A MAC protocol for high-speed multimedia WPANs

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Abstract

Among several wireless network scenarios, the in-home environment is one of the more challenging in the last years. In particular, the Wireless Personal Area Network (WPAN) seems one of the most interesting application scenario, as that networks work in small area for delivering multimedia traffic. The IEEE 802.15.3 is the emerging standard for WPAN. This standard is designed to provide low complexity, low cost and low power-consumption for personal area networks that manage multimedia traffic, video and audio between different devices in a small area environment. The piconet is the basic topology structure of a WPAN and it is defined as group devices, where one of them is the PicoNet Coordinator (PNC). A PNC manages the synchronization and controls the data traffic of the system. This paper proposes an adaptive Medium Access Control (MAC) technique for high data-rate WPANs. The proposed system aims to maximize the performance of the WPAN in terms of throughput, considering multimedia traffic.

I. Introduction

In the recent years, the short range communications have achieved a great importance due to the high degree of miniaturization in communication devices and achievable data rates. In the begin there was the Bluetooth [1], that was introduced as a wireless alternative for the wired interconnection of computer devices, such as mice and keyboards, or as a wireless connection between cellular phones and headsets. Since early, it was clear that the great limit for the Bluetooth expansion was the data rate: too low for supporting the emerging multimedia applications.

A new improvement in the small area network deployment was due to the introduction of the Ultra-Wide Band (UWB) technology [2], [3], that differs from previous communication systems for the use of radio impulses that allow to have an ultra-wide bandwidth occupation with low power emissions, leading to high data rate transmissions. Moreover, the UWB devices can be miniaturized very well becoming a interesting solutions for the interconnection of multimedia devices. At the same time the consumer electronics seem to marry the law of miniaturizing themselves from year to year, and the possibility to carry a great variety of media (e.g., music, video, photo) on the same device has led to the need of interconnecting all the personal devices between them.

For the above mentioned purposes, there was introduced the piconet, that are, as the name said, very small area networks. Their aims is to interconnect several multimedia devices, such as, DVD players, MP3 players, digital video cameras, digital picture cameras, and other digital devices between them or with PCs, Hi-Fi, digital TVs, and so on. Several standards have been introduced in the recent years; among them the IEEE 802.15 family is the one that seems to have the highest probability for becoming the universal standard for Wireless Personal Area Network (WPAN) communications.

In particular the IEEE 802.15.3 [4] have as goal the definition and standardization of physical and MAC layers for high data-rate WPAN [5]; the IEEE 802.15.3a version aims to use Ultra-Wide Band (UWB) communications at the physical layer.

In this paper, it has been proposed a novel management scheme at the MAC layer for improving the performance in terms of throughput for an IEEE 802.15.3a based WPAN, where data and video communications are presents between several devices. By choosing in an adaptive way the amount of time to assign to each type of traffic, it is possible to improve the network performance respect to the standard.

The paper is organized as follows. In the Section II, it has been introduced the IEEE 802.15.3 standard, and its framing structure. The proposed adaptive technique at the MAC layer is presented in Section III, while in Section IV the numerical results obtained via computer simulations are explained. Finally Conclusions are drawn.

II. IEEE 802.15.3

Among the various standards belonging to the IEEE 802 family, in the last decades it has been decided to develop a particular standard for communication in the short range environment. The IEEE 802.15 is the standard that aims to cope the physical and MAC layers of communications between devices in a so-called Wireless Personal Area Network (WPAN). The IEEE 802.15.3 standard [4] defines the PHY and MAC layers for high data rate wireless personal area network (WPAN). In particular, the IEEE 802.15.3a specifies a PHY layer with UWB technology, with the goal of achieving a data rate of about 110 Mb/s.

The 802.15.3 MAC works mainly with network with piconet topology. A piconet is defined as a wireless ad hoc data communications system which allows some independent data devices (DEVs) to communicate with each other; the standard supposes a maximum of 8 devices associated at the same time. In Fig. 1 it is showed an example of communications within

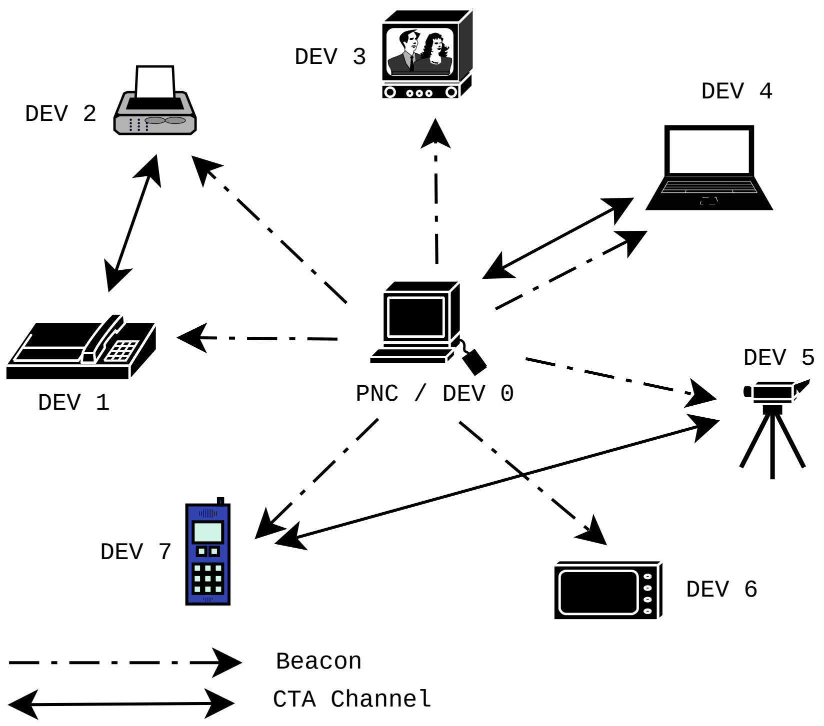


Fig. 1. An example of piconet scenario.

a piconet. It is foreseen that the piconets with more than 8 devices can disconnect that devices that are not communicating or split in sub-piconets.

One of the active devices is required to be the piconet coordinator (PNC); the PNC coordinates the other devices in a piconet, providing them the basic timing, the synchronization of the system and additional information about new incoming devices via a beacon, which is broadcast at the beginning of a superframe period. Moreover the PNC can implement some techniques for QoS management of energy consumption issues. The PNC broadcasts the information about all the devices periodically, by sending the information about how the frame will be divided among all the active devices.

When a new device joins a piconet, the PNC introduces it in the list of associated devices; the standard foresees the change of the PNC if the newcomer device has more computational capabilities of the actual PNC. As said earlier, in the case that the piconet has to support more than 8 devices it is possible to form a sub-piconet. In this case a particular device will become the PNC (Child PNC) of the new piconet [6].

The access technique is based on the Time Division Multiple Access Scheme (TDMA). The most important framing structure of a piconet based on the IEEE 802.15.3a standard is the superframe; it is defined as the time that exists between two successive beacons. The superframe is divided into three periods (Fig. 2):

Beacon It sets the timing allocations and management information for the piconet. It is broadcast from the PNC.

CAP The Contention Access Period (CAP) is used for the transmission of management information and, in the case, asynchronous data. In this period all the devices can transmit commands to PNC and back, and the devices can exchange asynchronous data each other. The CSMA/CA technique is applied in this period.

CFP The Contention Free Period (CFP), also called Channel Time Allocated Period (CTAP), is used for the transmission of isochronous streams and long asynchronous data. It is constituted by several Channel Time Allocation (CTA). This windows is TDMA based. The PNC manages this period by selecting the timing window of each device.

Every superframe is composed by several frame, whose structure and length depend on the type of associated data. The

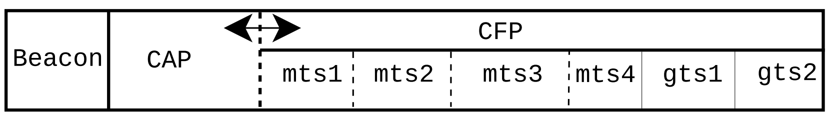


Fig. 2. The superframe structure.

elementary unit of a transmission is the slot and each frame is constituted by a different number of slots. In particular, each frame has a ten byte header, a four byte Frame Check Sequence (FCS) field and a variable length body.

There are three main frame type: beacon frame, command frame and data frame. The beacon frame has a fixed length and it is sent during the Beacon period, at the beginning of each superframe. The beacon is needed for the management of the piconet synchronization. A device has to listen to the beacon frame in order to synchronize to the superframe structure of a certain piconet. In the beacon frame there are the information about the structure of the successive superframe, as superframe length, CAP length, position and length of each CTA in the CFP. The beacon frame is also used by the PNC for broadcasting important information as the change of the PNC device or the communication of the association of a new device in the piconet.

The command frame has a fixed length and is used for carrying management information between devices or from the PNC. The data frame has a variable length and is used for carrying data traffic.

For what concerns the traffic types, they can be classified into three main types, that are asynchronous data, long asynchronous data and isochronous data. The asynchronous data are small size data without any temporal contiguities; they can be sent in the CAP without informing the PNC. If asynchronous data are longer than a predefined threshold, they have to be sent in the CFP by occupying a CTA; the CTA assignment is managed by the PNC. For what concerns the isochronous data, they are managed in a similar way as the long asynchronous data; each isochronous stream is assigned to a certain CTA

All data inside the piconet is exchanged in a peer-to-peer way in the CAP period or in the CFP period. If a device has to send management information or short asynchronous data, it tries to use the CAP channel by entering in the contention state. On the other hand, if a device has to send isochronous data or long asynchronous data, it makes a request to the PNC for the allocation of some reserved slots. In this case the PNC allocates a certain number of slots in CFP for the device, if the resources are available.

The CAP is the contention period where the devices and the PNC can transmit communicate each other frame commands or short asynchronous data. The CSMA/CA technique is applied in this time window. The standard IEEE 802.15.3a uses a handshaking protocol for sending frames in the CAP. This method consists on the transmission of a messages in the channel, after which the device enters in a waiting state. The device has to wait the response message (ACK). When a device is in the waiting state, it cannot transmit other frames. If the ACK message will not arrive before a fixed time, the device has to transmit again the data. A device listens the channel in continuous mode during all the CAP for waiting messages sent to it.

The CFP is the contention free period. If the CAP is distributed, i.e., all the devices are peer, the CFP is centralized and is managed by the PNC. The PNC chooses the number of slots to be allocated in each data channel. As shown in Fig. 2, each CTA can be named into two types belonging to the different nature of the traffic to be sent: GTS and MTS.

The GTS (Guaranteed Time Slot) is used to transmit isochronous traffic. This is the traffic with fixed rate in the time between two devices. For examples audio and video communications or multimedia communications belong to this type of traffic. The PNC chooses the GTS length in slot in order to satisfy the requested data-rate. A GTS will remain reserved to that communication during until the end of the data transmission.

The MTS (Management Time Slot) is used for transmit asynchronous traffic. The PNC can change the MTS length in every superframe, depending on the amount of data in the queues and the number and length of the GTS.

III. Adaptive MAC Technique

The optimization at MAC layer is one of the most important challenge for high data-rate WPAN [7], [8]. The proposed MAC protocol aims to maximize the performance in a high data-rate WPAN environment, by maximizing the total network throughput and minimizing the delay of each device pair. It has been supposed that some information about the superframe structure are broadcast in the Beacon frame, as the CAP duration and the CTA structure. The length of CAP is supposed to be dynamic varying frame by frame; its length is determined by the PNC after knowing the amount of data present in the devices. For what concerns the CTA, it has been supposed that it can be a GTS or a MTS; the choice is made by the PNC after a sending request made by a device in the piconet. Moreover, following the standard specifications, while the CAP is contention-based, i.e., all the devices, including the PNC, wait the channel until it is free, the CFP is directly managed by the PNC. It is supposed that at each superframe, the PNC knows the amount of data present in that moment in the network, choosing so the number of slot to be allocated to each peer-to-peer communication between devices.

As mentioned before, the PNC is the coordinator device; it provides the synchronization of the system and decides the superframe composition. The PNC has the list of all active CTA in each superframe. It knows the amount of data waiting in the transmitting queue of each device .

At first, it has been supposed that each MTS has a fixed length; even if this could lead to a simplified management of logical channels, it is a limit in heavy traffic conditions. For this reason it has been then supposed that the length of each MTS can vary superframe by superframe as the traffic conditions varies.

In the case a MTS between two devices is already active and a new data message has to be sent between them, it has been supposed that it can use the already active MTS; it is easily to understand how this choice can limit the amount of management data to be exchanged for the opening of a new session after the end of the previous one.

The PNC, after having allocated all the GTS, allocates the remaining slots of the CFP period to the MTS channel. It has been supposed that the length of the CAP depends on the amount of data already assigned to the CFP in that superframe, with the constraint of a minimum threshold. For what concerns the MTS, the PNC uses a mechanism that allocates a certain number of slots to every MTS proportional to the amount of traffic waiting inside the transmitting queues. In order to calculate the maximum period to be used by the CFP, it has been selected the following equation:

$$T_{\text{CFP}}^{\text{max}} = T_{SF} - T_B - T_{\text{CAP}}^{\text{min}} \tag{1}$$

where T_{SF} is the superframe duration, T_B is the beacon frame duration and $T_{\text{CAP}}^{\text{min}}$ is the minimum time duration for the CAP. If the total amount of data to be sent is less than $T_{\text{CFP}}^{\text{max}}$, the CFP is long as needed; in the other cases, it is calculated as explained in the following. The PNC calculates the loading factor L, that allows to give a weight at every slot of the CFP period:

$$L = \frac{T_{\text{CFP}}^{\text{max}}}{T_{\text{data}}} \tag{2}$$

where T_{data} is the sum of all the traffic that have to be transmitted in the CFP. In the case that there is sufficient space for the transmission of all data message in the MTS list, then $L = 1$ and the CAP period is longer. The number of slot of the i-th MTS can be then calculated in this way:

$$N_{\text{MTS}_i} = N_{\text{MTS}_i}^{\text{min}} + (L * N_{\text{data}_i}) \tag{3}$$

where N_{data_i} is the number of slot that have to to be transmitted in the i-th MTS, while $N_{\text{MTS}_i}^{\text{min}}$ is the minimum number of slot that is possible to allocate to a certain MTS channel. By using the above described mechanism, the devices with less data to be sent have higher priority, reducing so the average delay of each message in the transmit queue. The PNC, after having chosen the superframe composition, broadcasts this information to all the devices in the piconet, so that each device knows, for all the MTS present, its initial time and his length in slot.

IV. Numerical Results

In this Section, the numerical results obtained via computer simulation will be shown. By them it is possible to validate the proposed MAC protocol for an UWB based WPAN that uses the IEEE 802.15.3a standard. In particular it is possible to see how the proposed protocol can improve the performance of a piconet in the case of multimedia traffic. For our purpose we have considered a communication scenario with best-effort (WWW) data traffic and MPEG1 video traffic.

Even if in IEEE 802.15.3a it is possible to use a very high bit-rate, we have considered, due to computational capabilities, to use a physical channel supporting 11 Mbit/s. The numerical results will be obtained with the following parameters:

- One slot is composed by 512 byte and it lasts 3.5 μs;
- One superframe is composed by 200 slots and it lasts 70 ms;
- The command frame lasts 2 slots;
- The beacon frame lasts 3 slots;
- $N_{\text{MTS}_i}^{\text{min}}$ is equal to 2 slots

As said before, it has been supposed that two type of data traffics are present in the piconet. The first one is useful for modeling the web traffic and it is based on the joint use of a Poisson statistic for the message interarrival and a trunked Pareto for the message length, having a p.d.f.:

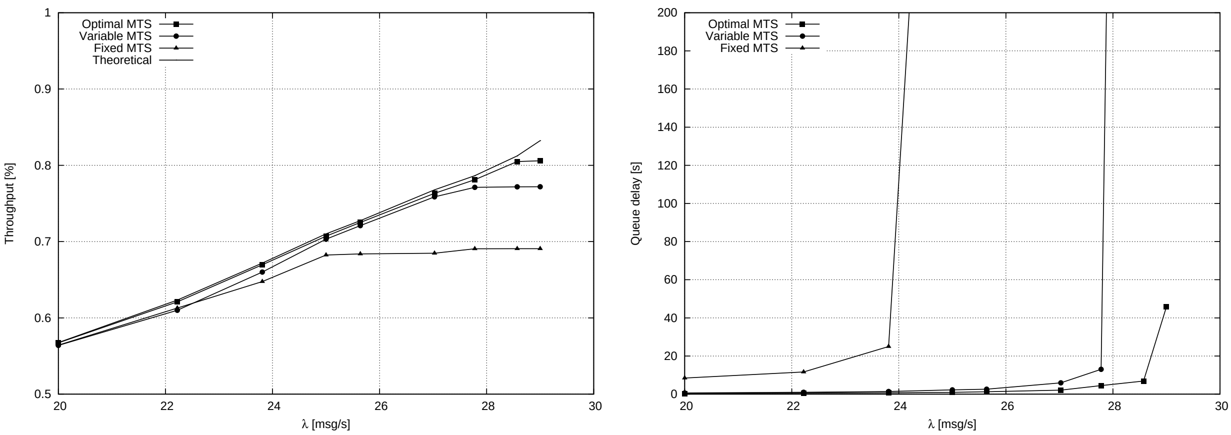
$$f(x) = \begin{cases} \frac{\alpha k^{\alpha}}{x^{\alpha+1}}, & k \le x < m \\ \frac{k^{\alpha}}{m^{\alpha}}, & x = m \\ 0 & x < k \quad \text{or} \quad x > m \end{cases} \tag{4}$$

where α=1.1 is the shape parameter, k=1858 bytes is the location parameter (corresponding to the minimum message length), and $m = 5 \cdot 10^6$ bytes is the maximum message length. By using the above parameters the average message length is about 12KB.

For what concerns the video traffic, is has been supposed to have a Constant Bit-Rate (CBR) MPEG1 streaming with 1.5 Mbit/s, that corresponds to have message with length equal to 16384 bit with an interarrival period equal to 10.4 ms.

The first considered scenario is constituted by only MTS channel and web traffic; three types of frame management has been foreseen, named fixed MTS, variable MTS and optimal MTS. The simulation scenario has been evaluated in terms of throughput and message delay. It has been also supposed that:

- the number of devices is 4;
- the minimum CAP length is $N_{\text{CAP}}^{\text{min}}$ = 35 slots;
- the maximum message length that can be transmitted in the CAP is $N_{\text{CAP}_i}^{\text{max}}$ = 10 slots.



(a) Throughput. (b) Message delay.

Fig. 3. Performance in terms of throughput and delay for the piconet scenario by using fixed MTS, variable MTS and optimal MTS.

In the fixed MTS policy, it has been supposed that each MTS frame has a fixed length throughout all the simulation, and it has been supposed that its length is 13 slots. This choice has been done in order to guarantee the communication between all possible active nodes within the piconet at the same time.

In the variable MTS policy it has been supposed to vary the number of slots per MTS frame according to the amount of data that each device has to send. As explained in the Section III, this management policy has as drawbacks the increasing of management traffic.

The idea that is behind the optimal MTS management is that when the traffic condition is heavy it is better to use more the Contention Free Period (CFP) while in the case of weak traffic conditions, it could be better to use more the Contention Access Period (CAP), that, despite a contention based access, does not need to notify the PNC of a new transmission, lowering so the management traffic. In the optimal MTS management, it has been calculated via computer simulations the optimal value of $N_{\text{CAP}}^{\text{min}}$ and $N_{\text{CAP}_i}^{\text{max}}$ for minimizing the queue delay in each device. The outlined optimization process can be easily implemented by each node also in real scenario considering that each one can calculate the delay of each message in the queue; the device communicates it to the PNC, approaching the optimal management in a distributed way.

In Fig. 3, the performance in terms of throughput and delay is shown. The comparison is made between the three above described MTS management policies (fixed MTS, variable MTS and optimal MTS) by varying the message interarrival time and supposing the trunked Pareto message length distribution in (4). In the case of the throughput, the comparison has been made also with the theoretical case, in which all the messages have been supposed to be sent without delay, that corresponds to:

$$\eta = N \frac{\bar{l} \cdot T_{\text{slot}}}{\overline{T}} \tag{5}$$

where N is the number of active devices in the piconet, $\bar{l}$ is the average message length in slots, T_{slot} is the slot duration and $\overline{T}$ is the average message interarrival time. It is possible to see hoe the proposed optimal MTS length management outperform the other techniques in terms of throughput and delay, allowing an almost ideal throughput performance with a sensibly lower delay.

In Fig. 4, it is shown the performance in terms of throughput for the optimal MTS management by considering the presence or not of control messages. It is possible to see that, even if the optimal policy increases the management messages the loss in terms of throughput is negligible.

Finally it has been considered a real scenario in which the web traffic uses the MTS and the video streaming uses the GTS. The GTS frames have been introduced in the standard in order to support multimedia traffic with a particular attention to the video streaming. In Fig. 5, the performance for the real scenario in terms of throughput and delay is shown. It has been supposed to have two MPEG1 video streaming on the two GTS channels, and to vary the interarrival time for what concerns the web traffic. The performance comparison has been made by considering also the overall throughput and delay and the theoretical throughput as defined in (5). It is possible to see how, also in this case, the overall throughput approach at most the theoretical case in terms of throughput performance, maintaining also a low message delay.

V. CONCLUSIONS

In this paper has been proposed a MAC technique for high data-rate WPAN. The interest to the WPAN is emerging in the last years due to the growing interest in multimedia communication scenarios. A MAC technique that takes into account the

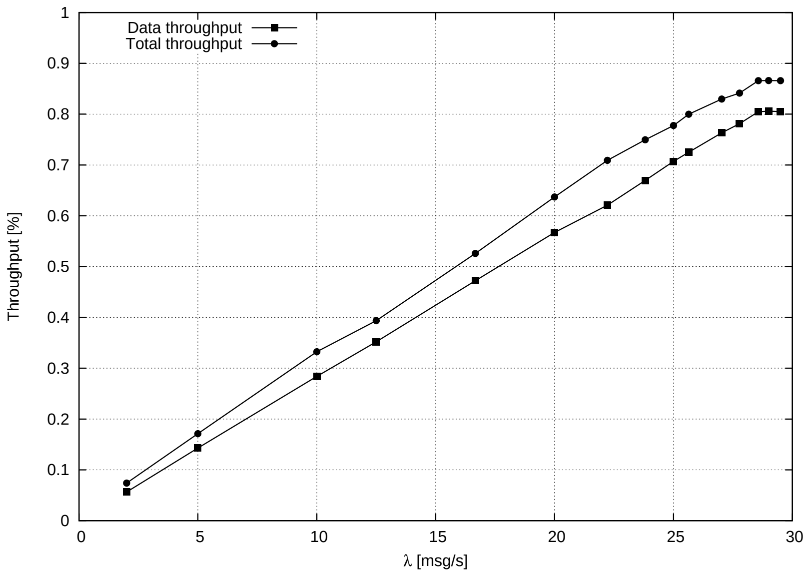
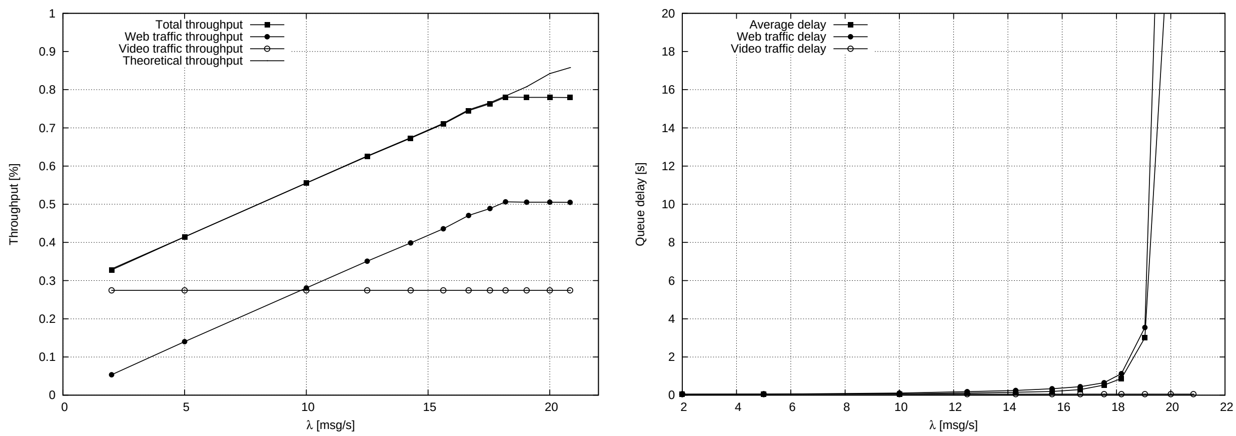


Fig. 4. Throughput comparison by considering the presence of management messages or not.



(a) Throughput.

(b) Message delay.

Fig. 5. Performance in terms of throughput and delay for the piconet scenario by using GTS and MTS.

amount of data in each device ahs been presented; an optimized version has been also considered showing the improvement in performance in terms of throughput allowable. Finally the case of a real scenario with data and video traffic present at the same time has been considered, showing the good performance of the proposed approach.

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