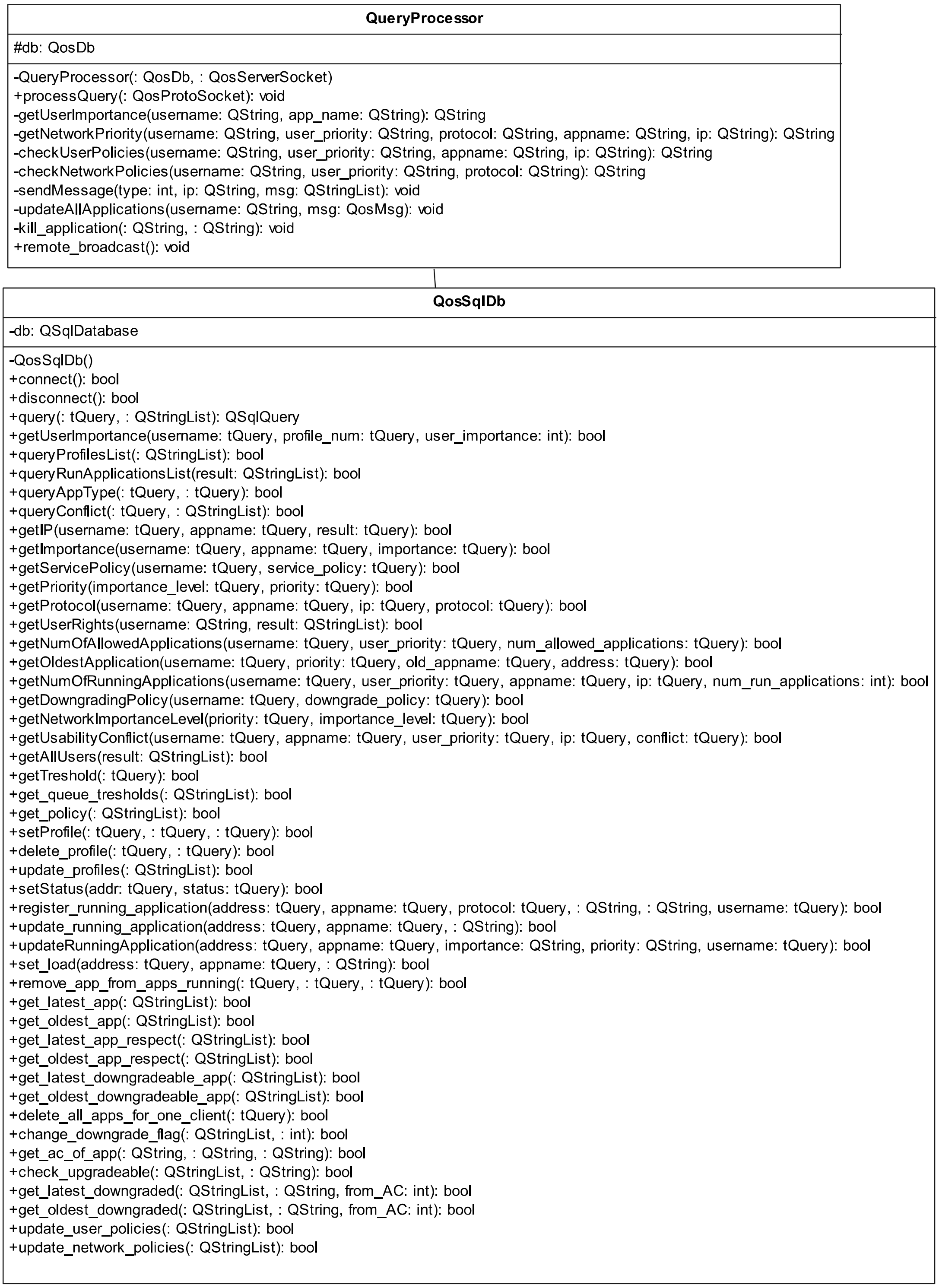


Figure 11.2: Class diagram for QoS Manager and QoS Policy Holder

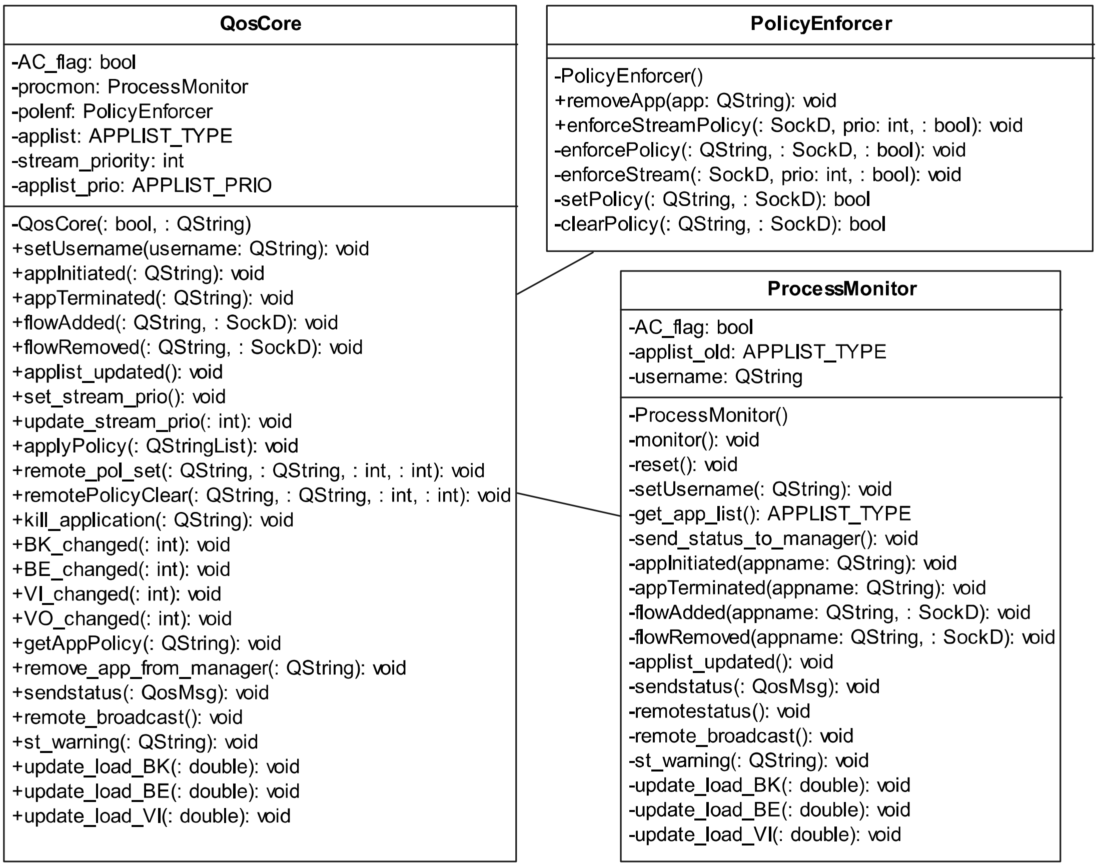


Figure 11.3: Class diagram for QoS Device

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