Quality of Service Provision for IP Traffic over Wireless Local Area Networks

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Abstract. This PhD dissertation deals with the provision of guaranteed quality of service (QoS) to the users of a Wireless LAN (WLAN) and the interworking between WLANs and the 3rd generation and IP networks. The work is divided into three main parts:
i) Study and development of Wireless Adaptation Layer (WAL), a shim, transparent –both for the IP layer and the underlying WLAN- layer that supports the interworking of WLANs with IP networks and provides guaranteed QoS over WLANs by utilizing the QoS mechanisms of WAL..
ii) Study of traffic scheduling algorithms for WLANs that are based on IEEE 80211e protocol, the extension of legacy IEEE 802.11 protocol for supporting guaranteed QoS over 802.11 WLANs. More specifically a new traffic scheduling algorithm for 802.11e called ARROW (Adaptive Resource Reservation Over Wireless) and an extension of ARROW called ARROW (P-ARROW) was developed and evaluated.
iii) Study of interworking between WLANs and UMTS for the provision of guaranteed QoS for the mobile users that perform a handover from one network to the other. The focus was on how the QoS mechanisms of UMTS and WLANs can interwork and combine so as to offer guaranteed QoS service to the users that perform a handover.

Keywords: Quality of Service (QoS), DiffServ, Wireless Adaptation Layer (WAL), IEEE 802.11e, Traffic Scheduling Algorithms, ARROW Scheduler, UMTS/WLAN Interworking, Seamless Handover

1 Introduction

The rapid development and the high transmission rates attained by the Wireless Local Area Networks (Wireless LANs - WLANs) have established them as one of the most attractive choices for supporting alternative access to large 3rd generation networks (3G) like UMTS or metropolitan IP networks. The installation of WLANs in places with a dense mobile user population (i.e. hot-spots like malls, airports, hospitals etc.) relieves the traffic load towards the metropolitan networks while, at the same time, achieves an improved level of quality of service for the mobile users.

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The work in hand deals with the provision of guaranteed quality of service (QoS) to the users of a WLAN and the interworking between WLANs and the 3rd generation and IP networks. The provision of quality of service to WLAN users at a level at least equal to that offered by the metropolitan network is deemed as especially important since the objective is to offer the mobile users a uniform level of quality of service regardless of their current location.

In this respect this work proposes the introduction of a new shim-layer called *Wireless Adaptation Layer (WAL)* that lies between the IP and the underlying wireless LAN DLC layer and aims at providing or complementing the QoS support for the underlying WLAN platform [1]-[3]. Further to this, the work delved into the QoS support mechanism of IEEE 802.11e WLAN protocol and proposed a novel traffic scheduling algorithm named *ARROW (Adaptive Resource reservation Over Wireless)* together with an extension of ARROW called *P-ARROW (Prioritized-ARROW)* [4]-[8]. Finally the work examined the interworking of WLANs with 3G networks like UMTS focusing again on the provision of QoS and proposing an architecture for supporting seamless handover for voice and video streams from one platform to the other [9]-[15].

1.1 Wireless Adaptation layer (WAL)

Several solutions are available in the literature, coping with limitations of the wireless links. Most of these solutions propose enhancements at the Transport or Application layers, while others focus on the Link Layer trying to transparently improve higher layers performance and thus avoid modifications. A number of these solutions fall into the category of Performance Enhancing Proxies (PEPs) that are defined as elements used to improve the performance of Internet Protocols on network paths where native performance suffers due to characteristics of a link or subnetwork path.

The approach proposed in this work is in line with the idea of PEPs but also tries to expand and generalize it. More specifically, it is based on the introduction of an intermediate layer called Wireless Adaptation Layer (WAL) between the IP and the Link Layer. WAL incorporates a set of functional modules, viewed as generalized PEPs, that can be dynamically combined and adapted to the special characteristics of the wireless link and the transport protocol.

WAL architecture is shown in Fig 1. A novel and key feature of the WAL is that it is an abstraction used for service provisioning at the link layer [1]-[3]. Each IP packet is classified by WAL into classes and associations. A WAL class defines the service offered to a particular set of IP packets and corresponds to a particular sequence of WAL modules that provide such a service. A WAL association identifies a stream of IP packets classified for the same WAL class and destined to or originated from a specific mobile terminal (MT). In other words, a WAL association corresponds to a particular type of service offered to a particular MT. In this way, we can differentiate the operation of WAL on a per-user basis. In addition, services for particular users can be customized to meet their specific QoS requirements and to implement a differentiated-charging policy.

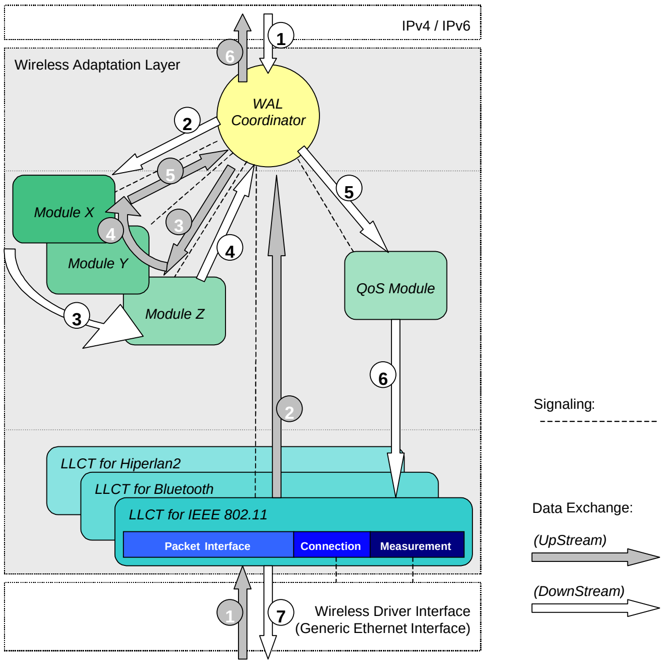


Fig. 1. WAL Architecture

The WAL Coordinator shown in Fig. 1 can be viewed as the central "intelligence" of the WAL. Both downstream (from IP layer) and upstream (to IP layer) traffic passes through the WAL Coordinator before being processed by other modules.

The QoS module (shown in Fig. 1) provides flow isolation and fairness guarantees through traffic shaping and scheduling. On the other hand, modules X/Y/Z comprise a pool of functional modules, aiming to improve performance in a number of ways. The modules that have been identified so far are: ARQ module, FEC module, Fragmentation module, IP Header Compression module, and SNOOP module.

Finally, in order to interface with a number of wireless drivers of different wireless technologies (such as IEEE 802.11, Bluetooth, HiperLAN/2, etc.), one Logical Link Control Translator (LLCT) module for each different wireless technology has been introduced. The main functions of this module manage the connection status with the wireless driver, and ensure the stream conversions toward the wireless driver.

For the classification of the IP packets to WAL classes a service differentiation is needed. Service differentiation in WAL is based on the DiffServ architecture. In this respect, the wireless access system can be viewed as a DiffServ domain with the Access Point acting as the DiffServ boundary node, interconnecting the wireless access system with the core network or other DiffServ domains.

1.2 Traffic Scheduling in IEEE 802.11e

The IEEE 802.11 standard is considered today the dominant technology for wireless local area networks (WLANs). Besides great research interest, 802.11 has enjoyed widespread market adoption in the last few years, mainly due to low-price equipment combined with high bandwidth availability. Recent improvements in the physical (PHY) layer provide transmission speeds up to hundreds of Mbps per cell, facilitating the use of broadband applications. However, one of the main weaknesses of the original 802.11, towards efficient support of multimedia traffic, is the lack of enhanced Quality of Service (QoS) provision in the Medium Access Control (MAC) layer.

In order to eliminate these weaknesses and respond to business requirements for multimedia over WLANs, IEEE is currently working on a set of QoS-oriented specification amendments, referred to as IEEE 802.11e, that enhance the existing MAC protocol and facilitate the multimedia QoS provision. In IEEE 802.11e, the QoS mechanism is controlled by the Hybrid Coordinator (HC), an entity that implements the so-called Hybrid Coordination Function (HCF). The HC is typically located in an Access Point (AP) and utilizes a combination of a contention-based scheme, referred to as Enhanced Distributed Coordination Access (EDCA), and a polling-based scheme, referred to as HCF Controlled Channel Access (HCCA), to provide QoS-enhanced access to the wireless medium. EDCA provides differentiated QoS services by introducing classification and prioritization among the different kinds of traffic, while HCCA provides parameterized QoS services to Stations (QSTAs) based on their traffic specifications and QoS requirements. To perform this operation, the HC has to incorporate a scheduling algorithm that decides on how the available radio resources are allocated to the polled QSTAs. This algorithm, usually referred to as the Traffic Scheduler, is one of the main research areas in 802.11e, as its operation can significantly affect the overall system performance [4]. Traffic Schedulers allocates resources to the QSTAs in the form of Transmission Opportunities (TXOPs). A TXOP is an interval of time when a QSTA obtains permission to transmit onto the shared wireless channel.

In the open technical literature, only a limited number of 802.11e traffic schedulers have been proposed so far and this work partially aims at filling this gap. The draft amendment of IEEE 802.11e includes an example scheduling algorithm, referred to as the Simple Scheduler, to provide a reference for future, more sophisticated solutions. The idea of this algorithm is to schedule fixed batches of TXOPs at constant time intervals. Each batch contains one fixed length TXOP per QSTA, based on the mean data rates as declared in the respective Traffic Specifications (TSPECs). With this discipline the Simple Scheduler respects the mean data rates of all TSs and performs well when the incoming traffic load does not deviate from its mean declared value (e.g., constant bit rate traffic). On the other hand, its performance deteriorates significantly when it comes to bursty traffic, as it has no means to adjust TXOP assignments to traffic changes. Identifying the weaknesses of the Simple Scheduler, SETT-EDD (Scheduling based on Estimated Transmission Times - Earliest Due Date) scheduler provides improved flexibility by allowing the HC to poll each QSTA at variable intervals, assigning variable length TXOPs. With SETT-EDD TXOP assignments are based on earliest deadlines, to reduce transmission delay and packet losses due to expiration. SETT-EDD is a flexible and dynamic scheduler, but it lacks an efficient mechanism for calculating the exact required TXOP duration for each QSTA transmission. Each TXOP duration is estimated based on the mean data rate of each TS and the time interval between two successive transmissions.

In order to overcome the disadvantages of Simple and SETT-EDD schedulers this work proposes a new scheduling algorithm, referred to as *Adaptive Resource Reservation Over WLANs (ARROW)* [4], [6], [7], that adapts TXOP durations based on the backlogged traffic reports issued by QSTAs. The novel characteristic of ARROW is that it exploits the Queue Size (QS) field, introduced by 802.11e as part of the new QoS Data frames, not supported by legacy 802.11 systems. The QS field can be used by the QSTAs to indicate the amount of buffered traffic for their TSs, i.e., their transmission requirements. Furthermore, in order to take advantage of the periodic nature of CBR streams, a CBR-enhancement of ARROW was also developed.

Simulation results show that ARROW achieves much more efficient use of the available bandwidth, compared to Simple and SETT-EDD, leading to better channel utilization and higher throughput. The increased transmission overhead percentage of the proposed scheduler turned to be not a significant performance issue. Finally, it is important to note that ARROW does not mandate any standards changes. It could be readily deployed and implemented in practice, provided that STAs populate the QS field as defined in the 802.11e standard.

An important extension of ARROW is *P-ARROW (Prioritized ARROW)* [5]. The main enhancement of P-ARROW compared to ARROW is its ability to efficiently handle different traffic classes. The novel characteristic of P-ARROW is the introduction of Priority Factor a, and the use of traffic priorities based on delay constraints. Performance results extracted from simulation models, show that P-ARROW is very efficient in supporting the desired level of service differentiation and prioritization among different traffic classes.

1.3 UMTS/WLAN Interworking

As the Internet technologies evolve, more sophisticated and Quality of Service (QoS) demanding multimedia services are being requested by the users. The Internet Protocol (IP), together with its QoS enhancement frameworks (namely the Integrated Services - IntServ - and the Differentiated Services - DiffServ), is currently the main transport technology for supporting all these new services and in this respect the motto “Everything over IP and IP over everything” has become the trend of the day. On the other hand, both UMTS and Wireless LANs (WLANs) are already commercially available and become increasingly popular. The number of mobile users is growing rapidly and so does the demand for wireless access to the Internet services, imposing the need for a unified QoS support framework in both UMTS and WLANs.

Despite the initial impression, expressed by several network technology vendors, that UMTS and WLANs will be competing technologies it appears that they can be combined and complement each other in an effective way. The approach followed in this work is that both UMTS and WLANs can act as access systems to one common

IP core network, efficiently covering both wide areas and hot-spots. One of the main requirements of this system is a unified QoS support for IP traffic. As RSVP is considered the dominant signaling protocol of IP traffic, the discussion focuses on the adoption of RSVP messages and parameters by UMTS or WLAN QoS mechanisms [12]-[15].

Further to this, as the next-generation networks (NGN) are expected to support a wide variety of service types, especially broadband multimedia services, including video conference, streaming, and advanced telephony services, a major objective is how these services should operate seamlessly across all diverse access systems (e.g. WLAN, UMTS, fixed broadband, WiMAX, cable, etc). This seamless operation presents several challenges especially when the different access systems are loosely coupled and therefore lack the tight integration we experience in GSM/UMTS radio environments for instance. To address this issue for the case of UMTS/WLAN interowrking this work proposes a specific architecture for the support of seamless voice and video handover between the two platforms [9]-[11]. The basic idea of the proposed architecture is that a new internal entity of UMTS calles Seamless Handover Control Function, located at the IMS (Internet-Multimedia System) will act as an anchor-point hiding user mobility from the external IP network. Both UMTS and WLAN are also equipped with appropriate entities that take care of interworking procedures such as re-routing of traffic and authentication of the roaming users. The proposed architecture for the case of seamless voice handover is depicted in Fig. 2.

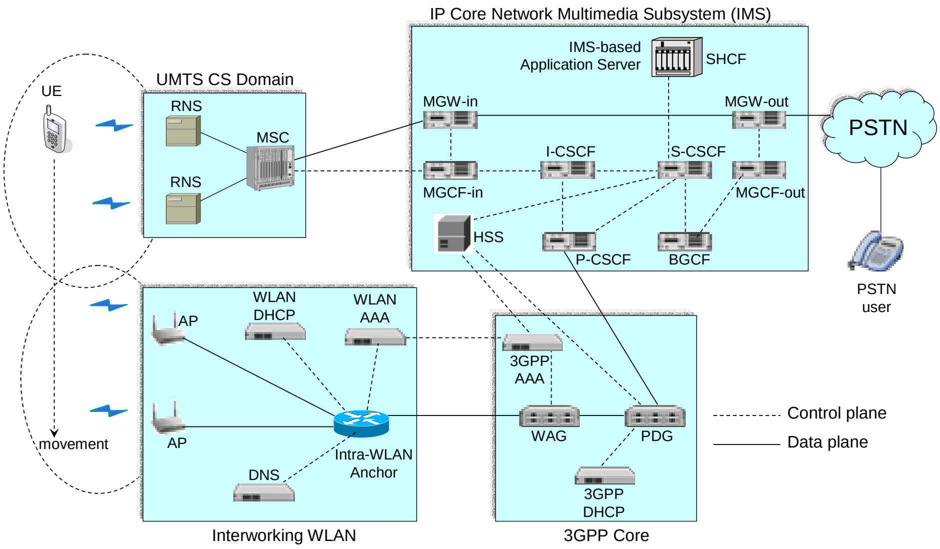


Fig. 2. IMS-based architecture for enabling seamless voice handover across UMTS and WLAN.

Simulation results indicate that WLAN can accommodate a limited number of UMTS roamers (i.e. users that perform a handover from UMTS to WLAN). This number depends on the bandwidth allocated for these users, their QoS requirements and also on the QoS support mechanism of WLAN [9]-[11].

2 The ARROW Scheduler

In IEEE 802.11e the traffic scheduler has to decide on the next TXOP assignment taking into account traffic characteristics and QoS requirements expressed through TSPEC parameters. As already mentioned, TXOP assignments are performed per QSTA, while TSPECs are defined per TS. Therefore, for each $QSTA_i$ having n_i active TSs (where i is the index of the QSTA), the traffic scheduler has to utilize some aggregate parameters, derived from the individual TSPECs, which are calculated as follows:

Minimum TXOP duration (*mTD*): This is the minimum TXOP duration that can be assigned to a QSTA and equals the maximum time required to transmit a packet of maximum size for any of the QSTA's TSs. Thus, mTD_i of $QSTA_i$ is calculated as:

$$mTD_i = \max\left(\frac{M_{ij}}{R_{ij}}\right),\ j \in [1,n_i] \qquad (1)$$

where M_{ij} and R_{ij} are the maximum MSDU size and the minimum physical rate for TS_{ij}, respectively.

Maximum TXOP duration (*MTD*): This is the maximum TXOP duration that can be assigned to a QSTA. It should be less than or equal to the transmission time of the **Aggregate Maximum Burst Size (*AMBS*)** of a QSTA. The *AMBS* is the sum of the maximum burst sizes (MBSs) of all TSs of a QSTA. Thus for $QSTA_i$ it holds:

$$AMBS_i = \sum_{j=1}^{n_i} MBS_{ij} \qquad (2)$$

and,

$$MTD_i \le \frac{AMBS_i}{R_i} \qquad (3)$$

where R_i is the minimum physical bit rate assumed for $QSTA_i$ ($R_i=min(R_{ij}), j \in [1,n_i]$).

Minimum Service Interval (mSI): It is the minimum time gap required between the start of two successive TXOPs assigned to a specific QSTA. It is calculated as the minimum of the *mSIs* of all the QSTA's TSs:

$$mSI_i = \min\left(mSI_{ij}\right),\ j \in [1,n_i] \qquad (4)$$

If not specified in the TSPEC, mSI_{ij} of TS_{ij} is set equal to the average interval between the generation of two successive MSDUs, i.e., $mSI_{ij}= L_{ij}/\rho_{ij}$.

Maximum Service Interval (MSI): It is the maximum time interval allowed between the start of two successive TXOPs assigned to a QSTA. Although no specific guidelines for calculating *MSI* are provided, an upper limit exists to allow an MSDU generated right after a TXOP assignment to be transmitted at the next TXOP. Accordingly:

$$MSI_i \le D_i - MTD_i \qquad (5)$$

where D_i is defined as the minimum delay bound of all TSs of $QSTA_i$ ($D_i=min(D_{ij}), j \in [1,n_i]$). This is an upper limit that ensures successive TXOPs will be assigned close enough to preserve delay constraints.

2.2 Operation of ARROW Scheduler

Both Simple and SETT-EDD, as briefly described above, decide on TXOP durations using some kind of estimation of the amount of data waiting to be transmitted by every QSTA. ARROW tries to overcome this drawback by adapting TXOP durations based on traffic feedback reports issued by QSTAs The novel characteristic of ARROW is that it exploits the *Queue Size (QS)* field, introduced by 802.11e as part of the new *QoS Data* frames, not supported by legacy 802.11 systems [4], [6], [7]. The QS field can be used by the QSTAs to indicate the amount of buffered traffic for their TSs, i.e., their transmission requirements.

An example of the use of the QS field in ARROW is depicted in Fig. 3. The allocation procedure will be described in detail later in this section. For simplicity reasons, one TS per QSTA is assumed. At time $t_i(x)$, $QSTA_i$ is assigned $TXOP_i(x)$, according to requirements expressed through the QS field of the previous TXOP as well as traffic characteristics and QoS requirements declared in the respective TSPEC. Using a *QoS Data* frame, $QSTA_i$ transmits its data together with the current size of its queue in the QS field ($QS_i(x)$). At time $t_i(x+1)$ the scheduler assigns $TXOP_i(x+1)$ to $QSTA_i$, in order to accommodate the requirements of $QS_i(x)$. During the interval [$t_i(x), t_i(x+1)$] new data is generated in $QSTA_i$, therefore $QSTA_i$ uses the *QoS Data* frame transmitted at $TXOP_i(x+1)$ to indicate the new queue size ($QS_i(x+1)$). In the same manner, at $t_i(x+2)$ the scheduler assigns $TXOP_i(x+2)$ to $QSTA_i$, accommodating the requirements of $QS_i(x+1)$ and gets the new queue size from $QSTA_i$ ($QS_i(x+2)$). As clearly shown, by utilizing the QS field, ARROW has very accurate information about the time varying properties of each TS, and is able to adapt the TXOP duration accordingly. This is considered essential, especially in the case of bursty and VBR traffic, where transmission requirements feature large time variations.

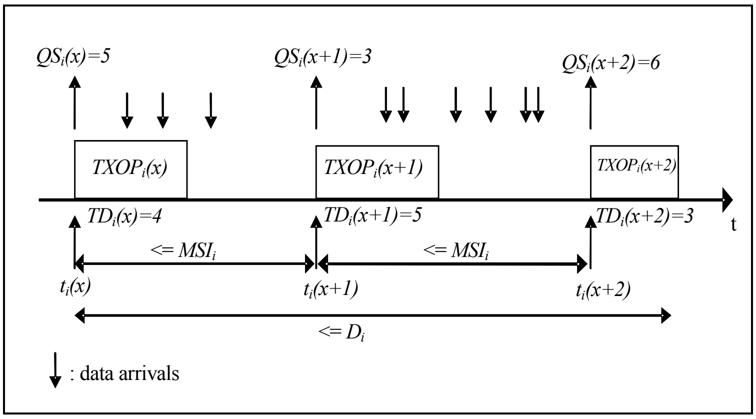


Fig. 3 TXOP assignment with ARROW

As can be observed in Fig. 3, for every $QSTA_i$, data arriving within the interval [$t_i(x), t_i(x+1)$] can be transmitted no earlier than $TXOP_i(x+2)$ starting at $t_i(x+2)$. Therefore, in order not to exceed the delay deadline of MSDUs, assuming the worst case that service intervals are equal to MSI_i and $TXOP_i(x+2)=MTD_i$, it should hold that:

$$D_i \geq 2MSI_i + MTD_i \Leftrightarrow$$

$$\Leftrightarrow MSI_i \leq \frac{D_i - MTD_i}{2} \qquad (6)$$

If the scheduler should also take into account possible retransmissions, relation (6) becomes:

$$MSI_i \leq \frac{D_i - MTD_i}{2+m} \qquad (7)$$

where m is the number of maximum retransmission attempts.

ARROW incorporates a traffic policing mechanism to ensure that the transmission requirements expressed through the QSs do not violate traffic characteristics expressed through the TSPECs. For that purpose, a *TXOP timer* is used, that implements the operation of a leaky bucket of time units. The TXOP timer value T_i for a $QSTA_i$ having n_i active TSs, increases with rate $r(T_i)$:

$$r(T_i) = \sum_{j=1}^{n_i} \left(\left(\frac{L_{ij}}{R_{ij}} + O\right) / \frac{L_{ij}}{\rho_{ij}} \right) \qquad (8)$$

where O is the overhead due to PHY and MAC headers measured in seconds.

Equation (8) means that during the time interval needed for the generation of an MSDU of Nominal Size at mean data rate, the TXOP Timer should be increased by the time required for the transmission of this MSDU. The maximum TXOP Timer value $\max(T_i)$ equals the time required for the transmission of all maximum bursts:

$$\max(T_i) = \sum_{j=1}^{n_i} \left(\frac{MBS_{ij}}{R_{ij}} + O \right) \qquad (9)$$

According to the operation of ARROW described below, no TXOP longer than the current value of T_i can be assigned to $QSTA_i$ at any time. After each TXOP assignment, the value of the respective TXOP timer is reduced accordingly.

The operation of ARROW can be divided in the following steps:

1. The scheduler waits for the channel to become idle.
2. When the channel becomes idle at a given moment t, the scheduler checks for QSTAs that:

   a. can be polled without violating mSI, i.e., for a $QSTA_i$ that was last polled at time t_i, it should hold that:

$$t \geq t_i + mSI_i \qquad (10)$$

   and,

   b. their TXOP timer value T is greater than the value of their mTD, to ensure enough time for the minimum TXOP duration.

3. If no QSTAs are found, the scheduler waits until (10) becomes true at least for one QSTA and returns to step 2.
4. In different case, the scheduler polls the QSTA with the earliest deadline. The deadline for a $QSTA_i$ is the latest time that this QSTA should be polled, i.e., t_i+MSI_i, where t_i is the time of the last poll for $QSTA_i$.

5. Assuming $QSTA_i$ having n_i active TSs is selected for polling, the scheduler calculates TD_i, as follows:

a. For every TS_{ij} of $QSTA_i$ ($j \in [1,n_i]$), the scheduler calculates TD_{ij}, as the maximum of (i) the time required to accommodate the pending traffic, as indicated by the queue size of that TS (QS_{ij}), plus any overheads (O), and, (ii) mTD_{ij}, to ensure that the assigned TXOP will have at least the minimum duration:

$$TD_{ij} = \max\left(\frac{QS_{ij}}{R_{ij}} + O, mTD_{ij}\right) \qquad (11)$$

In the special case where QS_{ij} is equal to zero, TD_{ij} is set equal to the time for the transmission of a Null-Data MSDU. In this way, $QSTA_i$ is allowed to transmit a Null-Data MSDU, in order to update the queue size information for TS_{ij}. TD_i for $QSTA_i$ is calculated as the sum of all TD_{ij}:

$$TD_i = \sum_{j=1}^{n_i} TD_{ij} \qquad (12)$$

b. Finally TD_i obtained from (12) is compared with the current TXOP Timer value T_i, to ensure conformance with the negotiated traffic profile:

$$TD_i = \min(TD_i, T_i) \qquad (13)$$

6. After the scheduler assigns the TXOP, it reduces the respective TXOP timer value accordingly and returns to step 1:

$$T_i = T_i - TD_i \qquad (14)$$

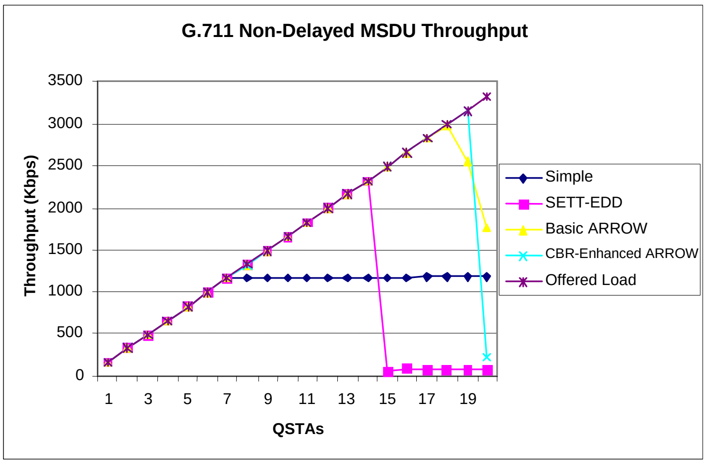
2.2 Simulation results

To measure the performance ARROW against Simple and SETT-EDD, a specialized 802.11e simulation tool developed by ATMEL Hellas was used [8]. The simulation scenarios considered an increasing number of QSTAs attached to a QAP. All QSTAs and the QAP were supporting the extended MAC layer specified in IEEE 802.11e and the PHY layer specified in IEEE 802.11g, with a transmission rate of 12Mbps. Each QSTA had two active sessions:

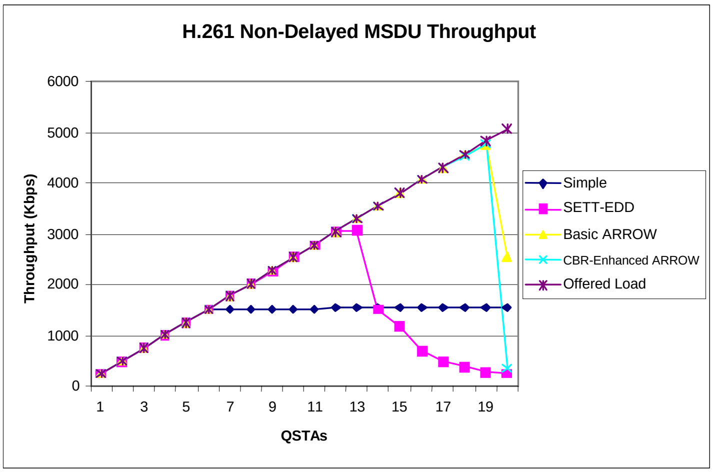
a. a bi-directional G.711 voice session (CBR traffic), mapped into two TSs (one per direction), and,

b. an uplink (from QSTA to QAP) H.261 video session at 256 Kbps (VBR traffic), mapped into one uplink TS.

Fig. 4 depicts throughput of non-delayed MSDUs for voice and video traffic. For voice traffic (Fig. 4a), basic ARROW accommodates up to 18 QSTAs, while SETT-EDD can manage up to 14 QSTAs and Simple up to only 7 QSTAs. Using the enhancement for CBR traffic, the number of QSTAs can be increased to 19 with CBR-enhanced ARROW, as a result of less required overhead. For video traffic (Fig. 4b), basic and CBR-enhanced ARROW outperform both SETT-EDD and Simple, accommodating up to 19 QSTAs, as opposed to 13 with SETT-EDD and 6 with Simple. The main reason for the considerably improved performance of basic ARROW is the accurate TXOP assignment it performs, by utilizing the queue size information. This is also shown in detail using more metrics later in this section. From Fig 4a and 4b it is clear that CBR-enhanced ARROW can extend the admission capability of the system, as it can accommodate up to 19 QSTAs with voice and video TSs.



(a) G.711 Voice



(b) H.261 video

Figure 2. Throughput of Non-Delayed MSDUs

It is interesting to observe that throughput of SETT-EDD and ARROW (both basic and CBR-enhanced) reduces rapidly immediately after reaching its maximum value. The reason is that, due to the dynamic TXOP assignment performed by these algorithms, new TSs entering the system can participate equally to the channel assignment. This means that, after the overall input traffic exceeds a value that corresponds to the maximum capability of the scheduler, none of the TSs (new or old) is serviced as required. The Simple Scheduler on the other hand, manages to provide a stable throughput regardless of the offered load, because static allocations for existing TSs are not affected by the traffic load increase. This effect highlights the need for an effective admission control scheme for SETT-EDD and ARROW that would prevent the offered load from exceeding the maximum scheduling capability.

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