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Abstract: Quality of Service (QoS) is a key problem of today's IP networks. Many frameworks (IntServ, DiffServ, MPLS, Traffic engineering, etc.) have been proposed to provide service differentiation in the Internet. At the same time, the Internet is becoming more and more heterogeneous due to the recent explosion of wireless networks. In wireless environments, bandwidth is scarce and channel conditions are time-varying and sometimes highly lossy. Many previous research works show that what works well in a wired network cannot be directly applied in the wireless environment. IEEE 802.11 wireless LAN (WLAN) is the most widely used WLAN standard today, but it cannot provide QoS support for the increasing number of multimedia applications. Thus, a large number of 802.11 QoS enhancement schemes have been proposed, each one focusing on a particular mode. This report summarizes all these schemes and presents a survey of current research activities. First, we analyze the QoS limitations of IEEE 802.11 wireless MAC layers. Then, different QoS enhancement techniques proposed for 802.11 WLAN are described and classified along with their advantages/drawbacks. Finally, the upcoming IEEE 802.11e QoS enhancement standard is introduced and studied in detail.

Key-words: IEEE 802.11, IEEE 802.11e, Medium Access Control (MAC), Quality of Service (QoS), Distributed Coordination Function (DCF), Point Coordination Function (PCF), Hybrid Coordination Function (HCF), Differentiated Services (DiffServ), Integrated Services (IntServ)

Support de Mécanismes de Différenciation de Services pour Réseaux Locaux sans Fil 802.11

Résumé : Le support de qualité de service (QoS) dans l'Internet reste encore aujourd'hui un verrou technologique important. De nombreux protocoles (IntServ, DiffServ, MPLS, etc.) ont été proposés pour apporter une différenciation de services dans l'Internet. D'un autre côté, avec l'explosion récente des réseaux sans fils, l'Internet devient de plus en plus hétérogène. Dans un environnement sans fil, la bande passante est beaucoup plus rare et les caractéristiques du canal de transmission varient au cours du temps. Les réseaux locaux sans-fil IEEE 802.11 sont les plus utilisés aujourd'hui mais ils n'offrent pas de services avec QoS. Or, des services différenciés sont nécessaires pour pouvoir maintenir une certaine qualité de service aux nouvelles applications multimédia. Aussi, de nombreuses propositions ont été faites pour rajouter de la QoS aux réseaux 802.11, chacune d'entre elles pour un mode de fonctionnement particulier du protocole. Dans cette étude, nous résumons tous ces nouveaux mécanismes et présentons une vue d'ensemble des activités de recherche et de standardisation en cours. Nous analysons d'abord les limitations de la couche MAC du protocole 802.11 de base. Puis nous décrivons et classons les différents mécanismes proposés pour rajouter de la qualité de service et étudions leurs avantages et inconvénients respectifs. Enfin, nous présentons le nouveau protocole IEEE 802.11e en cours de standardisation et l'étudions en détail.

Mots-clés : Réseaux Locaux Sans Fil, standards IEEE 802.11 et IEEE 802.11e, Contrôle d'Accès au Médium (MAC), Qualité de Service (QoS), Services Différenciés (DiffServ), Services Intégrés (IntServ)

Acronymes

AC	Access Category
ACK	Acknowledgement
AIFS	Arbitration Inter Frame Spacing
AP	Access Point
CA	Collision Avoidance
CAM	Continuously Active Mode
CAP	Controlled Access Period
CCI	Controlled Contention Interval
CCOP	Controlled Contention Opportunity
CDF	Complementary Cumulative Distribution Function
CFB	Contention Free Burst
CFP	Contention Free Period
CF-Poll	Contention Free - Poll
CF-End	Contention Free - End
CP	Contention Period
CSMA	Carrier Sense Multiple Access
CW	Contention Window
CWmax	Contention Window Maximum
CWmin	Contention Window Minimum
DCF	Distributed Coordination Function
EDCF	Enhanced Distributed Coordination Function
FEC	Forward Error Correction
HC	Hybrid Coordinator
HCF	Hybrid Coordination Function
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Science, and Medical
MAC	Medium Access Control
MSDU	MAC Service Data Unit
NAV	Network Allocation Vector

PC	Point Coordinator
PCF	Point Coordination Function
PF	Persistence Factor
PIFS	PCF Inter Frame Space
PSDU	Physical (layer) Service Data Unit
PSP	PS-Poll
QAP	QoS Access Point
QAPC-STA	QAP-capable QSTA
QBSS	Quality Of Service Basic Service Set
QIBSS	Quality Of Service Independent Basic Service Set
QoS	Quality Of Service
QSTA	QoS station
RS	Reed-Solomon
RTS/CTS	Request to Send/Clear to Send
SIFS	Short Inter Frame Space
TC	Traffic Category
TAID	Traffic And Association (Identifier)
TBTT	Target Beacon Transmission Time
TCID	Traffic Category Identifier
TID	Traffic IDentifier
TS	Traffic Stream
TSID	Traffic Stream IDentifier
TSPEC	Traffic Specification
TXOP	Transmission Opportunity
WLAN	Wireless Local Area Network
WSTA	Wireless Station

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1 Introduction

IEEE 802.11 wireless LAN (WLAN) [1] is one of the most deployed wireless technologies all over the world and is likely to play a major role in next-generation wireless communication networks. The main characteristics of the 802.11 WLAN technology are simplicity, flexibility and cost effectiveness. This technology provides people with a ubiquitous communication and computing environment in offices, hospitals, campuses, factories, airports and stock markets. Simultaneously, multimedia applications have experienced an explosive growth. People are now requiring to receive high-speed video, audio, voice and Web services even when they are moving at offices or travelling around campuses. However, multimedia applications require some QoS (Quality of Service) support such as guaranteed bandwidth, delay, jitter and error rate. Guaranteeing those QoS requirements in 802.11 WLAN is very challenging due to the QoS-unaware functions of its MAC layer and the noisy and variable physical (PHY) layer characteristics.

The primary objectives of this paper are to:

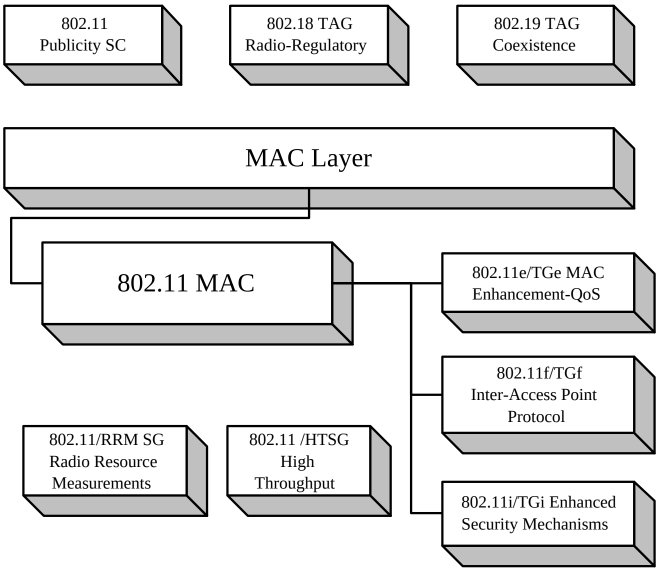
- Introduce an overview of IEEE 802.11 WLAN standard,
- Analyze the QoS problems of IEEE 802.11 MAC layer functions,
- Survey the main QoS enhancement schemes that have been proposed for 802.11 WLAN,
- Describe and study the new IEEE 802.11e QoS enhancement WLAN standard [2].

Some previous works have been done to survey the QoS support for IEEE 802.11 WLAN or mobile ad-hoc networks [5, 11, 37, 42], but they do not introduce the latest research works of IEEE 802.11e. Moreover, a broad survey is needed to summarize all the current research efforts on IEEE 802.11 WLAN. This paper surveys all these efforts and intends to provide a comprehensive view of the various works. Then, some hints for future research works on QoS enhancement are provided in this paper.

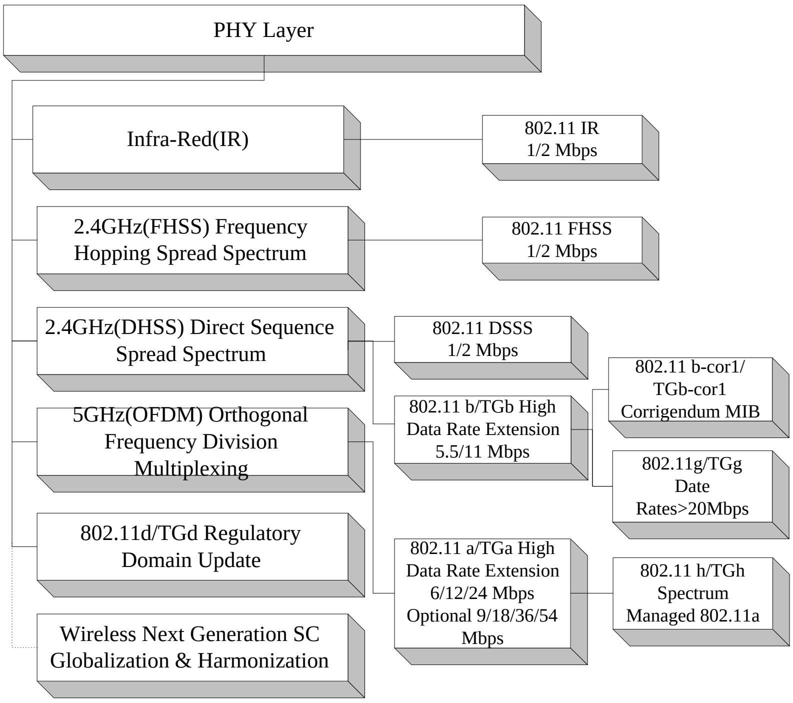
The rest of this paper is organized as follows. In Section 2 we introduce an overview of IEEE 802.11 WLAN. The limitations of QoS support in 802.11 MAC functions are addressed in Section 3. Section 4 surveys the different QoS enhancement schemes that have been proposed for 802.11 MAC layer. In Section 5, the upcoming QoS enhancement standard 802.11e is introduced and analyzed. Section 6 concludes the survey and presents future research areas.

2 An overview of IEEE 802.11 WLAN

In general, the IEEE 802.11 WLAN standard covers the MAC sub-layer and the physical (PHY) layer of the OSI (Open System Interconnection) network reference model [1]. Logical Link Control (LLC) sub-layer is specified in the IEEE 802.2 standard. This architecture provides a transparent interface to the higher layer users: stations may move, roam through an 802.11 WLAN and still appear as stationary to 802.2 LLC sub-layer and above. This allows existing network protocols (such as TCP/IP) to run over IEEE 802.11 WLAN without any special considerations, just like if IEEE 802.3 wired Ethernet was deployed. At PHY layer, first the IEEE provides three kinds of options in the 2.4 GHz band. The three PHY layers are an Infrared (IR) baseband PHY, a Frequency Hopping Spread Spectrum (FHSS) radio and a Direct Sequence Spread Spectrum (DSSS) radio. All three PHY layers support both 1 and 2Mbps (1/2 Mbps in Figure 1) operation. In 1999, the IEEE defined up to 11Mbps 802.11b in the 2.4 GHz free ISM (Industrial, Science, and Medical) band and up to 54Mbps 802.11a OFDM in 5GHz frequency. Ongoing 802.11g will extend 2.4GHz 802.11b PHY layer to support at least 20Mbps rate. Moreover, 802.11h will enhance 802.11a in the 5GHz band, adding indoor and outdoor channel selection for 5GHz license exempt bands in Europe. At MAC layer, ongoing 802.11e will deliver QoS support to the 802.11 WLAN. 802.11f will develop an Inter-Access Point protocol for mobile stations move between multi-vendor Access Points. 802.11i will enhance security and authentication mechanisms for 802.11 MAC. Figure 1 shows a diagram of the 802.11 MAC (Medium Access Control) and PHY layers' new activities and framework. In this section, we present the basic MAC functions of IEEE 802.11 WLAN.



(a) MAC layer activities



(b) PHY layer activities

Figure 1: 802.11 MAC and PHY activities and framework

The IEEE 802.11 MAC sub-layer defines two relative medium access coordination functions, the Distributed Coordination Function (DCF) and the optional Point Coordination Function (PCF) [1]. The transmission medium can operate both in contention mode (DCF) and contention-free mode (PCF). The IEEE 802.11 MAC protocol provides two types of transmission: asynchronous and synchronous. The asynchronous type of transmission is provided by DCF which implements the basic access method of the 802.11 MAC protocol. DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, and should be implemented in all the stations. The synchronous service (also called contention free service) is provided by PCF which basically implements a polling-based access method. The PCF uses a centralized polling approach which requires an Access Point (AP) that acts as a Point Coordinator (PC). The AP cyclically polls stations to give them the opportunity to transmit the packets. Unlike the DCF, the implementation of the PCF is not mandatory. Furthermore, the PCF itself relies on the asynchronous service provided by the DCF. There are two different ways to configure an 802.11 wireless network: ad-hoc mode and infrastructure mode. In an ad-hoc mode, the mobile stations communicate with each other in an independent Basic Service Set (BSS) without connectivity to the wired backbone. In an infrastructure mode, the mobile stations can communicate with the wired backbone through the AP. DCF function can be used both in ad-hoc and infrastructure mode. PCF is only used in infrastructure mode.

2.1 DCF: Distributed Coordination Function

DCF is a distributed medium access scheme. In this mode, a station must sense the medium before initiating a packet transmission by PHY and MAC layer virtual carrier sensing. If the medium is found idle for a time interval longer than Distributed InterFrame Space (DIFS), then the station can transmit the packet directly. Otherwise, the transmission is deferred and the backoff process is started, see Figure 2. Specifically, the station computes a random time interval named $Backoff\_time$, uniformly distributed between zero and the current Contention Window size (CW), $Backoff\_time = rand[0, CW]$, where $CWmin < CW < CWmax$ and $Slot\_time$ depends on the PHY layer type. The backoff timer is decreased only when the medium is idle, whereas it is frozen when another station is transmitting. Each time the medium becomes idle, the station waits for a DIFS and then continuously decrements the backoff timer. As soon as the backoff timer expires, the station is authorized to access the medium. Obviously, a collision occurs if two or more stations start transmission simultaneously. Unlike wired networks (e.g. CSMA/CD), in a wireless environment collision detection is impossible due to the significant difference between transmitted and received power levels. Hence, a positive acknowledgement is used to notify the sender that the transmitted frame has been successfully received, see Figure 2. The transmission of the acknowledgement is initiated at a time interval equal to the Short InterFrame Space (SIFS) after the end of the reception of the previous frame. Since the SIFS is smaller than the DIFS, the receiving station does not need to sense the medium before transmitting an acknowledgement. If the acknowledgement is not received, the sender assumes that the transmitted frame was lost and schedules a retransmission and then enters the backoff process again. To reduce the probability of collisions, after each unsuccessful transmission attempt, the contention window is doubled until a predefined maximum value CWmax is reached. To improve the channel utilization, after each successful transmission, the contention window is reset to a fixed minimum value CWmin. The Network Allocation Vector (NAV) is used for MAC virtual carrier sensing, by updating the local NAV with the value of other stations' transmission duration. By using NAV, a station can know when the current transmission ends and channel is idle.

In order to solve the so-called hidden terminal problem, an optional RTS/CTS (RequestToSend and ClearToSend) scheme is introduced, see Figure 3. The transmitter sends a short RTS frame (20 octets) before each data frame transmission. Note that a collision of the short RTS frames is less severe and probable than a collision of data frames (up to 2346 octets). The receiver replies with a CTS frame if it is ready to receive and the channel is reserved for the duration of packet transmission. When the source receives the CTS, it starts transmitting its frame, being sure that the channel has been reserved for it during the entire frame transmission duration. All other stations in the Basic Service Set (BSS) update their Network Allocation Vectors (NAVs) whenever they hear a RTS, a CTS or a data frame. The overhead of sending RTS/CTS frames becomes considerable when data frame sizes are small, thus the channel is used sub-optimally. Moreover, very large frames may reduce transmission reliability, e.g. an uncorrectable error in a large frame wastes more bandwidth and transmission time than an error in a shorter frame. So another optimization parameter of fragmentation_threshold is used. That means, when data frame size is larger than this threshold, the data frame will be partitioned into several smaller MAC level frames.

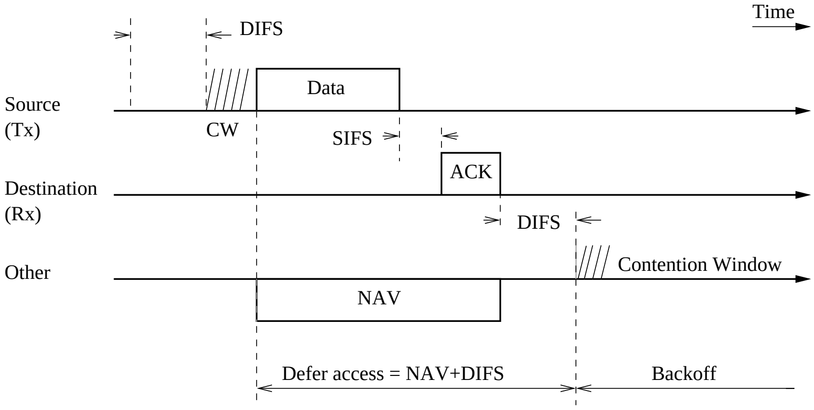


Figure 2: Basic DCF CSMA/CA

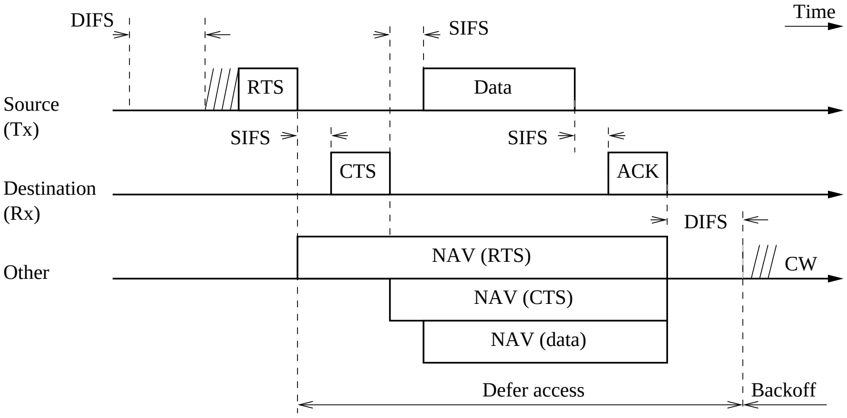


Figure 3: RTS/CTS access scheme

2.2 PCF: Point Coordination Function

Time-bounded data such as voice, audio or video is supported in the 802.11 MAC specification through the PCF optional function. In PCF mode, a single AP controls the stations to access the media. If a BSS is set up with PCF-enabled, the two access methods (DCF and PCF) alternate, with a Contention-Free Period (CFP) followed by a Contention Period (CP), see Figure 4. During the PCF mode, the Point Coordinator (PC) maintains a list of registered stations and polls each station one by one according to the list. No station is allowed to transmit unless it is polled, and stations receive data from the AP only when they are polled. Since PCF gives every station a turn to transmit in a predetermined order, a maximum latency is bounded. However, PCF is not scalable. A single access point dominates and controls medium access, and it must poll all the stations, which can be ineffective in large networks. Moreover, all the traffic must go through the AP, which wastes much bandwidth. So, the PCF is defined as an optional capability, which needs a PC to initiate and control the CFP. The PC first senses the channel for a PIFS interval (PCF InterFrame Space) and then starts a CFP by broadcasting a beacon signal. Note that PIFS is shorter than DIFS, which allows the AP to gain the control from DCF mode and no DCF stations are able to interrupt the operation of PCF mode. All stations add CFPmaxduration (the maximum possible duration of the Contention Free Period) to their own NAVs, which prevents themselves taking control of medium during CFP. Later, active users with time-bounded packet streams are periodically polled by the PC. The PC can terminate the CFP at any time by transmitting a CF-end packet, which occurs frequently when the network is lightly loaded. When a terminal's turn in the polling list comes, the PC sends a buffered data packet to it, piggybacked with a CF-Poll or an ACK for the previous transmission. The receiver sends back an ACK or any buffered data piggybacked with an ACK after a SIFS interval. Note that almost all packet transmissions are separated by SIFS except for one scenario: when the polled station does not respond the PC's poll within the SIFS period, the PC transmits its next packet after a PIFS from the end of the PC's last transmission [1]. Indeed, piggyback can improve the channel utilization greatly in the PCF mode. Normally PCF uses a round-robin polling algorithm, where each station is polled sequentially in the order in which it is placed in the polling list. Priority-based polling mechanisms can also be used if different QoS levels are requested by different polled stations. Stations who are idle repeatedly are removed from the poll cycle after several idle periods and polled again at the beginning of the next CFP.

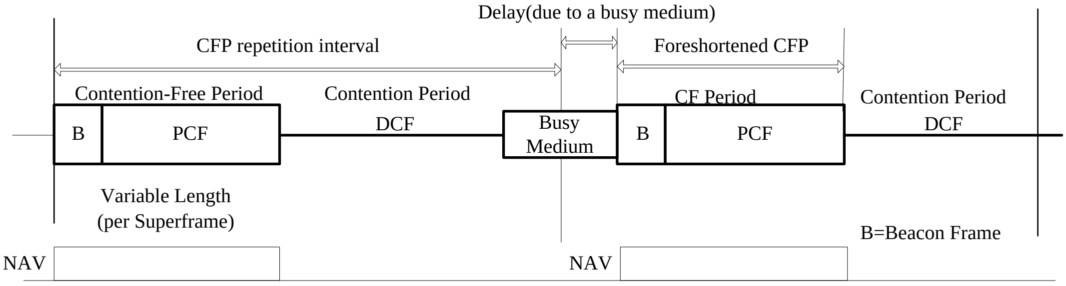


Figure 4: PCF and DCF cycles

2.3 Services supported in 802.11 MAC

IEEE 802.11 MAC functions can support nine types of services for higher-layer applications: (a) authentication, (b) association, (c) deauthentication, (d) disassociation, (e) distribution, (f) integration, (g) privacy, (h) reassociation and (i) MSDU delivery, which can be divided into two categories of IEEE 802.11 MAC services - the Station Service (SS) and the Distribution System Service (DSS). However, none of them provides support for WLAN applications with QoS requirements.

The Station Service (SS) is present in every IEEE 802.11 station (including APs, since APs include station functionality). The SS is specified for use by MAC sublayer entities, see Figure 5. All conformant stations provide SSs. The SS includes: (a) authentication, (b) deauthentication, (c) privacy, and (d) MSDU delivery.

The Distribution System Service (DSS) is represented in the IEEE 802.11 service architecture by bi-directional arrows within the APs, see Figure 5. The architectural component used to interconnect different BSSs is the Distribution System (DS). The DSSs are provided by the DS. The AP provides stations with access to the DSS. By using DS, an IEEE 802.11 WLAN service area can be extended to an arbitrary size. A mobile station can move from BSS1 to BSS2 service area through the DSS without losing connectivity to other stations. IEEE 802.11 refers to this type of network as the Extended Service Set (ESS) network. It means that several interconnected BSSs form an ESS via a DS. The key point is that stations within an ESS can communicate with each other and mobile stations can roam from one BSS to another BSS within the same ESS. It means that the movements are transparent to the LLC layer. The DSS is made up of follows: (a) association, (b) disassociation, (c) distribution, (d) integration, and (e) reassociation. Figure 5 shows the complete 802.11 service architecture.

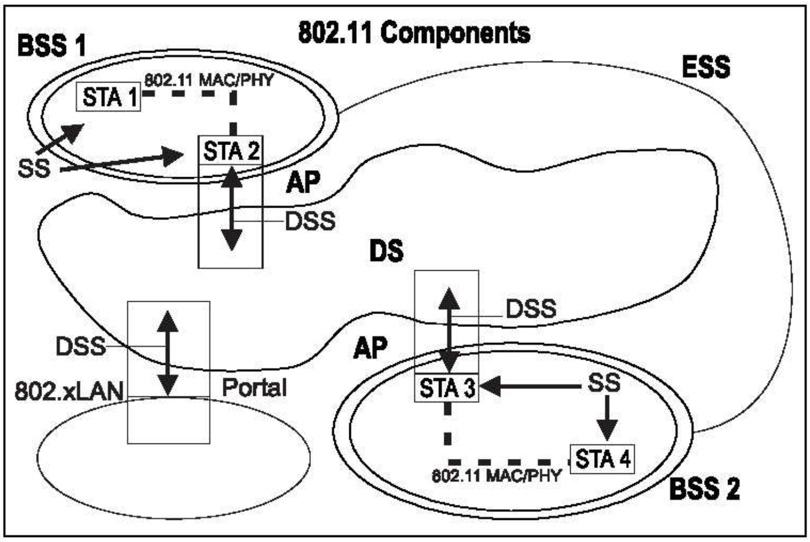


Figure 5: 802.11 service architecture

3 QoS limitations of 802.11 MAC

The most important functions of a wireless MAC layer include controlling channel access, maintaining QoS, and providing security. Wireless links have specific characteristics such as high loss rate, bursts of frame loss, packet re-ordering, large packet delay and jitter. Furthermore, the wireless link characteristics are not constant and may vary over time and place. Mobility of users may cause the end-to-end path to change when users roam. Users expect to receive the same QoS once changing their point of attachment. This implies that the new path should also support the existing QoS by service reservation, and problems may arise when the new path cannot support such requirements.

There are several ways to characterize QoS in WLAN such as parameterized or prioritized QoS [12]. Generally, QoS is the ability of a network element (e.g. an application, a host or a router) to provide some levels of assurance for consistent network data delivery. Parameterized QoS is a strict QoS requirement which is expressed in terms of quantitative values, such as data rate, delay bound, and jitter bound. In a Traffic Specification (TSPEC), these values are expected to be met within the MAC data service in the transfer of data frames between peer stations. Prioritized QoS is expressed in terms of relative delivery priority, which is to be used within the MAC data service in the transfer of data frames between peer stations. In prioritized QoS scheme, the values of QoS parameters such as data rate, delay bound, and jitter bound, may vary in the transfer of data frames, without the need to reserve the required resources by negotiating the TSPEC between the station and the AP. According to the definitions of QoS above, this section presents the QoS limitations of IEEE 802.11 MAC functions.

3.1 QoS limitations of DCF

DCF can only support best-effort services, not any QoS guarantees. Typically, time-bounded services such as Voice IP, audio and video conference require specified bandwidth, delay and jitter, but can tolerate some losses. However, in DCF mode, all the stations in one BSS or all the flows in one station compete for the resources and channel with the same priorities. There is no differentiation mechanism to guarantee bandwidth, packet delay and jitter for high-priority stations or multimedia flows. Throughput degradation and high delay are caused by the increasing time used for channel access contention. For example in Figure 6, there are three wireless stations WT1, WT2 and WT3 [3]. These stations are uniformly distributed around an AP and transmit their packets to a fixed host wired-attached to the AP. Only WT1 sends high priority traffic, the other stations send best-effort traffic. The wireless station WT1 starts sending CBR/UDP packets at time t = 50 second (s) and the sending rate is 1.76Mbps. The high priority application on station WT1 requires a minimal bandwidth of 1.0Mbps. During the second period $t \in [100s, 150s]$, a low priority station WT2 starts transmission. Then the two stations WT1 and WT2 share the medium equally since there is no service differentiation mechanism in DCF mode. During the third period $t \in [150s, 250s]$, another low priority station WT3 is also on. So, three stations have to share the channel, and station WT1 can only get bandwidth of about $700Kbps < 1.0Mbps$ (losing its QoS requirement). This experiment shows that no throughput differentiation is supported in DCF mode when there is an increase in the number of stations. Since all the stations share the medium with the same priorities, we cannot guarantee the QoS requirements for high-priority station. At the same time, delay, jitter and drop rate increase dramatically.

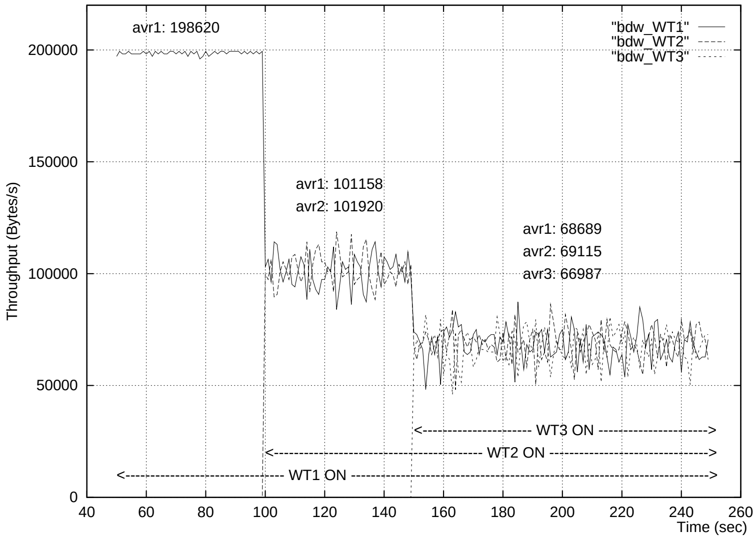


Figure 6: No service differentiation support in DCF

3.2 QoS limitations of PCF

Although PCF has been designed by the IEEE Working Group to support time-bounded multimedia applications, this mode has three main problems which leads to poor QoS performance [1, 6, 7, 34]:

The first problem is that its inefficient and complex central polling scheme deteriorates the performance of PCF high-priority traffic when the traffic load increases [6]. Moreover, in home networking, sometimes we just need direct communications between television (TV) and computer terminals. But according to the IEEE 802.11 standard [1], all the communications have to go through the AP in PCF mode. This mechanism degrades the bandwidth performance of WLAN.

The second problem of PCF comes from incompatible cooperation between CP and CFP modes which leads to unpredictable beacon delays [7, 34]. At Target Beacon Transition Time (TBTT), the Point Coordinator (PC) schedules the beacon as the next frame to be transmitted, and the beacon can be transmitted when the medium has been found idle for greater than a PIFS interval. Depending on whether the wireless medium is idle or busy around the TBTT, the beacon frame may be delayed sometimes. The time for which the beacon frame has been delayed, i.e., the duration it is sent after the TBTT, defers the transmission of time-bounded MSDUs (MAC Service Data Unit) that have to be delivered in the CFP mode. In the current 802.11 legacy standard, stations are allowed to start their transmissions even if the MSDU transmission cannot finish before the upcoming TBTT [1]. This may severely reduce the QoS performance by introducing unpredictable time delays in each CFP. In the worst case, the maximum beacon frame delays of around $4.9ms$ are possible in IEEE 802.11a. In the simulations of PCF performed in [7], the average beacon frame delays can reach up to $250\mu s$, see Figure 7.

The third problem of PCF is that transmission time of the polled stations is unknown. A station that has been polled by the PC is allowed to send a frame that may be fragmented into a different number of small frames. Furthermore, different modulation and coding schemes are specified in 802.11a, so the transmission time of the MSDU can change and is not under the control of the PC. This prevents the PC to provide QoS guarantees to other stations that are polled during the remaining CFP.

Such QoS problems for both DCF and PCF led to a large number of research activities to enhance efforts for 802.11 MAC (as discussed in Section 4).

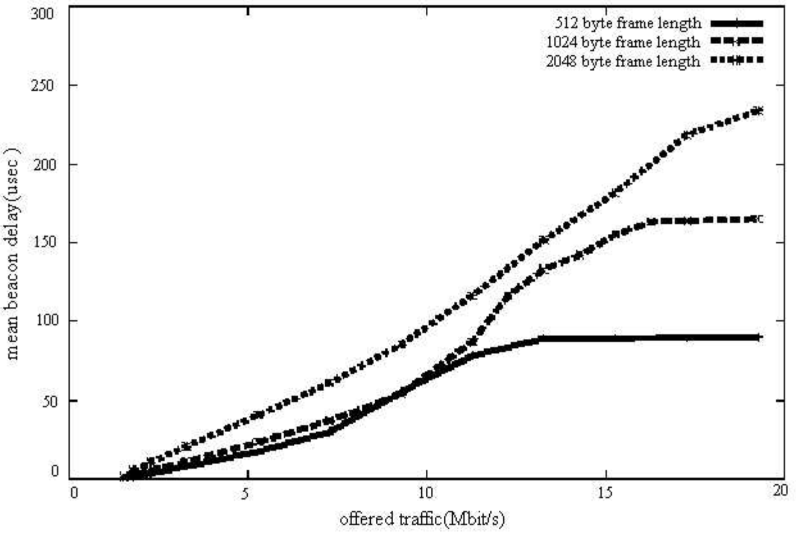


Figure 7: The problem of unpredictable beacon delay for different 802.11a PHYs [7]

4 QoS enhancement schemes for 802.11 MAC

Normally, the IP layer assumes that a LAN scarcely drops or delays packets. QoS issues in wired Ethernet (e.g. 802.3) have been neglected due to the relative ease with which the physical layer bandwidth has improved (1Gbps is now a common link speed between switches in enterprise LANs while 10 Gbps 802.3ae [31] will appear soon). However in WLANs, the challenges of the wireless channel make physical layer data rate improvements more difficult to achieve. IEEE 802.11 WLAN is originally designed for best-effort services. The physical layer's error rate is more than three orders of magnitude larger than that of wired LAN (802.3). High collision rate and frequent retransmissions cause unpredictable delays and jitters, which degrade the quality of real-time voice and video transmission. Enhanced QoS-aware coordination can reduce overhead, prioritize frames, and prevent collisions to meet delay and jitter requirements in mobile environment.

Currently, there are two main architectural approaches to add QoS support in the Internet: Integrated Services (IntServ) [25] and Differentiated Services (DiffServ) [26]. IntServ provides fine-grained service guarantees to individual flows. It requires a module in every hop IP router along the path that reserves resources for each session. However, IntServ is not widely deployed since its requirements of setting states in all routers along a path is not scalable. On the contrary, DiffServ only provides a framework offering coarse-grained controls to aggregates of flows. DiffServ attempts to address the scaling issues associated with IntServ by requiring state awareness only at the edge of DiffServ domains. At the edge, packets are classified into flows, and the flows are conditioned (marked, policed and possibly shaped) to a Traffic Conditioning Specification (TCS). In this way, simple and effective QoS can be built from the components during early deployments, and Internet-wide QoS can evolve into a more sophisticated structure. But until now, DiffServ has not been widely deployed mainly because it is difficult to map between different service domains or subnetworks such as 802.11 WLAN. The problems of both IntServ and DiffServ schemes led to the activities of Integrated Services over Specific Link Layers (ISSLL) Working Group at the IETF to provide IntServ over specific link technologies [44]. One of the key ideas is to provide IntServ QoS by using DiffServ network segments. This solution maintains the IntServ signalling, delay-based admission and the IntServ service definitions. The edge of the network consists of pure IntServ regions. However, the core of the network is a DiffServ region, and all flows are mapped into one of the few DiffServ classes at the boundary. So, in order to support both kinds of IP QoS approaches in 802.11 WLAN links, different kinds of QoS enhancement schemes for both infrastructure and ad-hoc modes have been proposed for 802.11 WLAN. In this section we classify and evaluate the performances of the main schemes. Since the services required by multimedia applications are based on parameters of bandwidth, delay, jitter and loss (or bit error) rate, we introduce bandwidth, delay and jitter based service differentiation in Section 4.1 and error control based enhancement schemes in Section 4.2.

4.1 Service (bandwidth, delay, jitter) differentiation based enhancement schemes

4.1.1 Classification of service differentiation based schemes

First of all, QoS enhancement can be supported by adding service differentiation into the MAC layer. This can be achieved by modifying the parameters that define how a station or a flow should access the wireless medium. Current service differentiation based schemes can be classified with respect to a multitude of characteristics. For example, a possible classification criterion is whether the schemes base the differentiation on per-station or per-queue (per-priority) parameters. Another classification depends on whether they are DCF-based (distributed control) or PCF-based (centralized control) enhancement. Figure 8 shows a classification in two levels. We distinguish between station-based schemes and queue-based schemes at the top-level and DCF-based versus PCF-based enhancement at the second level. Previous research works mainly focus on the station-based DCF enhancement schemes [3, 9, 10, 11]. Other recent works mainly focus on queue-based hybrid coordination (combined PCF and DCF) enhancement schemes [2,4,7,12-18,41] since queue-based schemes perform more efficiently.

4.1.2 Proposed schemes for service differentiation

(A) Station-based service differentiation using DCF enhancement

AC scheme: We denote in this paper the scheme proposed in [3] as AC scheme. To introduce priorities in the IEEE 802.11 using the DCF, Aad and Castelluccia propose three techniques in [3]:

(a) Different backoff increase function (also called scaling contention window scheme): each priority level has a different backoff increment function. Assigning a short contention window to those higher

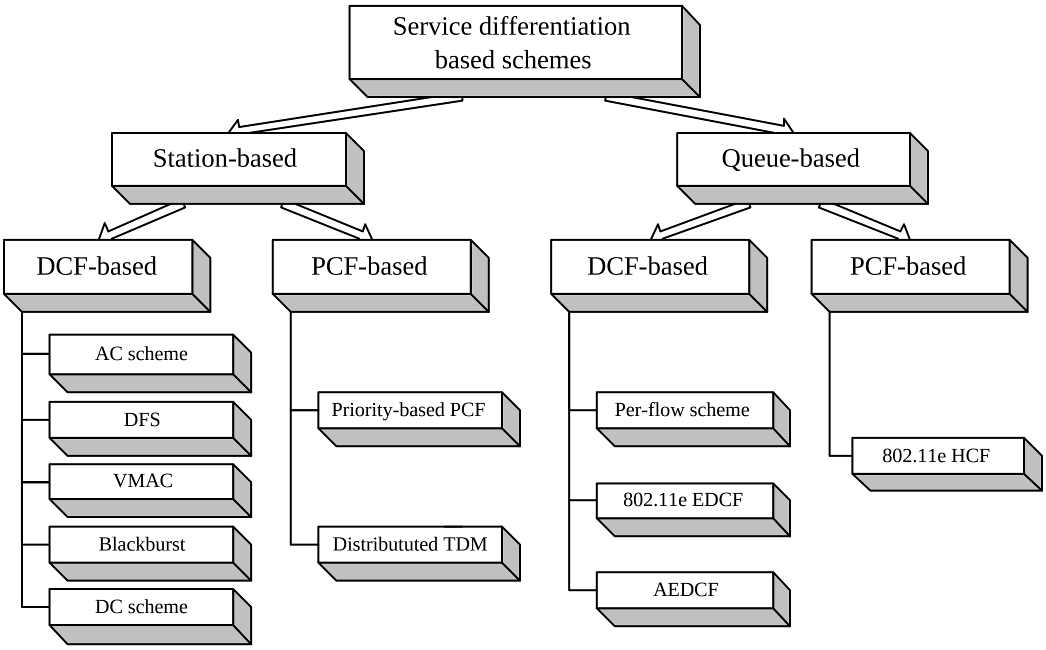


Figure 8: Classification of service differentiation based schemes

priority stations ensures that in most (although not all) cases, high-priority stations are more likely to access the channel than low-priority ones. This method modifies the contention window of the priority level j after i transmission attempts as follows: $CW_{new} = P_j^{2+i} \times CW_{old}$, where P_j is a factor used to achieve service differentiation which has the higher value for lower priority stations. Experiments show that this scheme performs well with UDP traffic but not well with TCP traffic because TCP ACKs affect the differentiation mechanism.

(b) Different DIFS: each station has a different DIFS according to its priority level. In IEEE 802.11, ACK packets have higher priority than RTS packets, simply by waiting for a SIFS which is shorter than DIFS (for RTS). The same idea is used to introduce priorities for data frames (in the basic scheme) and for RTS frame (in the RTS/CTS scheme). In this approach, each priority level has a different DIFS, for example, $DIFS_{j+1} < DIFS_j$. So before transmitting a packet, the stations having priority $j+1$ will wait for an idle period of length $DIFS_{j+1}$ slottime, which is shorter than that of station with priority j. To avoid collision between frames with a same priority, the backoff mechanism is maintained in a way that the maximum contention window size added to $DIFS_j$ is $DIFS_{j-1} - DIFS_j$. This ensures that no station of priority j has queued frames when station of priority $j-1$ starts transmission. The main problem of this scheme is that low priority traffic suffers as long as these high priority frames are queued. Sometimes the maximum Random Range (RR_j) after $DIFS_j$ can be greater than $DIFS_{j-1} - DIFS_j$, so the previous issue becomes less severe. In this case, a packet which failed to access the channel at the first attempt is likely to have its priority reduced after several consecutive attempts, depending on the DIFS and Random Range values. Experiments show that there is no backoff problem with TCP, but TCP ACKs also reduce the effects of service differentiation since all ACKs have the same priorities.

(c) Different maximum frame length: each station has a different maximum frame length according to its priority level. Here, two possibilities should be distinguished: one is either to drop packets that exceed the maximum frame length assigned to a given station (or simply configure it to limit its packet lengths), the other is to fragment packets that exceed the maximum frame length. This mechanism is used to increase both transmission reliability and differentiation, and works well for TCP and UDP flows. However, in a noisy environment, long packets are more likely to be corrupted than short ones, which decreases the differentiation efficiency of this scheme.

DFS scheme: In order to introduce better fairness, Vaidya et al. [8] propose an access scheme called Distributed Fair Scheduling (DFS) which utilizes the ideas of Self-Clocked Fair Queueing (SCFQ) in the wireless domain. In DFS, the backoff process is always initiated before transmitting a frame. The backoff interval calculated is proportional to the size of the packet to send and inversely proportional to the weight of the flow. This causes stations with low weights to generate longer backoff intervals than those with high weights, thus getting lower priority. Fairness is achieved by including the packet size in the calculation of the backoff interval, causing flows with smaller packet size to be sent more often. If a collision occurs, a new backoff interval is calculated using the original backoff algorithm of the IEEE 802.11 DCF. Moreover, various mapping schemes that can be used to choose the appropriate backoff interval are investigated. The throughput achieved by the exponential and square-root mapping schemes is higher than that with linear mapping scheme when the backlogged flows have low weights.

VMAC scheme: Based on DCF, Campbell et. al. [11] propose a fully distributed service quality estimation, radio monitoring, and admission control approach to support service differentiation. A Virtual MAC (VMAC) algorithm monitors the radio channel and estimates locally achievable service levels. The VMAC estimates MAC level statistics related to service quality such as delay, jitter, packet collision, and packet loss. The VMAC algorithm operates in parallel to the MAC in the mobile host but does not handle real packet transmission like in MAC. This is why it is called virtual MAC. The advantage of virtual MAC is that it can estimate higher order statistics than first-order performance statistics without too much overheads. By this way more sophisticated analyses and traffic control methods can be applied. Moreover, a Virtual Source (VS) algorithm can utilize the VMAC to estimate application-level service quality. The VS allows application parameters to be tuned in response to dynamic channel conditions based on "virtual delay curves". The goal of the VMAC is to estimate QoS parameters in the radio channel accurately since relative service differentiation is not enough for real-time services. Moreover, this scheme uses the following backoff timer differentiation: $CW_{min}^{high\_pri} < CW_{min}^{low\_pri}$, $CW_{max}^{high\_pri} < CW_{max}^{low\_pri}$. VMAC simulation results show that: (a). when these distributed virtual algorithms are applied to the admission control of the radio channel, then a globally stable state can be maintained without the need for complex centralized radio resource management. (b). delay differentiation can be increased by increasing the gap between $CW_{min}^{high\_pri}$ and $CW_{min}^{low\_pri}$, i.e., decreasing $CW_{min}^{high\_pri}$ and increasing $CW_{min}^{low\_pri}$ give high priority traffic lower delay than before, and low priority traffic higher delay than before. However, one drawback of the virtual algorithm is that it consumes extra processing capacity in the mobile host [11].

Blackburst scheme: The main goal of Blackburst [10] is to minimize the delay of real-time traffic. Unlike the other schemes, it imposes certain requirements on high priority stations: 1) all high priority stations try to access the medium with equal and constant intervals, t_{sch}, and 2) the ability to jam the medium for a period of time. When a high priority station wants to send a frame, it senses the medium to see if it has been idle for a PIFS and then sends its frame. If the medium is busy, the station waits for the medium to be idle for a PIFS and then enters a black burst contention period: the station sends a so-called black burst to jam the channel. The length of the black burst is determined by the time the station has waited to access the medium, and is calculated as a number of black slots. After transmitting the black burst, the station listens to the medium for a short period of time (less than a black slot) to see if some other station is sending a longer black burst which would imply that the other station has waited longer and thus should access the medium first. If the medium is idle, the station will send its frame, otherwise it will wait until the medium becomes idle again and enters another black burst contention period. By using slotted time, and imposing a minimum frame size on real time frames, it can be guaranteed that each black burst contention period will yield a unique winner [10]. After the successful transmission of a frame, the station schedules the next transmission attempt t_{sch} seconds in the future. This has the nice effect that real-time flows will synchronize, and share the medium in a TDMA (Time Division Multiple Access) fashion [10]. In Blackburst scheme, low priority stations use the ordinary CSMA/CA access method of IEEE 802.11. This means that unless some low priority traffic comes and disturbs the order, very few blackburst contention periods will have to be initiated once the stations have synchronized. The main drawback of Blackburst is that it requires constant access intervals for high-priority traffic, otherwise the performance degrades considerably.

DC scheme: We denote in this paper the scheme proposed in [9] as DC scheme. Deng and Chang propose a service differentiation scheme [9] which requires minimal modifications of the basic 802.11 DCF. This scheme uses two parameters of IEEE 802.11 MAC, the backoff interval and IFS between each data transmission, to provide the differentiation. Thus, the backoff time is divided into two parts and each interval is combined with two different IFS lengths PIFS and DIFS, as shown in Table 1. Where rd is a uniform variable in $(0, 1)$, and $\lfloor x \rfloor$ represents the largest integer less than or equal to x. Therefore, four classes of priorities can be supported. A station that uses PIFS gets higher priority than a station using DIFS.

Priority	IFS	Backoff algorithm
0	DIFS	$B = 2^{2+i}/2 + \lfloor rd \times 2^{2+i} \rfloor$
1	DIFS	$B = \lfloor rd \times 2^{2+i} \rfloor$
2	PIFS	$B = 2^{2+i}/2 + \lfloor rd \times 2^{2+i} \rfloor$
3	PIFS	$B = \lfloor rd \times 2^{2+i} \rfloor$

Table 1: DC scheme's priority classes

(B) Station-based service differentiation using PCF

Priority-based PCF [6, 33]: Since PCF is optional in 802.11 standard, not too much research works extend station-based PCF to support service differentiation. However, PC (Point Coordinator) can be used to provide service differentiation support using a priority-based polling scheme instead of the default round-robin polling scheme. Indeed, the AP sends priority-based polling packets to a succession of stations in the wireless BSA (Basic Service Area), which can give different stations different priorities.

Distributed TDMA: This mechanism does not modify the polling scheme of PCF, but sets up Time Division Multiplexing Access (TDMA)-like timeslot periods, and specifies which station gets which timeslot to provide differentiation. Once the timeslots have been assigned, each station knows when it can transmit, and packet transmissions can take place with very little intervention from the AP (in contrast with PCF, where the AP has to use its polling capability to direct the transfer of every frame to be sent).

(C) Queue-based service differentiation using DCF

Per-flow scheme [4]: The motivation to use queue-based differentiation scheme comes from the following observations: (1). In station-based schemes, when several TCP senders with different priorities share the same receiver, they all receive the TCP-ACKs with the same priority (limited to the same receiver priority). This tends to reduce the differentiation effect. Furthermore, if the shared receiver is slow, the observed relative priority is also reduced. (2). Moreover, when one sender sends two flows to two receivers, differentiation effect will also reduce. Since there is a multi-path fading effect in wireless channel, one receiver may stay in a good channel condition (e.g. low error rate), another receiver may stay in a bad channel condition (e.g. high error rate), which causes the contention window of the sender to be large. So it is unfair to the first receiver. These two issues motivate the use of per-flow or per-queue differentiation where the shared node uses different priorities for different flows. The authors in [4] introduce a per-flow differentiation, and all packets are put in the same queue, independent of their priorities. But this scheme introduces mutual interferences between priorities: when the AP serves a low priority and slow flow, the global speed and efficiency of AP depends on the occupation time of this slow flow. If most of the time this flow occupies the AP, even if there are other high-priority fast flows, the AP has to be slow, and service differentiation gets lower. A possible solution is to assign to a priority to each of the different queues in the AP like 802.11e EDCF. Simulations [4] show that there is a total independence between priorities: even if a low priority flow passes through the AP, it does not slow down the AP (the shared node), and differentiation effect is much better than one-queue per-flow scheme. Note that when using this approach with CWmin differentiation, the collision rate of the shared node (e.g. the AP) is less than that of wireless stations. In fact, when a single queue per MAC sub-layer is used, we just have one packet per station contending to access the channel. However, when a station has several queues for multiple TCP connections, there are multiple packets per CW period. Internal collisions in one station will increase when there is an increase in the number of connections. This tends to use the TXOP (Transmission Opportunity) scheduler in EDCF scheme [2].

EDCF [2]: To introduce better queue-based differentiation performance than per-flow scheme, IEEE 802.11e EDCF extends the basic DCF to support up to eight queues in one station and each queue contends for TXOP (Transmission Opportunity) in one station to send the packets. We will discuss EDCF in detail in section 5.

AEDCF [41]: One problem of the basic EDCF ad-hoc mode is that the values of CW_{min}, CW_{max} and backoff function of each queue are static and cannot take into account dynamicity of wireless channel conditions [2]. In AEDCF (Adaptive EDCF) scheme, relative priorities are provisioned by adjusting the size of the contention window of each traffic class taking into account both application requirements and network conditions. After each successful transmission, AEDCF does not reset the contention window to CW_{min}. Instead, the scheme takes into account the estimated collision rate in each station noted by f^j_{curr}. A multiplicator factor for each class i is introduced by: $MF[i] = min((1 + 2 \times i) \times f^j_{curr}, 0.8)$, where $f^j_{avg} = (1 - \alpha) \times f^j_{curr} + \alpha \times f^{j-1}_{avg}$. Then, the contention window is updated as follows: $CW_{new}[i] = max(CW_{min}[i], MF[i] \times CW_{old})$. After each collision, a persistence factor $PF[i]$ is introduced in AEDCF for further differentiation. Performance comparisons between AEDCF and 802.11e EDCF scheme show that AEDCF outperforms the EDCF, especially at high traffic load conditions: AEDCF increases the medium utilization ratio and reduces more than 50% of the collision rate. While achieving delay differentiation, the overall goodput obtained is up to 25% higher than EDCF.

(D) Queue-based service differentiation using PCF

HCF [2, 18]: HCF (Hybrid Coordination Function) is a queue-based service differentiation scheme using both PCF and DCF enhancements, which is proposed by IEEE 802.11e working group. It combines the advantages of both distributed contention access (EDCF) and centralized polling access (PCF) methods. HCF uses QoS access point (QAP) as a traffic director for different queues and cooperate with distributed EDCF. The QAP uses a polling technique as the traffic control mechanism and establishes a polling priority based on what the QoS priority should be. HCF is discussed in detail in Section 5.

4.2 Error control based enhancement schemes

In parallel, QoS enhancement can also be obtained by error control enhancements. In the Internet architecture, the end-to-end reliability should be entirely provided by the end nodes. The Internet may occasionally drop, corrupt, duplicate or reorder packets. So, the transport protocol (e.g., TCP) or the application itself (e.g., if UDP is used as the transport protocol) must recover from these errors on an end-to-end basis. Error recovery in the subnetwork is justified only to the extent that it can enhance overall performance. However, some subnetworks like wireless links require link layer error recovery mechanisms to enhance the performance, these enhancements should be lightweight. For example, wireless links normally require link-layer error recovery (such as 802.2 LLC) and MAC-level error recovery in subnetwork. Generally, there are two basic categories of error recovery schemes: ARQ (Automatic Repeat reQuest) [19,21-22,27-28] and FEC (Forward Error Correction) [20, 40].

4.2.1 (Automatic Repeat reQuest (ARQ)

ARQ is an error control protocol which is mostly implemented at both link and transport layers. It may cause a large delay when a lot of retransmissions are introduced on a slow link. But on a high speed local WLAN channel, the round trip delay is very small, so ARQ is an efficient method to be used.

(A) Stop and Wait ARQ (SW-ARQ) [20]

SW-ARQ is the simplest and a more efficient technique for data communications. A SW-ARQ protocol transmits a single packet and then waits for the response. The receiver sends an Acknowledgement (ACK) for each packet correctly received, or a Negative Acknowledgement (NACK) in case of packet loss. If there is no response after a time out, the sender retransmits the packet. Under normal transmission, the sender receives an ACK for the data and then starts transmission of the following data packet. The sender may have to wait a considerable time for this response. While it is waiting, the sender is unable to send other packet. In fact, the current MAC mechanism of IEEE 802.11 WLAN uses this kind of error control since it is more efficient and simpler than FEC [28, 1].

(B) Selective Repeat ARQ (SR-ARQ) [21]

Unlike SW-ARQ, when using SR-ARQ, packets are transmitted continuously by the Data Link Control (DLC) layer. The receiver acknowledges each successfully received packet, bearing the sequence number of the packet being acknowledged. If the acknowledgment is not received for a packet after the expiration of a timeout, the packet is retransmitted. Once a packet has been retransmitted, the sender resumes transmission of packets from where it left off, i.e., if j is the packet with the largest sequence number that has been transmitted, packet with sequence number j+1 is transmitted next (assuming that no other timers have expired in the meantime). Note that with SW-ARQ mechanism, there is much idle time that is wasted for waiting the sequenced ACKs. When the SR-ARQ protocol is used, packets are continuously transmitted, which eliminates the idle time associated with SW-ARQ. In fact, when SR-ARQ is used, packets can be accepted out of sequence. Hence, packets received out of sequence have to be buffered and re-sequenced before they can be delivered to the application layer. Indeed, SR-ARQ is the most efficient scheme for saving end-to-end delay. However, it is the most complex error recovery mechanism.

(C) Go-Back-N ARQ (GBN-ARQ) [21]

When GBN-ARQ is used, packets are transmitted continuously as in SR-ARQ. However, the receiver accepts packets only in the order in which they have been transmitted. The packets received out of sequence are discarded and not acknowledged. Since the receiver accepts packets only in-sequence, the sender retransmits the packet that timed out and all the following packets. Hence, each time a timeout occurs, all the packets that have not been acknowledged are retransmitted. It is important to observe that GBN-ARQ attempts to combine the desirable features of SR-ARQ and SW-ARQ, i.e., packets are transmitted continuously, as in SR-ARQ scheme, without the need to buffer out of sequence packets and there is no re-sequencing overhead.

4.2.2 Forward Error Correction (FEC)

FEC involves addition of redundant bits that help to recover erroneous bits. It has been suggested for real-time applications due to the strict delay requirements and semi-reliable nature of media streams. However, FEC incurs constant transmission overhead even when the channel is error free [20, 40].

In ARQ scheme, the receiver requests retransmission when it detects an error, but ARQ leads to variable delays which are unacceptable for real-time services. FEC scheme maintains homogeneous throughput and bounded time delay. However, the decoding error rate of FEC increases rapidly with the increase of channel error rate. So when channel error rate is high, a long FEC code is necessary. This makes the coder-decoder pair complex and also imposes a high transmission overhead. Furthermore, the wireless channel is non-stationary and the channel bit error rate varies over time. Only FEC or ARQ scheme is not very efficient for high-speed error-prone WLAN channel. In order to overcome their individual drawbacks, hybrid FEC-ARQ schemes have been developed [19, 22, 27, 29]. In the next subsection we present two kinds of error control mechanisms that combine FEC with ARQ: Type-I and Type-II Hybrid FEC-ARQ schemes.

4.2.3 Hybrid FEC-ARQ

(A) Type-I Hybrid FEC-ARQ

The Type-I Hybrid FEC-ARQ suggests sending data and proactively transmitting FEC repairs, but retransmitting data frames directly if these FEC correction repairs are insufficient. The sender retransmits the same codeword. When the retransmitted codeword is received, the decoder attempts to correct the errors within the error capability of the code. If the packet arrives with detectable and uncorrectable errors, the receiver discards the received codeword and a retransmission is requested again. This process continues until the packet is successfully received or the maximum number of retransmissions has been reached.

(B) Type-II Hybrid FEC-ARQ

Type-II Hybrid FEC-ARQ uses FEC to send repairs based on retransmission requests. Unlike the Type-I hybrid scheme, the receiver saves the packet which cannot be successfully decoded while requesting for a retransmission [19, 22]. In case the packet cannot be successfully decoded at the destination, the receiver uses the saved code to help the decoding processor to correct the detected errors. Note that the transmitter can use different codewords in the retransmissions. The design of hybrid error control schemes is critically dependent on the application itself. Furthermore, the throughput and delay which are expected to be improved, depend mainly on the coding scheme and the channel error probability.

SW-ARQ is the current mechanism used in the 802.11 MAC layer because it is very simple and easy to be deployed. The other proposed techniques such as Type-I Hybrid FEC-ARQ and Type-II Hybrid FEC-ARQ schemes are able to reduce delay for high priority traffic. They are meant to be used in the next-generation high-throughput wireless networks [43]. But their implementation is complex despite of their benefits. Therefore, an overall optimal solution does not exist because many conditions need to be considered.

In the new IEEE 802.11e [2], MAC-level FEC can also be used to enhance the error control in WLANs in conjunction with ARQ and physical layer error correction. However, the co-existence of PHY/LLC/MAC layers and higher layer error recovery can lead to inefficient interactions between the different layers. For example, when the link layer retransmits (segments of) a packet, the link latency momentarily increases. Since TCP (or some UDP-based multimedia applications) bases its retransmission timeout on prior measurements of end-to-end latency (including that of the lossy link), this sudden increase in latency may trigger an unnecessary retransmission by TCP of a packet currently retransmitted by the link layer. Such spurious end-to-end retransmissions generate unnecessary load and reduce end-to-end throughput. One may even have multiple copies of the same packet in the same link queue at the same time. It is necessary to optimize the error control schemes at different layers and provide efficient signaling between upper and lower layers.

5 Upcoming IEEE 802.11e QoS enhancement standard

IEEE 802.11 TGe was firstly formed in September 1999, the Project Authorization Request (PAR) was approved in March 2000 [23]. In the PAR it defined the scope and purpose of the TGe project: enhancing the 802.11 MAC (DCF, PCF) to support QoS, providing the classes of service, enhanced security and authentication mechanism. It aims to enhance the ability of all the physical layers of 802.11b, 802.11a and 802.11g to deliver time-critical multimedia data, in addition to traditional data packets. As comparised with original 802.11 MAC, 802.11e can support 10 types of services, the new service is QoS-capable WLAN application. There are many new features in 802.11e draft 3.0 [2] such as HCF, direct communication/side traffic, WARP, AP mobility, MAC-level FEC, etc. to support new QoS applications. In the remainder of this section, we firstly describe the main new features of the IEEE 802.11e draft 3.0, secondly we present the applications that the 802.11e standard can support and thirdly we present simulation-based evaluations of the IEEE 802.11e.

5.1 Main new features of 802.11e standard

5.1.1 HCF: Hybrid Coordination Function

In order to support both IntServ and DiffServ QoS approaches in 802.11 WLAN, TGe has defined a new mechanism of Hybrid Coordination Function (HCF). This mechanism is backwardly compatible with basic DCF/PCF. It has both polling-based and contention-based channel access mechanisms in a single channel access protocol. HCF is composed of two access methods: EDCF and HCF controlled channel access mechanisms, which are respectively detailed in sub-sections (A) and (B). According to the definition of QoS classification in Section 3, three QoS levels are supported in HCF (see Table 2):

QoS levels	Channel access mechanism	Scheduling policy
Level 3	HCF (EDCF and HCF controlled channel access)	parameterized
Level 2	HCF (EDCF and HCF controlled channel access)	prioritized
Level 1	HCF (EDCF only)	prioritized
Level 0	DCF, PCF	none

Table 2: QoS levels in HCF

In 802.11e, two types of signalling can be used for traffic originating at clients. The first one uses a connectionless queue state indicator, which is based on the arrival rate measurements, supporting 802.1D priority and IP DiffServ accordingly. With this kind of signalling, only notification between the peer entities is used, but there is no negotiation between peer entities. The second one negotiates a traffic specification (TSPEC) between AP and wireless stations and it is based on RSVP (ReSerVation Protocol). It is a MAC layer service negotiation and resource reservation that provides more strict and parameterized services.

A station (STA) that implements both the QoS facility and HCF function is denoted by QSTA (QoS Station) in IEEE 802.11e [2]. A Hybrid Coordinator (HC) is defined as a centralized controller in one QBSS (QoS Basic Service Set), which implements the frame exchange sequences and MSDU handling rules defined by the HCF. The HC operates during both the Contention Period (CP) and Contention Free Period (CFP). It performs bandwidth management including the allocation of Transmission Opportunities (TXOPs) to QSTAs and the initiation of Controlled Contention Intervals (CCIs). A QBSS is defined as a specific BSS which includes an 802.11e-compliant HC and stations. The HC typically resides within an 802.11e AP (also called QAP). A QAP differentiates frames with different traffic identifiers within the traffic, which are to or from each associated QSTA. Indeed, a QAP provides at least 4 access categories (ACs). With 802.11e, a superframe (also called beacon interval) is composed of two modes CFP and CP, which alternate over time continuously. The EDCF is used in the CP mode only, while the HCF is used in both modes, which explains why it is called hybrid coordination function. Note that in the basic 802.11, PCF is an optional function, whereas HCF is a mandatory function defined in 802.11e [2]. A TXOP is defined as the interval of time when a station has the right to initiate transmissions to the wireless medium. The TXOP is denoted by a starting time and a maximum duration. During the CP, each TXOP begins either when the medium is determined to be available under the EDCF rules (EDCF-TXOP), or when the station receives a special polling frame (polled-TXOP) from the HC. This special polled-TXOP frame from the HC can be sent after a PIFS idle period without any backoff limit. So the HC can issue the polled-TXOPs in the CP using the prioritized medium access. The duration of an EDCF-TXOP is limited by a QBSS-wide TXOP limit distributed in beacon frames, while the duration of a polled-TXOP is specified in the frame header of a special QoS (+)CF-Poll packet. Each QoS station (QSTA) makes local decisions which MPDUs (MAC Protocol Data Units) can be transmitted during each TXOP interval. By this way, internal collision in one station is avoided. In the following subsections (A) and (B), we describe HCF (e.g. EDCF and HCF controlled channel access mechanisms) in detail.

(A) EDCF: Enhanced Distributed Coordination Function

EDCF is a contention-based HCF channel access scheme [2]. It is part of the HCF, but not a separate coordination function. The goal of this extension is to enhance current DCF access mechanisms of IEEE 802.11 to support service differentiation using a distributed control approach. Both contention-free and contention-based channel access mechanisms are provided by a HC in the CP. The proposed approach provides capability for up to 8 different traffic classes (8 queues) in one mobile staion, see Figure 9. Each QSTA may have up to 8 Access Categories (ACs), i.e. 8 queues at MAC layer to support 8 User Priorities (UPs). In each station, one or more applications' user priorities (UPs) are assigned to each AC. Different from mobile station, a QAP shall support at least 4 ACs. In EDCF, relative priorities are provisioned by configuring the time to access the channel once it is sensed idle and by changing the size of the contention window. EDCF uses the contention window to change the priority of each traffic category. Assigning a short contention window to a high priority class ensures that in most cases, high-priority class is able to transmit ahead of low-priority one. Indeed, the CWmin, CWmax parameters can be set differently for different priority classes, for example, a high priority traffic with small CWmin and CWmax. For further differentiation, various InterFrame Spaces (IFSs) can be used by different traffic classes, see Figure 10. Instead of using a DIFS, a new kind of interframe space called Arbitration Interframe Space (AIFS) is used in EDCF. The AIFS for a given class should be a DIFS plus some (possibly zero) time slots. Class with a small AIFS has a high priority. Each different Traffic Category (TC) within the station, behaves like a virtual station. It contends to access to the medium and starts independently its backoff time after sensing the medium idle for at least AIFS. If the backoff counters of two or more parallel TCs in one station reach zero at the same time, a scheduler inside the station avoids the virtual collision by granting the TXOP to the highest priority Traffic Category (TC) or Access Category (AC), see Figure 9. At the same time, the lowest priority colliding ACs behave as if there is an external collision on the wireless medium. However, this collision behavior does not include setting retry bits in the MAC headers of MPDUs at the heads of lower priority ACs. Since EDCF can only solve the problem of internal collisions for high-priority traffic, there is still a possibility that external collisions between stations occur [7].

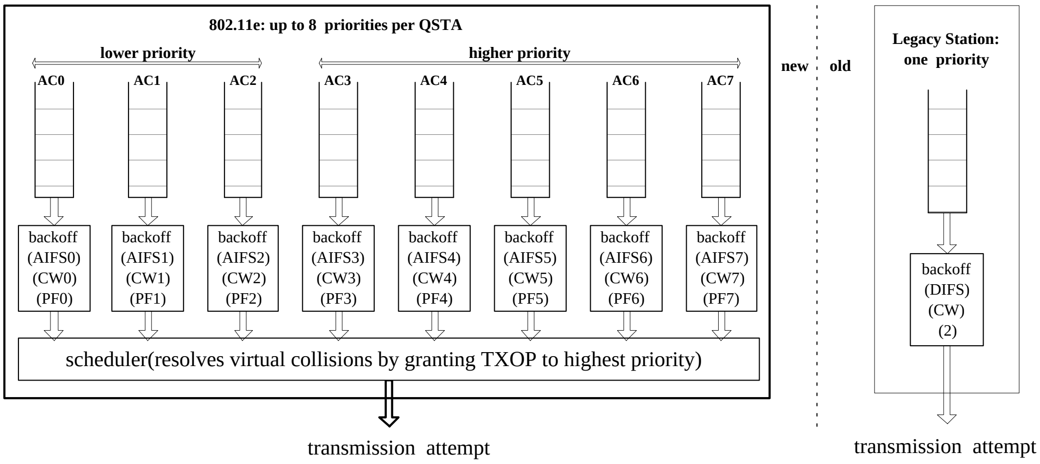


Figure 9: 802.11e EDCF vs Legacy DCF

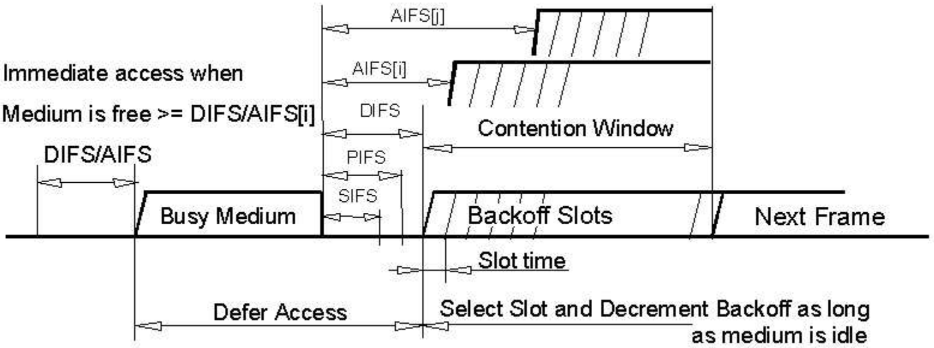


Figure 10: Some IFS Relationships

To enhance the performance and achieve better medium utilization, packet bursting such as EDCF bursting and Contention Free Burst (CFB) can be used in 802.11e [2,15-16], meaning that once a station has gained access to the medium, it can be allowed to send more than one frame without contending for the medium again. After getting access to the medium, the station is allowed to send as many frames it wishes as long as the total access time does not exceed a certain limit, e.g. TxOpLimit. To ensure that no other station interrupts the packet bursting, a shorter IFS (i.e. SIFS) than usual is used between packets. If a collision occurs, the packet bursting is terminated. EDCF bursting can reduce the network overhead and increase throughput by multiple transmissions using SIFS and burst acknowledgements. EDCF bursting can also provide better fairness among the same priority queues since it is independent from the frame sizes. However, EDCF bursting may increase the delay jitter, so TxOpLimit should not be longer than the time required for the transmission of the largest data frame. At the same time, Contention Free Burst (CFB) can solve two kinds of problems of PCF: (1) The CFP can only be sustained if the queues on the AP or stations are adequately backlogged. Light-loaded conditions cause early termination of the CFP and forces the system to operate in the DCF mode uncorrectly. By using multiple short CFB intervals, the HC can temporarily give up medium control (to possibly another QBSS) and defer control until new frames of other CFBs are available. (2) The PCF does not work very well when multiple BSSs overlap. By using the CFB, the HC can relinquish medium control to other QBSSs in the same area to solve the problem of BSS overlap [16].

(B) HCF controlled channel access

The HCF controlled channel access mechanism uses an HC, which operates under different rules than the Point Coordinator (PC) of the PCF. The HC is collocated with the QoS enhanced Access Point (QAP) of the QoS Basic Service Set (QBSS). It uses the PC's highest priority to access the wireless medium, initiate frame exchange sequences and allocate TXOPs to Wireless Stations (WSTAs). HC traffic delivery and TXOP allocation may be scheduled during both CFP and CP in order to meet the QoS requirements of particular Traffic Categories (TCs) or Traffic Streams (TSs). Contention free transfers of traffic from the HC can be based on the HC's QBSS-wide knowledge of the amounts of pending traffic belonging to different TSs and TCs.

In HCF controlled channel access mode, Controlled Access Periods (CAP) are defined as several intervals within one CP when short bursts of frames are transmitted using polling-based controlled channel access mechanisms. During the remainder of the CP, all frames are transmitted using the EDCF contention-based rules. Figure 11 shows the relationship of CFP, CP and CAPs within one 802.11e superframe [14]. CAPs may also include Controlled Contention Intervals (CCIs), during which contention occurs only when QSTAs need to request new TXOPs. Basically, Integrated Services (IntServ) such as Guaranteed Services [45], e.g. strict bandwidth, delay, and jitter bounds requirements cannot be provided absolutely using the pure EDCF. By introducing Controlled Contention (CC) in

CAP, the HCF model can provide Guaranteed Services with a much higher probability than pure EDCF, specially under heavy load. A signaling protocol can be used to facilitate admission control and specify service rate requirements during the period of CCI. Different from pure EDCF, the HCF controlled channel access mechanism effectively provides policing and deterministic channel access by controlling the channel. Controlled Contention (CC) is a way for the HC to learn which station needs to be polled, at which time, and for which duration. The CC mechanism allows stations to request the allocation of polled TXOPs by sending Reservation Request (RR) frame, without contending with other EDCF or DCF traffic. The Controlled Contention Interval (CCI) is started when the HC sends a specific control frame. This specific control frame forces legacy stations to set their NAVs until the end of the CCI, thus legacy stations keep silent during the CCI. This control frame defines a number of Controlled Contention Opportunities (CCOP, i.e., short intervals separated by SIFS interval) and a filtering mask containing the Traffic Categories (TC) in which Reservation Request (RR) may be placed. Each station with queued traffic for a TC matching the filtering mask chooses one CCOP interval and transmits a RR frame containing its requested TC and TXOP duration, or the queue size of the requested TC. For fast collision resolution, the HC acknowledges the RR frame by generating a control frame with a feedback field so that the requesting stations can detect collisions during the CCI.

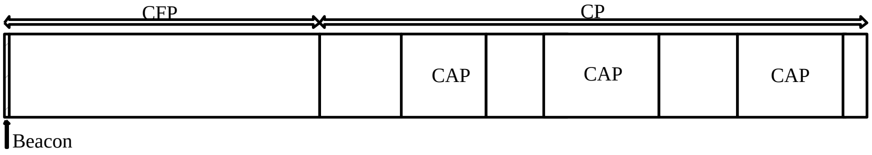


Figure 11: Relationship of CFP, CP and CAP within one superframe

Moreover, the HC provides improved protection of the CFP using virtual carrier sense mechanism which solves the problem of unpredictable beacon delay, see Section 3.2. In the 802.11 legacy standard [1], this protection solely depends on having all the stations in the BSA (Basic Service Area) setting their NAVs to the value of the maximum duration of CFP at TBTT (Target Beacon Transmission Time). The CFP ends after the time announced in the beacon frame or by a CF-End frame sent from the HC. Figure 12 is an example of typical 802.11e superframe (also called beacon interval) [7, 14]. While in controlled channel acces mechanism, polled-TXOP is used to determine which station can send traffic and how long. The HC sends a frame of QoS Data+CF-Poll+CF-Ack, piggybacking an MPDU with the ACK to the QoS data. So, the QSTA's initial TXOP limit is extended by this piggybacked frame of additional CF-Poll. More delay-bounded data frames can be sent by this controlled channel access mechanism, see Figure 13 [18].

5.1.2 Direct communication (also called Side Traffic)

In the basic 802.11 specification [1], traffic are only allowed to run between stations and AP in an infrastructure network. Stations cannot send traffic to each other without connection with AP. 802.11e [2] adds capability for stations to send traffic directly to each other in the infrastructure mode, which significantly improves the bandwidth, especially in home networks. In other words, direct communication means that two wireless stations (WSTAs) can communicate with each other without any intermediate entity. The setup of direct communication is illustrated in Figure 14 and consists of the following steps:

(a) Registration. WSTA2 sends a request to the QAP to use the direct communication option.

(b) Location discovery procedure. It consists of an exchange of management action frames with the QAP:

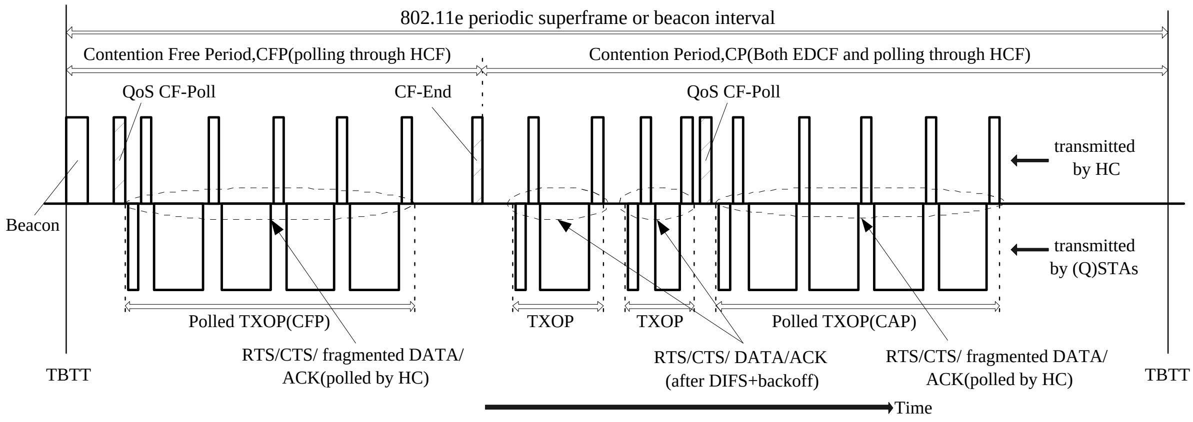


Figure 12: A typical 802.11e HCF superframe (both CFP and CP)

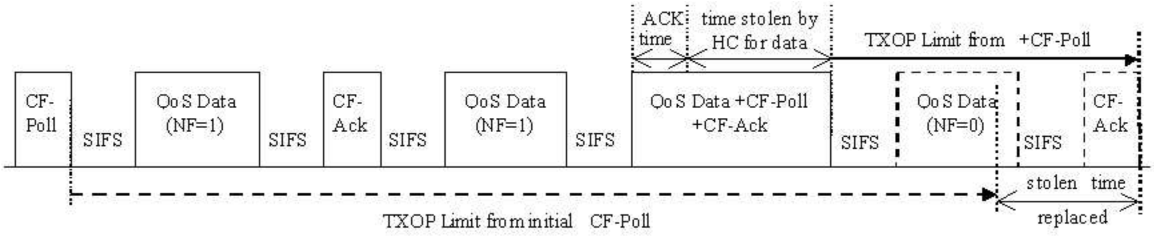


Figure 13: Polled TXOP

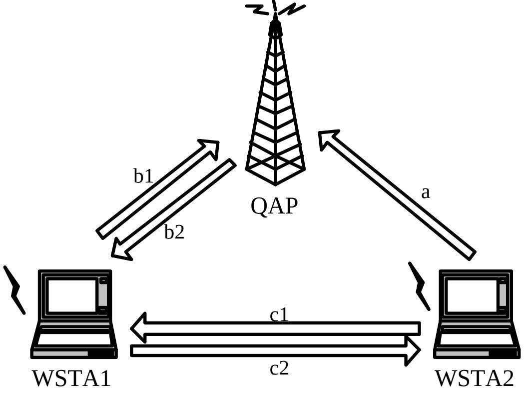


Figure 14: Direct communication setup

b1) A transmitting WSTA1 that has traffic to send to WSTA2, sends an inquiry MAC Management Protocol Data Unit (MMPDU) to the QAP in order to determine whether the WSTA with that specific MAC address is likely to be available for direct communication.

b2) The QAP sends a response MMPDU, indicating that the WSTA with that MAC address is in its QBSS area and wants to participate in direct communication.

(c) Direct negotiation procedure. It occurs after a successful location discovery procedure, and consists of an exchange of management action frames between the two WSTAs:

c1) WSTA1 sends a direct communication setup request MMPDU to WSTA2 to select the required data rate and power level.

c2) WSTA2 sends a correspondent reply MMPDU to WSTA1, using the same rate required.

Any of the above steps may fail and cause the setup attempt to be aborted. For example, if the receiver has not registered its request to receive direct traffic with the QAP, the QAP will return a location discovery response action frame indicating a failure. So in this case, the transmitting WSTA would not proceed to the direct negotiation procedure. If after a successful location discovery procedure, transmission of the direct communication setup request fails, the transmitting station should send a new set up request with a lower data rate.

5.1.3 Wireless Address Resolution Protocol (WARP)

The Wireless Address Resolution Protocol (WARP) [2] is used by stations in order to determine whether it is possible and optimal to transmit frames using the direct communication option in the infrastructure mode. This protocol does not apply in a QoS Independent Basic Service Set (QIBSS), since in that case frames are always sent directly from one station to another. WSTAs that wish to send frames using direct mode maintain a WARP cache, which contains the list of known destination MAC addresses and associated data required to send direct frames. Completion of the direct communication setup procedure results in an entry being added to the WARP cache. An entry in the WARP cache indicates that the associated MAC address is not reachable directly. A transmitting WSTA can only send frames in direct mode if it has a WARP cache entry indicating that it can do at that time. By default all frames must be sent via the Distributed System (DS). Stations may arbitrarily disable WARP cache entries, but can only enable them after successful completion of the direct communication setup procedure.

5.1.4 AP mobility

In the 802.11e, AP mobility [2] is introduced by a concept of QAP-Capable station (i.e. QAPC-STA). Actually, it does not mean real physical movement of an Access Point (AP). Such a QAP-capable station (QAPC-STA) is allowed to operate either as a real QoS AP (QAP) or a wireless station (WSTA). A QAPC-STA can be enabled or disabled depending on the parameters of the MLME (MAC Layer Management Entity)-START.request primitive [2]. A disabled QAPC-STA operates only as a WSTA. While an enabled QAPC-STA can work in active or inactive mode. An active QAPC-STA acts as a QAP and provides all the functionalities of a QAP. But an inactive QAPC-STA just operates as a WSTA. An active QAPC-STA is backwardly compatible with an AP, and thus is able to function as an AP for legacy STAs. By introducing the concept of QAPC-STA, an AP can continue (with reassociations) the operation of a particular Service Set IDentifier (SSID) if it moves out of range or becomes unavailable from the original SSID. So in the 802.11e draft 3.0 [2], AP mobility means the transfer of the AP function between different QAPC-STA devices, i.e. a station can become an AP and then back to a station again. Note that a group of stations containing at least one QAPC-STA or a real AP can form an infrastructure network.

5.1.5 MAC-level FEC

MAC-Level FEC is an optional function that may be used to reduce both the rates of retransmission and MSDU (MAC Service Data Unit) loss [2]:

(a) MAC-Level FEC is indicated by a separate bit in the Capability Information field. The use of MAC-Level FEC may be negotiated between QSTAs when desired, and may be used for transfers with no QoS delivery requirements. Note that a support for the QoS facility is a prerequisite to support for MAC-Level FEC, because the indication that an MPDU has been FEC-encoded is required in both the Frame Control field and the QoS Control field, and the QoS Control field is only present in QoS data type frames and only exchanged by QSTAs in a QBSS.

(b) When using the TSPEC, if the recipient QSTA is capable of performing FEC decoding within a SIFS duration, it may be possible to use immediate acknowledgements. In such a case, FEC may be enabled by using the QoS action frame of Add-TS-Request with the FEC bit set to 1 and ACK Policy set to immediate acknowledgement. If such a combination of FEC and ACK policy is sent to a recipient that cannot do immediate acknowledgement, the receiver will set the FEC bit to zero in the TSPEC of Add-TS-Response QoS action frame to indicate it cannot respond with an ACK frame within a SIFS duration. The requestor may resend the request using the Add-TS-Request QoS action frame for the traffic stream, with FEC set to 0 or 1 and ACK Policy set to either Burst Acknowledgement or No Acknowledgement in the TSPEC. The receiver then replies according to the QSTA's ability to support FEC with or without Burst Acknowledgment.

The MAC-level FEC operation allows for error detection to take longer than a SIFS interval. FEC-capable QSTAs that are unable to distinguish receptions with uncorrectable errors from those with correctable errors within a SIFS interval may require that all FEC-encoded frames be sent to them using an acknowledgment policy that does not include immediate acknowledgement. The non-use of immediate acknowledgement is negotiated as part of the TSPEC and/or Burst Acknowledgement signaling. However, this may increase the processing delay.

5.2 Applications of 802.11e

The IEEE 802.11e focuses on three kinds of multimedia applications: IP-based applications, IEEE 1394-based consumer device applications, and finally converged 1394 and wireless IP multimedia applications [24]:

5.2.1 IP-based multimedia applications

IEEE 802.11e supports high-quality IP streaming multimedia applications between computers, gateways, PDAs (Personal Digital Assistants), STB (Set-in-Box) TVs and so on. Higher layer multimedia applications can use RTP/RTCP protocol and IP DiffServ to map the user prority to IEEE 802.1D-based MAC priority and then passed the prioritized datas to different access categories (ACs) of 802.11e MAC. They communicate to the 802.11e MAC through the 802 Data Service Access Point (DSAP) and Management SAP (MSAP).

5.2.2 IEEE 1394-based multimedia applications

IEEE 1394 [35, 39] is an evolutionary standard over current I/O interfaces and provides a good networking foundation for consumer electronic devices, with hot plug and play, high data rate, and QoS support benefits. The IEEE 802.11e will support at least three simultaneous 1394-based DVD rate MPEG-2 channels, or one HDTV rate MPEG-2 channel over IEEE 802.11a [24]. The IEEE 1394 applications can directly run over the IEEE 802.11e MAC or use an IP encapsulation to run over 802.11e MAC. Since IEEE 1394 bus is a link layer network with isochronous transfer mode capability, it is quite natural that the following demands appear: (1)Transmit specific IP flow through a certain isochronous channel of IEEE1394 bus. (2)Transmit specific AV flow (such as MPEG2-TS) through a certain isochronous channel of IEEE 1394 bus. So it is necessary to notify the relationship between channel ID and IP flow, the bandwidth of the isochronous channel, the direction of the IP flow transmitted through the channel and the attribute of the flow.

5.3 Simulation-based evaluations of 802.11e

Basically, CSMA in 802.11 DCF is efficient for bursty traffic, but not efficient for predictable traffic. On the other hand, PCF is more efficient for predictable traffic, but not efficient for bursty traffic due to wrong prediction and assignment of timeslots. 802.11e HCF combines the advantages of both techniques. In HCF, short point-coordinated bursts (CFBs) provide efficient channel access for traffic that the coordinator can predict, and contention-based CSMA mechanism provides efficient access for bursty traffic and retransmissions [24]. However, in 802.11e standard, AIFS is defined as an interval larger than or equal to DIFS. So, EDCF stations cannot have a higher priority than legacy DCF stations, especially in an IBSS (Independent Basic Service Set). How can EDCF support higher priority access than basic DCF in IBSS? Simulation results in [7] show that if there is a small number of contending stations, setting a very small CWmin can help EDCF stations have priority access. But if the number of stations increases, current pure ad-hoc EDCF cannot support efficient priority access, an adaptive scheme of changing CWmin value according to the station number or load rate is needed [41].

Performance analysis shows that EDCF scheme can support better QoS than DCF and PCF during low and medium load conditions. However, the EDCF-based ad-hoc network saturates and throughput decreases when the load increases [6]. It is very difficult to find the optimal EDCF parameters that can give the best performance, since the parameters are static and cannot be adapted to the traffic load rate. In fact, the collision rate increases very fast when there is an increase in the number of stations. Our ns simulation results in Figure 15-16 show that the high collision rate affects the EDCF goodput and latency, thus decreasing the performance of real-time multimedia traffic. In this simulation we increase the number of stations from 2 to 50 which corresponds to load rates from 7.5% to 187.5%. Figure 15 shows that the total goodput increases from 2 to 15 stations and then decreases very fast. Figure 16 shows that the average delay of EDCF always increases when there is an increase in the number of stations. At the same time, HCF controlled channel access mechanism uses a QoS-aware HC scheduling for different queues in each QSTA, which performs much better than EDCF. However, simulation results show that admission control is required for both EDCF and HCF since they only work well when traffic load is less than the maximum QoS load upbounds but both fail when load exceeds the QoS load upbounds [13]. That means, strict service guarantees of 802.11e can only be provided when admission control is applied simultaneously.

6 Conclusions and future research areas

This survey analyzes the QoS support and problems of original IEEE 802.11 wireless LAN MAC layer. We evaluate and classify different QoS enhancement techniques proposed for IEEE 802.11 wireless LAN and study their advantages and drawbacks. Moreover, the research activities and performance evaluations of the upcoming IEEE 802.11e QoS enhancement standard are also introduced and analyzed in detail. Note that many QoS enhancement schemes have been proposed to improve the performance of original 802.11 wireless LAN. Among them the upcoming queue-based 802.11e standard will offer some improvements. But it is still unapproved, unstable and needs to be tested more. There are still many research topics and open issues for QoS enhancement in IEEE 802.11 WLAN, among them we cite:

- Adapt the parameters to the traffic load and channel condition efficiently in ad-hoc EDCF mode,
- Optimize the tradeoff between channel efficiency, priority and fairness,

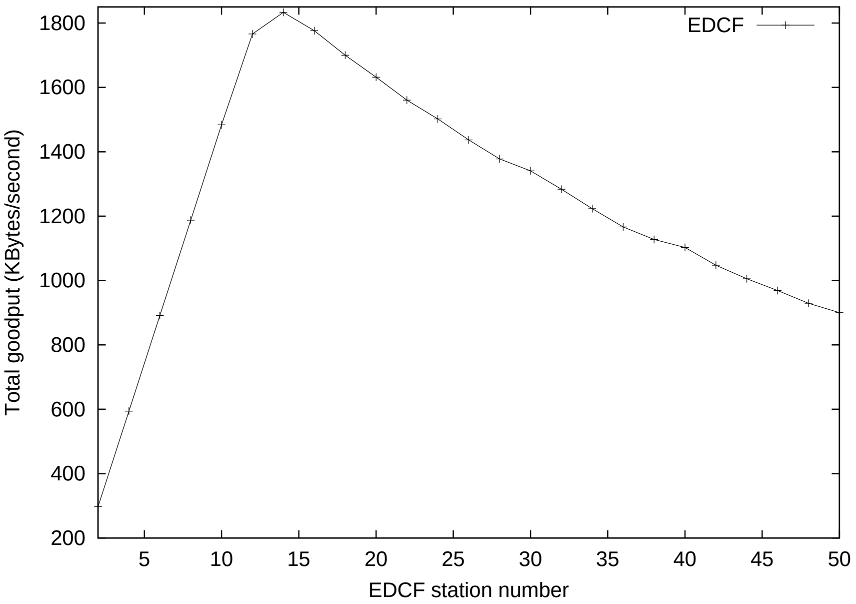


Figure 15: EDCF goodput degradation

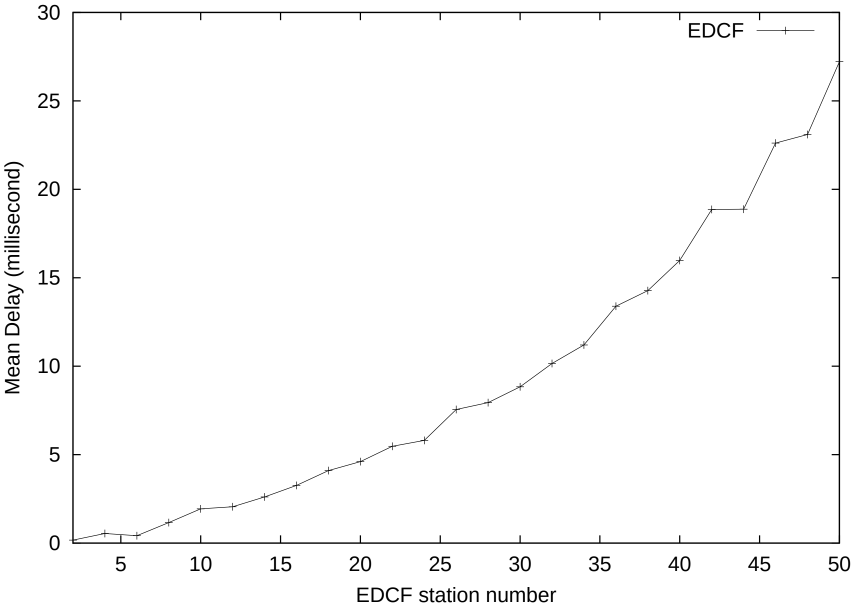


Figure 16: EDCF delay performance

- Evaluate the efficiency and performance of EDCF packet bursting and Contention-Free Burst (CFB),
- Design a model to evaluate HCF controlled channel access mechanism,
- Cooperate between MAC-level FEC and other layer's error control protocols,
- Map between IP DiffServ (AF, EF), IntServ priorities and IEEE 802.11e MAC priorities,
- Support simultaneously IP-based and IEEE 1394-based multimedia applications,
- Standardize good 802.11e simulation models and tools,
- Verify IEEE 802.11e with different QoS requirements under different scenarios.

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