Simulation Model for the IEEE 802.15.3/3b WPAN Standard

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Abstract
The IEEE 802.15.3 is an emerging technology for high data rate wireless multimedia applications in Wireless Personal Area Networks (WPAN). In this paper, a discrete event simulation model has been implemented using OPNET[2] Modeler to simulate the essential characteristics of the IEEE 802.15.3 MAC protocol. The model allows for studying multiple channel access mechanisms defined by the standard and some network management features. Using this model, we have evaluated this protocol over different traffic scenarios. It is shown how network configuration parameters could influence aggregate throughput performance.

Keywords
Wireless Personal Area Network (WPAN), 802.15.3, 802.15.3b, Medium Access Control (MAC), Ad Hoc Networks

1. Introduction
Wireless personal area networks enable wireless connectivity between small electronic devices operating within short distances (i.e. personal space). This space is abstractly defined as an area within 10 m radius of the user location. The IEEE Standards 802.15.4 [1] and 802.15.3 [2] are two different WPAN technologies that define Medium Access Control (MAC) and Physical Layer (PHY) specifications. Development and commercialization of these technologies have offered a simple, inexpensive and efficient solution to interconnect small personal devices. This paper focuses on the IEEE 802.15.3 technology which is intended for multimedia applications, characterized by high data rate, low power consumption, stringent time delivery requirements and support of Quality of Service (QoS).

Simulation models and tools that allow for quantitative performance evaluation of these protocols are extremely helpful for network designers and engineers [5]. As such, we have developed a discrete event simulation model that can assist in characterization of the IEEE 802.15.3 MAC using OPNET Modeler. The model implementation includes three data stream configurations supported by the Standard: asynchronous best effort traffic transmitted through CSMA/CA, asynchronous and isochronous guaranteed traffic transmitted through Time Division Multiple Access (TDMA). The ability to support multiple types of traffics is a distinguishing feature of the 15.3 MAC. Here, we have focused our effort in developing a model that allows us to evaluate the performance of the aggregate network throughout for both isochronous and asynchronous data. For a simple network topology, we have conducted multiple simulations varying both the traffic characteristics (i.e. packet size and packets arrival rate) and the channel access parameters (i.e. size of the TDMA slots and ratio of the shared medium access vs. guaranteed slots access). The numeric results show the impact of the channel access parameters on the protocol performance i.e. streams with different characteristics will achieve the highest aggregate throughput under different network configurations. Such simulations highlight optimal channel access techniques that can simultaneously accommodate different data streams.

The rest of this paper is organized as follows. Section 2 briefly describes the main characteristics of the IEEE 802.15.3 MAC, and its amendment in IEEE 802.15.3b. The protocol implementation with OPNET Modeler will be presented in Section 3. Performance evaluation in terms of the throughput under different traffic scenarios and operating parameters is provided in Section 4. Finally, conclusions and future work will be discussed in Section 5.

2. IEEE 802.15.3 MAC
2.1 Overview
A piconet is defined as a wireless ad-hoc data communication network covering a circular area of 10 m radius. A piconet consists of many devices, as shown in Figure 1.

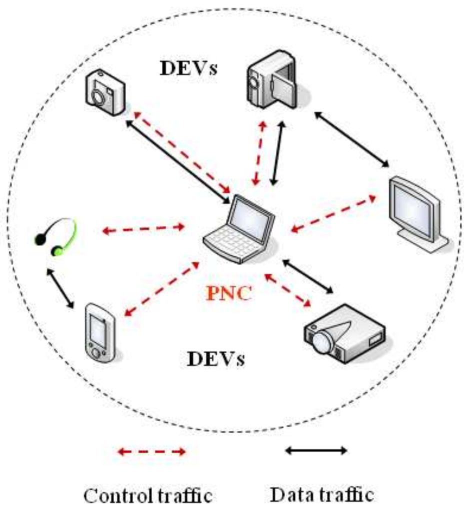

Figure 1: IEEE 802.15.3 piconet

Within a piconet, up to 245 electronic devices can communicate at transmission speeds from 11 to 55 Mb/s. The basic component is the DEV, which represents the simple wireless node of the network. Additionally, there is one DEV within the piconet that is required to assume the role of the piconet coordinator (PNC). The PNC manages the overall functioning of the piconet, coordinating the channel access, sending out information to

[1] This research was performed during author's stay as a guest scientist at National Institute of Standards & Technology located in Maryland USA.
[2] OPNET is registered trademark of OPNET Technologies, Inc. The OPNET Modeler has been used in this research to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standard and Technology, nor does it imply that this product is necessarily the best available for the purpose.

DEVs and responding to associations and channel time requests. After having scanned for existing piconets, a DEV that has the PNC functionality enabled can start its own piconet by sending out beacons on a periodic base.

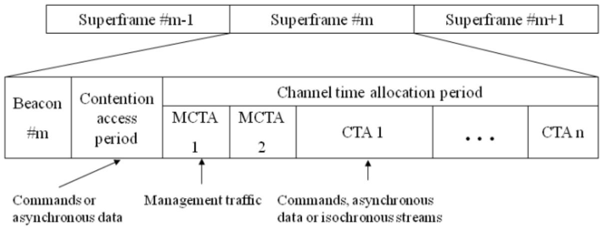

Figure 2: IEEE 802.15.3 Superframe Structure

By sending out beacons, the PNC marks the start of a time period called superframe, which defines a TDMA structure across all devices. As illustrated in Figure 2, the superframe consists of three parts:

- The beacon which is sent by the PNC at periodic intervals and used to spread channel time allocations and management information to the other DEVs.
- The Contention Access Period (CAP) which is used to transmit asynchronous data traffic and commands through CSMA/CA.
- The Channel Time Allocation Period (CTAP) which is composed of Channel Time Allocations (CTAs) and Management CTAs (MCTAs); utilized to transmit commands, isochronous and asynchronous data traffic through TDMA. (According to the IEEE Standard 802.15.3b specifications, CAP and CTAP durations are variable and are set by the PNC.)

By receiving beacons, a DEV can be synchronized with the PNC. It can then transmit its traffic during the CAP or request CTAs (or MCTAs) by requesting the PNC for a specific number of time units. If the PNC accepts the request, it will reserve the necessary number of CTAs in which the requesting DEV has ownership and can transmit to its peer destination without sharing the wireless medium with other DEVs.

The IEEE 802.15.3 standard allows DEVs to create dependent piconets which rely on the parent PNC to allocate dedicated time slots for their operation. Two types of dependent piconets exist: child and neighbor. A child piconet uses a private CTA assigned by the parent PNC to create its own network; the child PNC will coordinate its DEVs, while being a DEV itself in the parent piconet. On the other hand, a neighbor piconet is an autonomous entity. This is because, the neighbor PNC is not a member of the parent piconet, but it is constrained to operate in its CTA assigned from the parent PNC. The latter functionality is used, for example, when there is a need of sharing the same frequency spectrum between several piconets.

2.2 Main Functionalities

The following subsections describe the main functionalities of the MAC protocol described in the IEEE 802.15.3 (3b).

2.2.1 Start of a piconet

A DEV uses passive scanning to determine if there is an active piconet around. This is identified by beacons sent out from the PNC. If there is already a piconet present, the DEV needs to associate with it in order to exchange data with other DEVs. Otherwise, a DEV that has the capability to become PNC can start creating a piconet by sending out beacons.

2.2.2 Association and Disassociation Processes

Both association and disassociation processes have to happen in the CAP part of the superframe. The importance of the association process is stressed by the fact that no data communication is possible between DEVs that are not associated. Moreover, the PNC assigns an 8-bit device ID (DEVID) to each node that will be used instead of the 64 bits MAC address in all communications.

The association process starts when an unassociated DEV sends an Association Request command to the PNC. The PNC answers with an Association Response command including the DEVID to be used within the piconet. After the DEV receives the response, it sends another Association Request to the PNC, using its newly assigned DEVID. During this handshake, a timer called Association Timeout Period (ATP) is created. It is used to check if the DEV sends frames often enough to the PNC. If it does not, it will be disassociated from the network.

The disassociation process can be initiated by either PNC or DEV. The PNC checks periodically on its list to see if some DEVs have an expired ATP. If it finds a DEV with expired ATP, it sends a Disassociation Request command to the DEV. DEVs can also disassociate from the piconet whenever they need by sending a Disassociation Request command to the PNC.

2.2.3 Acknowledgment Strategies

Three acknowledgment strategies as defined in the IEEE 802.15.3 (with an addition in the 3b amendment) are:

- *No-ACK*: no acknowledgment required by the intended recipient.
- *Immediate ACK (Imm-ACK)*: the intended recipient has to send an acknowledgment after a Short Interframe Space (SIFS) from the end of the packet reception.
- *Delayed ACK (Dly-ACK)*: the ACK packet is delayed to acknowledge a burst of packets from the same source DEV. This is used only for isochronous streams.
- *Implied ACK (Imp-ACK)*: the receiver acknowledges the sender by piggybacking the information in its frame to the original sender. This was introduced in 802.15.3b to allow bidirectional data communication inside the CTAs.

2.2.4 CAP Access

Most of the command packets and the asynchronous data traffic are sent during the CAP period through CSMA/CA. The contention based access scheme used here is slightly different from what is used in WLAN [4]. The CAP access procedure is shown in Figure 3 where B represents the beacon packet sent by the PNC.

A DEV that wants to transmit a command or an asynchronous data frame in the CAP has to make sure it has enough time for successful transmission before the end of the CAP. It then waits for a fixed time called Backoff Interframe Space (BIFS) from the time the medium is determined to be idle before beginning the following backoff algorithm.

- Compute *backoff_count=Rand*$_{Unif}$*[0,backoff_window(retry_count)]* where:
  - *retry_count* can take integer values in the range [0,3]
  - *backoff_window(retry_count)* is a table with values [7,15,31,63]
  - *Rand*$_{Unif}$ is a function that draws a random integer from a uniform distribution over the interval [a.b]
- Decrement the backoff counter only when the medium is idle for the entire duration of a time slot called pBackoffSlot, otherwise it has to be suspended.
- When the backoff counter reaches zero, DEV can transmit the frame.
- Reset the *retry_count* if the transmission was successful (i.e. acknowledgment packet received) or increase it if a retransmission is needed.

The backoff counter needs to be suspended outside the CAP period or when there is not enough time remaining in the CAP for the DEV to send the frame. Moreover, the backoff counter needs to be reset at the start of every CAP (as specified in the IEEE 802.15.3b).

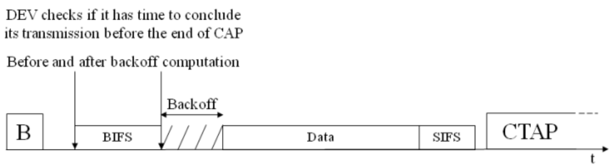

Figure 3: CAP Access

2.2.5 CTAP Access

During the CTAP, PNC assigns CTAs to DEVs; and therefore, guaranteeing that no other DEVs will compete for the channel during these time slots. DEVs in the piconet can use the assigned CTAs for either asynchronous or isochronous data streams. An isochronous stream represents data that has to be sent from the sender to the receiver with a guaranteed data rate.

With the exception of the PNC, which can reserve its own CTAs, all other DEVs need to request channel time from the PNC in order to send packets to other DEVs. Figure 4 shows the Isochronous Channel Time Reservation process.

As shown, DEV-1 sends a Channel Time Request (CTRq) asking for a minimum and desired number of time units (TUs) in order to send its isochronous stream to DEV-2. A TU can be thought of as the minimum amount of time necessary to successfully send a frame. If the requested resource is available, the PNC sends a positive Channel Time Response, indicating the available number of TUs. In the next beacon, the PNC announces the allocation of CTAs for the two communicating DEVs and then DEV-1 can start transmitting at either the desired or minimum data rate. The CTAs will be kept allocated in the next superframes.

The process for reserving Channel Time for asynchronous data is similar. This is illustrated in Figure 5. DEV-1 sends a CTRq asking for a certain number of TUs necessary to send its asynchronous data to DEV-2. When receiving the request, the PNC checks if resource is available and in that case it allocates the necessary CTAs and broadcasts the information through the beacon. In the next superframe, DEV-1 can send its packets to DEV-2 but the CTAs will not be reserved for this traffic in the following superframes. If there is no channel time available at the time, the PNC will not send a negative Channel Time Response command; instead, it will wait until the resource becomes available.

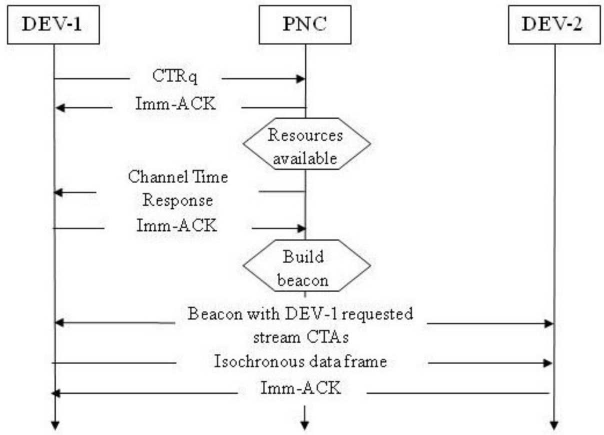

Figure 4: Isochronous Channel Time Reservation

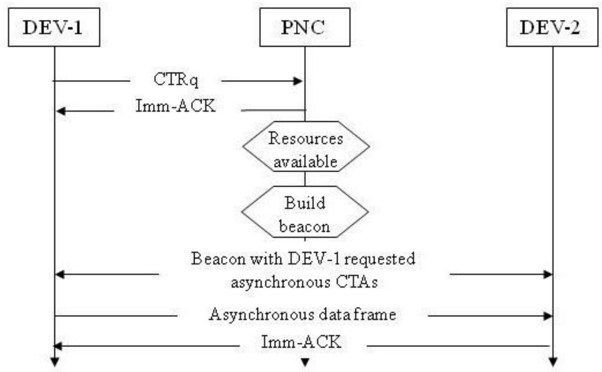

Figure 5: Asynchronous Channel Time Reservation

3. Simulation Model

In our simulation, we have considered a single piconet with no dependent piconets. Inside the piconet, DEVs that are up to 20 m apart are assumed to be able to communicate with each other. Nodes model within a piconet has been implemented to study the protocol according to the standard. DEVs and the PNC use the same node model, but the node that becomes the PNC will execute many more features than the other DEVs in a piconet.

The IEEE 802.15.3 node model is shown in Figure 6. It consists of 4 layers which is a simplification of the OSI 7-layer stack. This would prevent slowing down both the implementation and evaluation processes.
The packet flow within the node model is as follows. At the Application layer packets are created by the source module and sent to the Interface layer which forwards traffic to the MAC layer. The MAC is responsible for controlling the access to the wireless medium. Packets are sent through the TX block (i.e. transmitter) of the wireless PHY layer. At the receiver side of the node, packets arrive at the PHY RX block and get processed

and forwarded to the MAC. The MAC in turn processes the arriving packets and forwards only the data packets to the Interface. From this module, packets go to the sink where they are marked as received at the Application layer.

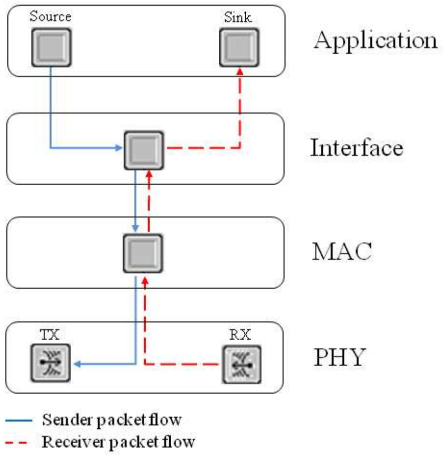

Figure 6: Node Model

3.1 Application Layer

This layer is composed of two blocks: the Source and the Sink. The Source can model up to two asynchronous traffic sources, (i.e. traffic to be transmitted in the CAP or CTAP respectively) and one isochronous traffic source (to be transmitted in the CTAP). The two asynchronous traffic sources generate bursty traffic with variable inter-arrival times and packet sizes. The isochronous source interacts with the MAC by asking for the minimum and the desired data rates. Pending on the answer, it will then generate packets of constant size at the confirmed rate. The Sink module simply receives the data packets; collects the necessary statistics and destroys them.

3.2 Interface Layer

The Interface layer is a very simple component that only checks for the destination to be a valid address and in that case it forwards the traffic to the MAC. On the other direction, packets coming from the MAC are forwarded to the Sink.

3.3 MAC Layer

This block exhibits the modeled features of the IEEE 802.15.3 (3b) MAC. The role of the MAC module is two-folds: 1) it has to perform all the operations that guarantee communication within the piconet and 2) it has to manage the traffic coming from the upper layers to be transmitted on the wireless medium.

3.3.1 Piconet Operations

The main functionalities described in section 2.2 along with some simplifying assumptions listed below have been implemented for simulation of the piconet operation.

- *Fragmentation* and *defragmentation*: used for packets bigger than the MAC Protocol Data Unit (MPDU).
- *Association Maintenance*: DEVs that do not any traffic send a Probe Request command with an empty body to the PNC so that the ATP does not expire.
- *No-ACK* and *Imm-ACK* strategies: a DEV can decide whether data packets need to be acknowledged; and only Imm-ACK has been implemented.
- *Retransmissions*: packets are retransmitted only for asynchronous traffic during the CAP (i.e. if they have the Imp-ACK policy set).
- *No variable length CTAs*: the CTAs in the CTAP part of the superframe all have equal lengths.

3.3.2 MAC Traffic Management

The source traffic arriving at the MAC layer is treated differently based on the type of the application and the part of the superframe that it needs to be transmitted. For this reason, three packet queues have been implemented: Asynchronous CAP, Asynchronous CTAP and Isochronous CTAP. Figure 7 shows this concept.

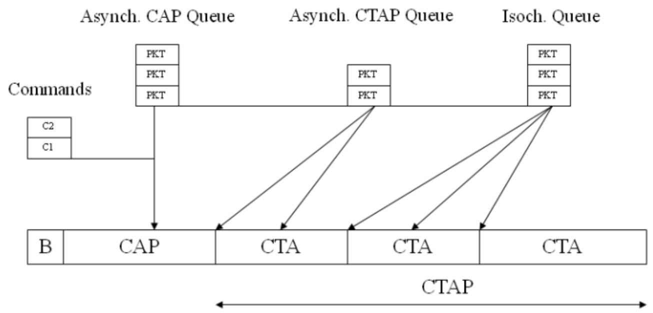

Figure 7: MAC Traffic Management

Packets coming from the first queue together with command packets (which have priority over data traffic) are sent during the CAP. The Asynchronous and Isochronous CTAP queues store packets that need to obtain reserved CTAs in order to be transmitted. When the CTAs are allocated, the DEV can send the queued data packets.

3.4 PHY Layer

The TX and RX blocks model a single-channel simplification of the IEEE 802.15.3 PHY, using only the CHID1, characterized by center frequency fc = 2.412 GHz and Bandwidth B = 15 MHz. No fading is considered in the channel model, thus the power received by terminals is characterized only by path loss given by the Friis formula:

$$P_r = P_t \frac{G_t G_r \lambda^2}{16\pi^2 d^\beta} \quad (1)$$

where Pr and Pt are the power received by the receiving antenna and the power input to the transmitting antenna respectively; Gt and Gr are the antenna gains; λ is the wavelength for the given center frequency; d is the distance between the two entities. For our simulations, we have set Gt, Gr and β to 1, 1 and 2 respectively. Finally, packets are all sent at the mandatory transmission speed of 22 Mb/s using QPSK modulation with transmitting power of 100 mW.

4. Performance Evaluation

In this section, we present our preliminary simulation studies regarding the piconet aggregate throughput. We consider a simple topology characterized by two nodes and a PNC as displayed in Figure 8.

Figure 8: Piconet Scenario for Performance Evaluation

DEV-1 has traffic to be sent to DEV-2 and vice versa. The PNC sends beacons, coordinates the piconet and grants access to the medium during the CTAP. The simulations are conducted separately for isochronous and asynchronous traffic, as they need to be evaluated under different configurations.

4.1 Isochronous Traffic

Since isochronous streams have to be transmitted within reserved CTAs during the CTAP, it is clear that the performance of the protocol is strongly influenced by the choice of the CTAs that best match the characteristics of the traffic (i.e. packet size and data rate). The parameters used in the simulation are listed in Table 1.

Parameter	Value
Superframe Duration	30 ms
CAP Duration	1 ms
CTAP Duration	29 ms
# of CTAs	16-35

Table 1: Parameters for Isochronous Traffic Simulations

The superframe is composed of a very short CAP (used for a few necessary control packets) and a larger CTAP. The CTA slot duration is varied throughout the simulation by dividing the CTAP first into longer duration (i.e. 16 CTAs) and then increasing the number to 35 to achieve shorter CTA duration.
DEVs have the minimum rate equal to the desired data rate. Therefore, if the PNC cannot allocate the necessary slots, the DEV will not transmit any data. Different simulations are performed with both DEVs desired data rates ranging from 1 to 20 Mb/s.

Two traffic scenarios are considered:

1. $packet\_size_{DEV-1}$ = 1000 bytes
   $packet\_size_{DEV-2}$ = 200 bytes
2. *$packet\_size_{DEV-1}$ = 800 bytes*
   $packet\_size_{DEV-2}$ = 400 bytes

Under these assumptions we have made two types of analysis:

- *Unconstrained Maximal Aggregate Throughput*: This shows that given the traffic characteristics, an optimal CTA exists that can achieve the maximum aggregate throughput.

Figure 9 shows the piconet maximal aggregate throughput for different number of CTAs in the CTAP under traffic scenarios 1 and 2. Every bar represents the highest aggregate throughput achievable in the network for every specific CTAP configuration (i.e. number of CTAs, which is inversely proportional to the CTA length). Blue and yellow blocks show the ratio of the aggregate throughput assigned to DEV-1 and DEV-2 respectively. Two-colored blocks signify that the resource was used by both DEVs (under separate simulation runs) to reach the same aggregate throughput value.

For Scenario 1, it is clear that the traffic stream characterized by larger packets gets higher assigned rate and the maximum values are achieved when DEV-1 takes most the resource (transmitting at a desired data rate of 15 Mb/s and DEV-2 transmitting at 1 Mb/s).

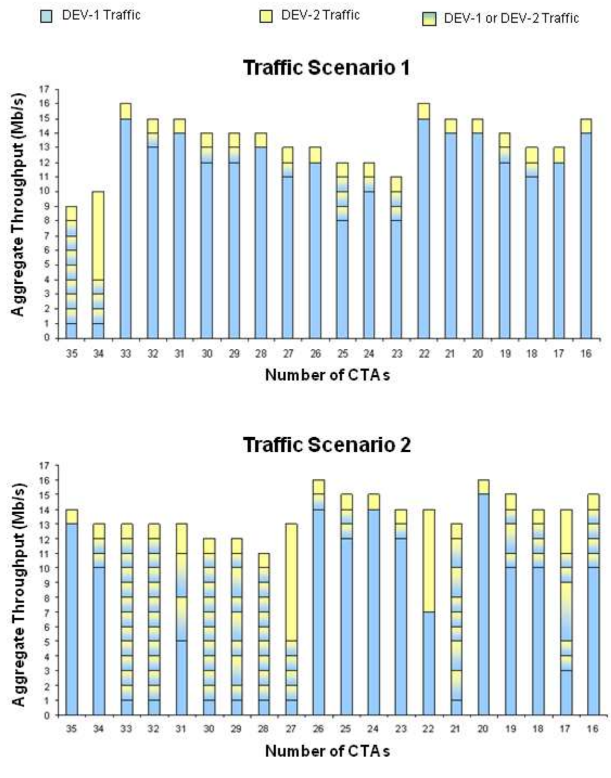

Figure 9: Unconstrained Isoch. Aggregate Throughput

Only the configuration with the number of CTAs equal to 34 fits favors the traffic of DEV-2 compared to that of DEV-1; allowing it to transmit up to 6 Mb/s. In the 2nd scenario where packets sizes from the two DEVs are closer to each other, it is easier to find CTA configurations that can well accommodate both data streams. The highest aggregate throughputs are still reached for unbalanced resource assignments. However, as seen, traffic from DEV-2 can reach reasonably high data rates.

- *Constrained Maximal Aggregate Throughput*: This shows that given the traffic characteristics and equal data rate assignments between DEVs, optimal CTA exists that achieve the maximum aggregate throughput.

Figure 10 shows the maximal achievable aggregate throughput for scenarios 1 (in red) and 2 (in blue) under the assumption that DEV-1 and DEV-2 are transmitting at the same desired data rate. It is clearly seen that the maximal achievable aggregate throughput is higher when packets sizes differ slightly. This is because CTA configurations can easily satisfy the two traffic streams when they are more similar.

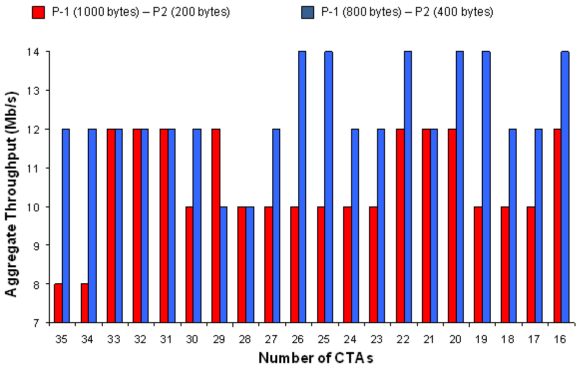

Figure 10: Constrained Isoch. Aggregate Throughput

4.2 Asynchronous Traffic

As explained before, asynchronous traffic can be sent both in the CTAP and in the CAP. When packets are sent during the CTAP we can vary the number of CTAs per CTAP (i.e. CTA length) and study the variations of the aggregate throughput. Here, the asynchronous traffic is modeled by having both DEV-1 and DEV-2 creating x=50 packets at every superframe with a packet size randomly generated following the probability density function of an exponential distribution with mean 1/λ:

$$f(x,\lambda) = \begin{cases} \lambda e^{-\lambda}, & x \geq 0 \\ 0, & x < 0 \end{cases} \qquad (2)$$

Two traffic cases are considered:

1. $\frac{1}{\lambda_{DEV-1}}$= 500 bytes , $\frac{1}{\lambda_{DEV-2}}$= 100 bytes
2. $\frac{1}{\lambda_{DEV-1}}$= 300 bytes , $\frac{1}{\lambda_{DEV-2}}$= 200 bytes

Channel Time Requests are made to the PNC that computes the number of TUs based on the time it takes to successfully transmit the largest packet generated during the superframe.

The network parameters used in the simulations are summarized in Table 2. We have taken three different CTAP durations (and consequently three CAP durations) determined by the CTAP ratio which is the ratio of CTAP over the superframe duration. The number of CTAs varies from 1 to 9.

Parameter	Value
Superframe Duration	10 ms
CTAP Ratio	0.25,0.5, 0.75
# of CTAs	1-9

Table 2: Parameters for Asynchronous Traffic Simulations

Figure 11 shows the graph for the maximum aggregate throughput obtained for the 2 traffic cases and the three CTAP Ratio values, varying the number of CTAs. Curves are paired together (e.g. Case 1 and Case 2 with CTAP Ratio of 0.75) by the same order of magnitude because of results collected with the same CTAP Ratio. As CTAP Ratio decreases, aggregate throughout drops, since CTAs become too small for packets to be transmitted.

The highest aggregate throughput values are reached for Case 1 with unbalanced packet streams. However, for this Case, the aggregate throughput is dominated by the data stream with the larger packets, whereas in Case 2 a more balanced contribution by the two streams is observed. Mid-point number of CTAs (i.e. 5) seems to satisfy both traffic cases.

5. Conclusions

In this paper, we have presented a detailed simulation model for the IEEE 802.15.3 MAC that can be used to study the performance of multimedia applications in WPANs. We have evaluated the protocol performance under different traffic conditions; showing that the aggregate throughput strongly depends on the type of traffic presented to the piconet. We have seen that the size of CTAs could play an important role in determining the fair access to the channel by DEVs. Additional research will be conducted considering more traffic scenarios (and sources) and different access configurations offered by the IEEE 802.15.3 piconet. Other acknowledgment policies could also be added to study their impact on throughput and delay.

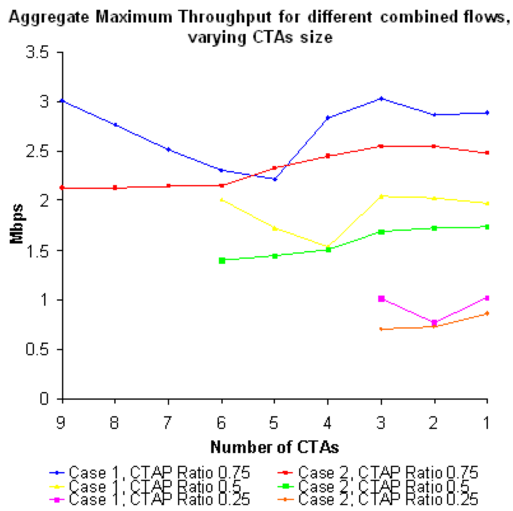

Figure 11: Asynch. Aggregate Maximum Throughput

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