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Efficient Support for Video Communications in Wireless Home Networks

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***Abstract*—This paper investigates the performance of video communications over wireless networks employing the recently proposed Time-Division Unbalanced Carrier Sense Multiple access (TDuCSMA) coordination function. TDuCSMA is fully IEEE 802.11 standard compliant but offers novel bandwidth management capabilities. In this work the peculiar characteristics of TDuCSMA are configured and exploited to maximize the performance of video communications in a realistic home networking scenario. Simulation results show significant performance improvements with respect to legacy IEEE 802.11 network. The video quality gains are up to 13 dB PSNR with 500 ms playout buffer, while the average delay of the video packets is much lower, for the same amount of video traffic offered to the network. These results significantly contribute to enhance the quality of experience of the users of the video communication.**

I. Introduction

The IEEE 802.11 standard [1] undoubtedly defines the most used technology in wireless home networks. One of its greatest advantages is to provide network services without the need for a wired infrastructure, making the technology suitable for a wide range of scenarios. However, the use of a wireless medium as opposed to structured cabling imposes some limits, namely the necessity to share the wireless bandwidth among several users.

The first IEEE 802.11 standard introduced a distributed coordination function implementing the CSMA/CA channel access scheme. In CSMA/CA the decision making process is distributed among all nodes. Each node individually determines when it is the right time to access the channel. Indeed CSMA/CA is a distributed solution relying on the principle of random access. However, even if distributed, easy to implement and scalable, CSMA/CA suffers from limited performance especially in case of many users due to collisions and sub-optimal decisions. Also, its performance is scarce when strict quality-of-service (QoS) is required. To support the increasing demand for QoS the IEEE 802.11e amendment was proposed. It introduces the Hybrid Coordination Function (HCF) that defines two channel access mechanisms, namely, Enhanced Distributed Channel Access (EDCA) for differentiated QoS provisioning and the HCF Controlled Channel Access (HCCA) for parametrized QoS.

The EDCA coordinates channel access in a distributed fashion and provides a flexible and scalable solution for differentiated QoS provisioning. EDCA introduces the Access Category (AC) concept to differentiate traffic whereas it differentiates services by prioritizing channel access using AC-specific EDCA parameters. Several works assessed the EDCA performance [2] and proposed further optimizations [3]–[5] to minimize contention delays and collision rates, hence improving throughput and delays. Other works studied the issue of tuning the EDCA parameters [6] to provide good service differentiation in specific traffic scenarios. However, in all cases the efficiency with which the shared medium is used in congested scenarios is not high.

The HCCA is a polling mechanism where channel access is arbitrated centrally by the hybrid controller (HC). A node willing to transmit negotiates with the HC channel access during a negotiation EDCA based phase. The HC offers transmission opportunities (TXOPs) in response, if enough resource are available to meet QoS requirements, during the controlled access period (CAP). As a result HCCA avoids, during CAPs, collisions that can lead to breaking established QoS and degradation of the overall performances and allows the HC to implement bandwidth reservation policies enabling parametrized QoS provisioning. However the need for a centralized HC potentially increases the complexity of the solution and faces scalability issues. Moreover HCCA potentially presents inefficiencies in dealing with short-lasting and/or very bursty traffic and in reallocating TXOPs reserved but currently unused, due to on/off traffic. Additionally, it requires extensions to the standardized MAC layer. For all the previous reasons the HCCA has never been implemented in practice.

A novel coordination function called Time-Division Unbalanced Carrier Sense Multiple access (TDuCSMA) has been recently proposed [7]. It relies on synchronization among nodes and time-driven switching of contention parameters inside nodes to provide a viable solution for bandwidth management, while exploiting all the available bandwidth. The TDuCSMA is flexible enough to provide to the upper layers the knobs for driving its operation, hence to implements dynamic and distributed bandwidth and traffic managements by means of

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a signaling architecture [8]. The TDuCSMA operating principles have been extensively investigated in single [7] and multi-hop [9] scenarios by simulations and analytical models. Moreover the work in [10] proved the full compliance with the IEEE 802.11 standard and designed an architecture enabling the coexistence of TDuCSMA and EDCA entities on the same node.

While these works assessed, from the network point of view, the TDuCSMA as a coordination function for broadband access in metropolitan area networks, to the best of our knowledge no works have investigated its performance in term of quality-of-experience (QoE) in a home networking scenario. This work investigates the performance of video communications over a TDuCSMA wireless network by means of *ns-2* simulations showing how to optimally configure its parameters to maximize the multimedia performance.

The paper is organized as follows. Section II recalls the TDuCSMA operating principles firstly described in [7] and presents the generalized bandwidth reservation model. Section III addresses how to exploit TDuCSMA for video communications. Section IV describes the simulation setup and provides quantitative results in terms of network and application level performance metrics. Finally conclusions are drawn in Section V.

II. Time-Division Unbalanced Carrier Sense Multiple Access

A. Operating Principles

In TDuCSMA networks all nodes are synchronized with a common time reference (CTR) whose structure is depicted in Fig. 1. The CTR is a periodical time structure where the time-frame TF is the time unit and *k* TFs are grouped in a time-cycle TC. The time-cycle length T_c — measured in TFs — provides the periodicity of the CTR structure. Both the time-frame duration T_f and T_c are configurable system parameters. The synchronization can be distributed using the coordinated universal time (UTC) to derive T_f from a global navigation satellite system (GNSS) or by a distributed leaderless solution [11], where nodes collaboratively reach a consensus on a common clock.

Although a typical TDMA time structure is employed, the decision making process about channel access is distributed among all nodes following the CSMA/CA rules. Each node maintains two sets of EDCA parameters, which include the Arbitration Inter-frame Space Number (AIFSN) and the minimum and maximum Congestion Windows. More formally, the set is defined as $(AIFSN, CW_{min}, CW_{max})$. These two sets are referred to as *high-priority* set $EDCA^H$ and *low-priority* set $EDCA^l$. The EDCA parameters are *unbalanced* in the two sets. More formally $AIFS^H < AIFS^l$ and $CW^H_{min} \leq CW^H_{max} < CW^l_{min} \leq CW^l_{max}$ such that node i, contending for channel access in accordance to $EDCA^H$, has almost strict priority on node j using $EDCA^l$ settings.

The underlying idea is to synchronize the contextual switching of EDCA parameters at each node such that (*i*) only one node contends for channel access in accordance to $EDCA^H$ at a time and (*ii*) all nodes maintain $EDCA^H$ for a predefined periodical time interval, referred to as T_H (measured in TFs.)

Fig. 1 shows the time-driven switching of EDCA parameters inside three nodes sharing the same collision domain. As depicted, only one node contends for channel access in accordance to $EDCA^H$ during one TF, whereas the time periods in which nodes operate in accordance to $EDCA^j$ $\forall j = H, l$ can change over the nodes. As a result, following the TDuCSMA operating principles a node i is very likely to gain access to the channel and maintain it for the full period T^i_H. It is worth noting that this happens due to the CSMA/CA operations and due the values of the access parameters in $EDCA^H$ and not because of a predefined channel access as in TDMA-based solutions[1].

In principle the EDCA parameter sets are switched over time on a per-node basis, so that each node handles QoS-demanding traffic as a single aggregate. Thus, bandwidth management is performed on a per-node basis by assigning different T_H to nodes sharing the collision domains. However a sub-set of TFs can be left un-allocated to let node send background traffic in accordance to either the best-effort or the differentiated service discipline as addressed in [10].

Moreover, since TDuCSMA preserves the CSMA/CA nature, if a node i does not have enough traffic to send before the end of its T^i_H, any other node can gain access to the channel, thanks to CSMA/CA, and transmit. Hence, bandwidth reuse is easily and intrinsically implemented and bandwidth waste, as a side effect of reservation, is avoided.

B. Bandwidth Reservation Model

The work in [7] showed two important consequences of the TDuCSMA operating principles:

1) only node i gains access to the channel during T^i_H, thus the congestion windows in $EDCA^H$ can be minimized to reduce back-off time between two consecutive transmissions hence bandwidth utilization is increased without affecting collision probability;
2) if node i tends to use its T^i_H with poor efficiency due to short packets, this does not affect the transmissions of the other nodes in their respective T_H periods.

Therefore, assuming $CW^H_{min} = CW^H_{max} = 1$ and neglecting the propagation delays, the theoretical bandwidth G_{id}, available for reservation, can be expressed as the efficiency in channel utilization considering only the protocol overheads as follows:

$$G_{id} = \frac{R \cdot t_p}{t_p + AIFS^H + 2 \cdot t_{plcp} + t_h + SIFS + t_{ack}}, \quad (1)$$

where R is the linerate, t_p and t_h are the MAC payload and header transmission times, t_{plcp} is the transmission time of PLCP header and preamble and t_{ack} is the acknowledgment transmission time.

[1]The transmission opportunity *TXOP* mechanism is not exploited in TDuCSMA because if a node were delayed in its channel access, *TXOP* would enforce this delay and propagate it with a disruptive effect on the underlying TDuCSMA operating principles.

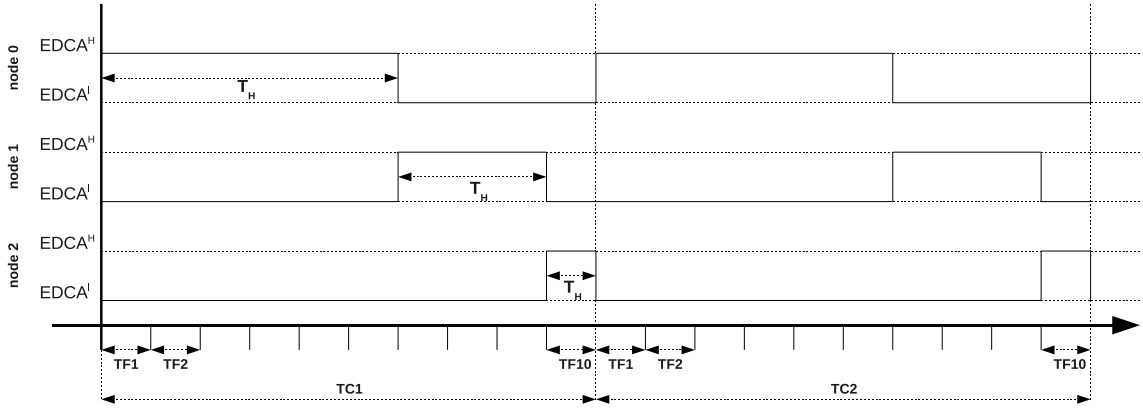

Fig. 1. Time-driven EDCA parameters switching inside three nodes; $T_H^0 = 6$, $T_H^1 = 3$, $T_H^2 = 1$ over a time cycle with $k = 10$ TFs.

In TDuCSMA bandwidth reservation is performed, on a per-node basis, by allocating one or more TFs to contend for channel access in accordance to $EDCA^H$. Therefore it is possible to reserve, to node i, a bandwidth equal to:

$$G_i = \frac{T_H^i}{T_c} \cdot G_A, \tag{2}$$

where G_A is the available bandwidth. Nodes sending QoS-demanding traffic experience very few collisions, basically at the boundaries of their T_H, *e.g.,* at the beginning of TF 1, 7 and 10 in the example depicted in Fig. 1. Thus, G_A can be estimated from G_{id} with a tolerance of about 10% as shown in [7], [9], [10].

Reverting Eq. (2), it is possible to compute the number of TFs n_i that must be allocated to node i to reserve the bandwidth G_i as follows:

$$n_i = \left\lfloor \frac{T_c}{T_f} \cdot \frac{G_i}{G_A} \right\rceil = \left\lfloor \frac{k \cdot T_f}{T_f} \cdot \frac{G_i}{G_A} \right\rceil = \left\lfloor k \cdot \frac{G_i}{G_A} \right\rceil \tag{3}$$

where the $\lfloor \cdot \rceil$ is the round operator.

It is worth noting that each node on a multi-hop route can exploit Eq. (1) to estimate the available bandwidth G_A and Eq. (3) to calculate the number of TFs, whose allocation is required to reserve bandwidth G, independently of the others.

However, Eq. (1) can be applied only with constant packet length. As shown in [9] the mean packet length alone provides itself a good approximation of the statistic and the detailed nature of the distribution has only a second order effect when dealing with reservations in TDuCSMA. Therefore Eq. (1) and consequently Eq. (2) and Eq. (3) can be generalized to work with variable packet lengths as follows:

$$G_{id} = \frac{R \cdot T_P}{AIFS^H + 2 \cdot t_{plcp} + T_P + t_h + SIFS + t_{ack}}, \tag{4}$$

where $T_P = E\left[t_p\right]$ is the expected value of the MAC payload transmission time.

III. Video Communication over TDuCSMA

Multimedia communications need to periodically receive data in order to operate correctly. Differently from generic data transmissions, a few packet losses can be tolerated provided that the QoE is not significantly affected. However, since the transmission must be carried out in a real-time fashion, a certain minimum bandwidth and maximum transmission delay must be guaranteed at all times in order to timely provide the receiver with the data needed for content playout. The requirements varies depending on the application type. Videoconferencing applications, for instance, impose very low delay in the order of few hundreds of milliseconds. On the contrary, streaming applications such as live video have more relaxed delay requirements, in the order of one second, while video on demand sessions can reach several seconds.

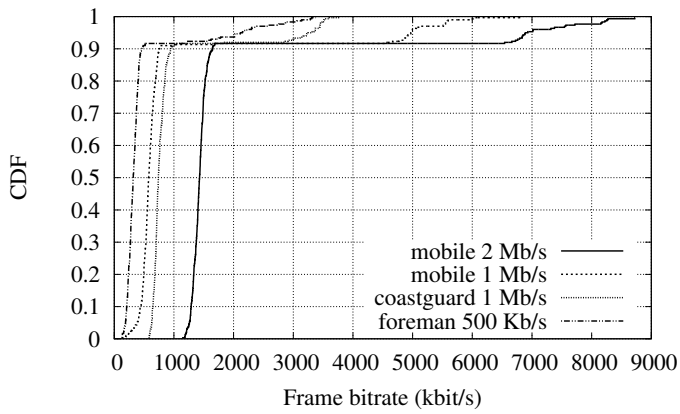

Fig. 2. CDF of the instantaneous bitrate of the video sequences.

The management capabilities offered by TDuCSMA assure bandwidth and bounded delay, hence it can be efficiently exploited by multimedia communications. The entire bandwidth reservation process for VBR video traffic can be split into two steps. The first one is the estimation of bandwidth requirements, based only on bitrate statistics whereas the second step, instead, takes into account packet-length statistics according to the rules defined in Section II-B.

Fig. 2 shows the cumulative density function (CDF) of the instantaneous bitrate for the video sequences considered in this work. The CDF presents a flat zone at a certain percentile value due to the difference between the average size of I-type and P-type frames. In our case, every 12 frames there are 11 P-type frames and one I-type frame, hence the flat area is

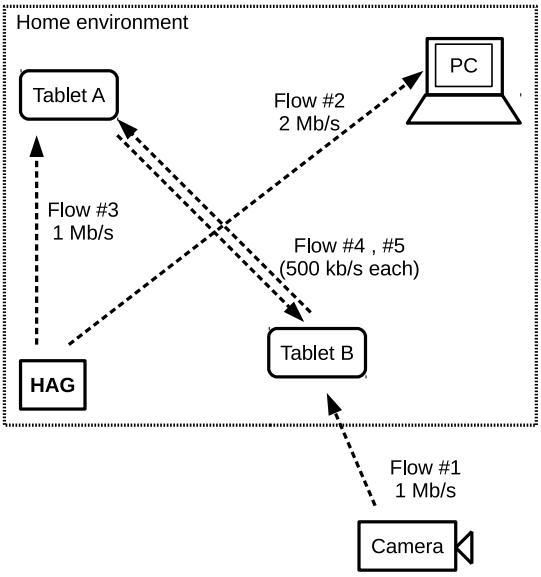

Fig. 3. The simulated home networking scenario. It comprises five wireless devices exchanging five video flows.

TABLE I
CHARACTERISTICS OF THE VIDEO FLOWS.

Flow #	Sequence	Length (s)	Bit-rate (kbit/s)	Mean packet length (bytes)
1	*mobile*	60	1006	875
2	*mobile*	60	2009	922
3	*coastguard*	60	1005	880
4	*foreman*	60	503	810
5	*foreman*	60	503	810

at $11/12 = 0.92$ percentile. The bandwidth required by each video flow is approximately equal to the bitrate at the knee of the CDF curves since it approximates the mean value of the video flow bitrate. Despite only a small fraction of the peak bitrate is reserved, a high percentage (92%) of the video fit into the reservation. This reservation point has been shown to be a good compromise between efficient resource utilization and video communication performance [12], [13]. Moreover TDuCSMA has been shown to be adaptive since it intrinsically allows bandwidth reuse. Hence the remaining part of the video can exploit the bandwidth unused by the other devices, with obvious benefits in terms of QoE. This is a great advantage with respect to traditional HCCA based solutions where reuse must be implemented with specific functions and indeed it represents a cost in terms of complexity.

In the second step of the bandwidth reservation process, the needed amount to be reserved inside the TDuCSMA nodes is computed by means of Eq. (2), (3) and (4), given an estimation of the mean packet length.

IV. SIMULATION ANALYSIS

A. Simulation Setup

Simulation were run in *ns-2* to assess the performance of TDuCSMA in the home networking scenario depicted in Fig. 3. It comprises a home access gateway (HAG), a video surveillance camera, two mobile devices that are presented as Tablet A and Tablet B in the picture and a laptop. The devices communicate wirelessly in accordance with the mesh paradigm, that is, they send data directly to the destinations without using an access point. The devices operate in accordance with the IEEE 802.11a standard at the physical layer. Hence $SIFS = 16\mu s$, $slotTime = 9\mu s$ and the PLCP preamble and header are 96 and 24-bit long respectively. Moreover the MAC header length is 34 bytes and the ACK length is 14 bytes. In all the simulations the liberate R and the basic linerate are set to 6Mb/s with auto-fall-back disabled.

In TDuCSMA nodes:

$$AIFS^i = SIFS + AIFSN^i \cdot slotTime \; \forall i = H, l$$

where $AIFSN^H = 2$ and $AIFSN^l = 7$, $CW^H_{min} = CW^H_{max} = 1$ whereas $CW^l_{min} = 31$ and $CW^l_{max} = 1023$. Moreover $T_c = 33$ TFs and $T_f = 1ms$. This particular configuration of the CTR match the periodicity of the video framerate, hence potentially reduces the delay at the sender side [14].

All the simulations were also performed with legacy IEEE 802.11 nodes based on EDCA. Since the traffic scenario comprises only video flows and they all fall within the same video AC, the corresponding EDCA parameters are configured as follows:

$$AIFS = SIFS + 7 \cdot slotTime \tag{5}$$

and the congestion window varies between $CW_{min} = 31$ and $CW_{max} = 1023$ to decrease collision probability hence to make the comparison with TDuCSMA fair in this particular traffic scenario.

The scenario includes five video traffic flows with various characteristics, which are summarized in Table I. The bitrates are chosen in order to be suitable for the application envisioned in the home networking scenario and to simulate a congested scenario; in fact the total offered traffic load is 5 Mb/s that is 83% of the linerate deployed in the simulation.

Videos are encoded using the H.264/AVC video coding standard [15] using the test model software [16]. Video resolution is CIF (352×288 pixels) at 30 frames per second (fps). For robustness, one frame every twelve has been encoded as an I-type frame while the other frames are coded as P-type. The IP/UDP/RTP protocol stack has been used. In case a slice is lost, the decoder applies a simple temporal concealment technique, *i.e.*, it replaces the missing data with the pixels in the same position in the previous frame.

Video quality is evaluated by means of the peak signal-to-noise ratio (PSNR) which, despite its limitations, is a widely used measure in the multimedia research community. The PSNR of one frame is computed (in dB) as $10 \log_{10} \frac{255^2}{MSE}$ where the mean squared error (MSE) is the average of the pixel-by-pixel squared difference between the image under test and the original uncorrupted image. The PSNR of the sequence is computed as the average of the PSNR of all the images.

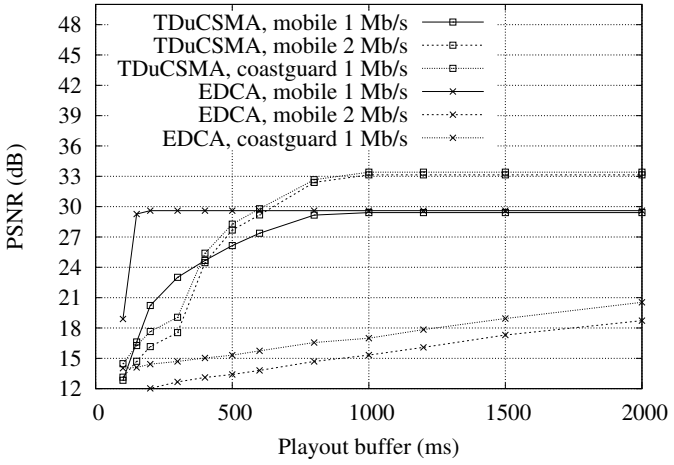

Fig. 4. PSNR performance as a function of the playout buffer size for the non-videoconferencing video sequences, with EDCA or the proposed TDuCSMA scheme (flow number #1, #2 and #3 in the scenario.)

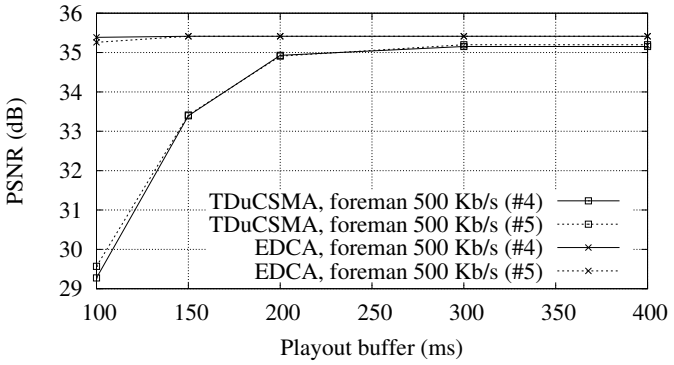

Fig. 5. PSNR performance as a function of the playout buffer size for the videoconferencing video sequences, with EDCA or the proposed TDuCSMA scheme (#4 and #5 refers to the flow numbering in the scenario.)

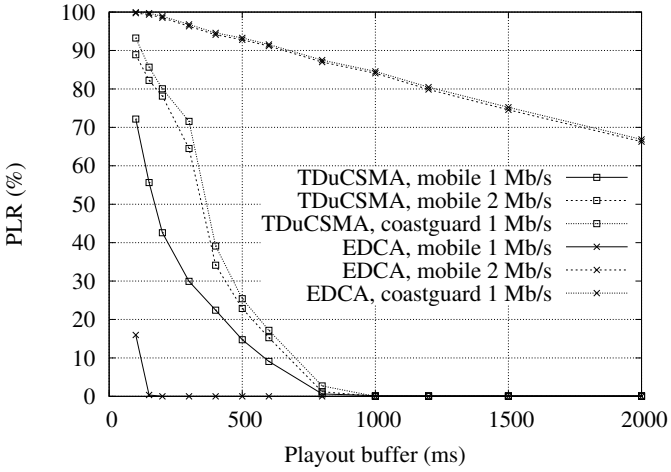

Fig. 6. Packet loss rate as a function of the playout buffer size for the non-videoconferencing video sequences, with EDCA or the proposed TDuCSMA scheme (flow number #1, #2 and #3 in the scenario.)

TABLE II
DELAY STATISTICS OF VIDEO FLOWS IN THE CONSIDERED WIRELESS HOME NETWORKING SCENARIO.

Flow #	Scheme	Delay (ms) Avg. (ms)	Std. dev.	Max.
1	TDuCSMA	243	204	900
1	EDCA	52	42	167
2	TDuCSMA	361	197	851
2	EDCA	2809	1505	5312
3	TDuCSMA	388	197	857
3	EDCA	2838	1504	5324
4	TDuCSMA	53	44	230
4	EDCA	20	20	109
5	TDuCSMA	50	43	221
5	EDCA	20	20	107

Moreover, as in any multimedia communication system, a playout buffer is simulated to discard packets that arrive too late for playback. Various playout buffer sizes are simulated to assess the performance as a function of different application level requirements. Generally, for Internet videoconferencing purposes the maximum end-to-end delay should be not higher than 400 ms, while for video communication applications the maximum transmission delay strongly depends on the application. For a live streaming, it should be limited to about one second not to affect the QoE. Indeed it is necessary to keep the delay low in the live scenario since if other nearby users are watching the same transmission using a different technology it is extremely annoying to listen to what is going to happen in advance because of the transmission delay (think about, *e.g.*, a soccer game). On-demand streaming, instead, can tolerate several seconds.

B. Simulation Results

This section shows the performance that can be achieved by TDuCSMA for video communication in the wireless home networking scenario shown in Fig. 3. When TDuCSMA is exploited, a share of the wireless bandwidth is reserved to each device in accordance with the mean bitrate of the streamed video sequence as addressed in Section III.

Fig. 4 shows the PSNR performance of the video sequences simulating video surveillance and video entertainment applications as a function of the playout buffer size. The performance with both TDuCSMA and EDCA is shown for comparison. It is clear that TDuCSMA provides huge advantages over EDCA while maintaining the compatibility with the IEEE 802.11 standard. For instance, gains are up to 13 dB PSNR with a 500 ms playout buffer and it is still up to 12 dB PSNR when the playout buffer is increased to 2000 ms.

Fig. 5 shows the PSNR performance of the video sequences simulating the videoconferencing as a function of the playout buffer size. The performance with both TDuCSMA and EDCA is shown. When the playout buffer is set to about 200 ms the performance with TDuCSMA and EDCA is nearly the same. Therefore, the video quality performance that can be achieved by TDuCSMA is comparable with EDCA. The devices willing

to transmit traffic within the same AC tends to have the same chance to get access to the wireless medium due to the fairness behavior of EDCA among the same ACs. Therefore, devices transmitting low bitrate video, as the ones involved in videoconferencing, having much less packets to transmit, do not experience any losses due to missed access to the wireless medium. However, note that with TDuCSMA the slight performance decrease of the videoconferencing application is more than adequately counterbalanced by the huge quality improvements on the other video flows, as shown in Fig. 4.

Moreover, Fig. 6 shows the packet loss rate (PLR) experienced at the application layer by the video sequences simulating the video surveillance and video entertainment applications as a function of the playout buffer size. The performance of TDuCSMA greatly improves, reducing the PLR to nearly zero, as soon as the playout buffer is increased at about 1 second, which is a value certainly suitable for the considered applications. In the same conditions, the EDCA exhibits large unfairness among the video flows. While one of the sequences experiences nearly zero losses, the others experience very high losses due to their packet transmission delay. Therefore, it is clear that TDuCSMA allows the network to provide each video flow, with different QoS requirements, an adequate service from the QoE point of view. This is due to the advanced bandwidth management capabilities provided by TDuCSMA. The same result cannot be achieved by means of EDCA in the same conditions.

Table II shows the average, standard deviation and maximum packet delivery delay for each sequence and each coordination function. It is clear that for video flows #2 and #3 the average is well above the maximum tolerable delay by the application level, about 1 second in the considered scenario, while the TDuCSMA is able to provide less than 400 ms average delay and maximum delay is equal to 857 ms, well below the application maximum tolerable delay. For flow #1, the situation is similar, however due to the particular scenario setup the flow experiences a low delay also with EDCA. For the remaining flows, *i.e.*, #4 and #5, belonging to the videoconferencing session, both coordination functions provide very low average, standard deviation and maximum delay values, which are suitable to achieve a good QoE at the application layer. Note however that in the same conditions TDuCSMA provides good QoE to all flows while EDCA is only suitable for three out of five flows.

V. Conclusions

This paper investigated the performance of video communications over wireless networks employing the TDuCSMA coordination function. The peculiar characteristics of TDuCSMA have been exploited to maximize the performance of video communications in a realistic home networking scenario. Simulation results show significant performance improvements with respect to legacy IEEE 802.11 network. The video quality gains are up to 13 dB PSNR with 500 ms playout buffer, while the average delay of the video packets is much lower for the same amount of video traffic offered to the network. Thus TDuCSMA can play a key role in enhancing the QoE of the users of the video communications while retaining compatibility with the IEEE 802.11 standard.

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