WPAN MAC Protocol: Designing and Analysis with Different ACK Policies

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Abstract: *The Wireless Personal Area Network (WPAN) is an emerging wireless technology for future short range indoor and outdoor communication applications. The IEEE 802.15.3 Medium Access Control (MAC) is proposed, specifically, for short range and high data rates applications, to coordinate the access to the wireless medium among the competing devices. This paper uses analytical model to study the performance analysis of WPAN (IEEE802.15.3) MAC in terms of throughput, efficient bandwidth utilization, and delay with various acknowledgment schemes and aggregation mechanism under different parameters. From the performance analysis we can determine the optimal payload size, burst-size, and ACK policy for a given set of parameters. Moreover, numerical results demonstrate the advantage of frame aggregation with Dly-ACK policy over basic policies of WPAN.*

Keywords: *MAC protocol, IEEE802.15.3, performance analysis, analytical modelling.*

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1. Introduction

The IEEE standard 802.15.3 MAC layer [11] is based on a centralized, connection oriented topology which divides a large network into several smaller ones termed as “piconets”. As shown in Figure 1, a piconet consists of a Piconet Network Controller (PNC) and DEVs (Devices).

The DEV, sensor node, is made to be low power and low cost. In a given piconet one DEV is required to perform the role of PNC (Piconet Coordinator), which provides the basic timing for the piconet as well as other piconet management functions, such as power management, Quality of Service (QoS) scheduling, and security. Using the formation of child and neighboring piconets user can increase the range of network span. The WPAN starter piconet is called as “parent piconet” and child/neighbor piconets are called “dependent piconets”. These piconets differ in the way they associate themselves to the parent piconet.

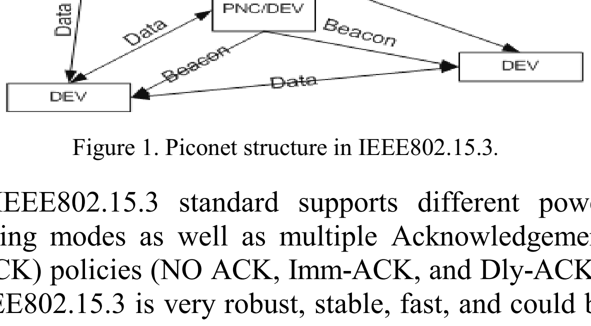

Figure 1. Piconet structure in IEEE802.15.3.

IEEE802.15.3 standard supports different power saving modes as well as multiple Acknowledgement (ACK) policies (NO ACK, Imm-ACK, and Dly-ACK). IEEE802.15.3 is very robust, stable, fast, and could be coexist with other wireless technologies such as IEEE802.11. In IEEE802.15.3 MAC protocol, at the start, communications are connection based under the Supervision of PNC, however, at later stage connections and data transfer can be made in peer to peer fashion.

In IEEE802.15.3 MAC protocol, the channel time is divided into superframes, where each superframe beginning with a beacon. The superframe is made of the three major parts: the beacon, the optional Contention Access Period (CAP), and the Channel Time Allocation Period (CTAP) or Channel Time Allocation time (CTA), as shown in Figure 2.

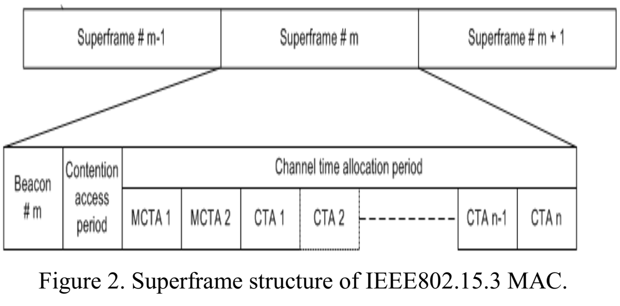

Figure 2. Superframe structure of IEEE802.15.3 MAC.

Wireless channel is usually vulnerable to errors. Hence, error control mechanism is an essential part of any MAC protocol design. A good error control mechanism provides a certain level of reliability in terms of communication robustness and dependability for higher network layers.

In accordance with that, IEEE802.15.3 standard defines three types of acknowledgment mechanisms for CTAs and CAPs as follow: in No-ACK, Imm-ACK, and Dly-ACK [14]. In [11] and some other literature proposed implied-acknowledgment Imp-ACK for bidirectional Communication. Implied acknowledgement Imp-ACK permits a CTA to be used bi-directionally within a limited scope. During the CAP, Imp-ACK is not allowed to avoid ambiguities between two frames:

a. The frame that is transmitted in response to a frame with an implied ACK request.
b. The frame that is transmitted independently when the original frame is unsuccessfully received.

In this paper we focused only on the three aforementioned acknowledgement schemes as Imp-ACK is neither widely accepted in research literature nor in standard documents. To reduce the overhead of the IEEE802.15.3 MAC, we use the concept of frame aggregation. The idea of frame aggregation is to aggregate multiple MAC frames into a single or approximately single transmission [12].

In this paper we combine the frame aggregation concept and Dly-ACK mechanism with minor modification and we define this new mechanism as K-Dly-ACK-AGG, where K is the burst size of data frames [9]. Imm-ACK with aggregation method act same as Dly-ACK-AGG so there is no point to consider Imm-ACK policy individually with aggregation.

All these ACK policies have a large impact on the throughput, delay, and channel utilization of the network and required a detailed study to find overall performance or channel capacity of the network. In this paper, we present the performance analysis of IEEE 802.15.3 from protocol architecture's point of view. Furthermore, we show the effect of aggregation with Dly-ACK,i.e., *K*-Dly-ACK-AGG, on the network performance. In nutshell, the main contributions of this paper are as follows.

- To present an analytical model to understand the designing of WPAN MAC protocol.
- To present a detail performance evolution study to understand the effect of each designing parameters.
- To show the advantage of combining frame aggregation and acknowledgement policies over standard acknowledgement policies.

2. Related Work

In [5], the authors presented the implementation of IEEE802.15.3 module in ns-2 and discuses various experimental scenario results including various scheduling techniques. Specifically, to investigate the performance of real-time and best-effort traffic with various super frame lengths and different ACK policies. In [4], the authors presented an adaptive Dly-ACK scheme for both TCP and UDP traffic with two main contributions. The first one is to request the Dly-ACK frame adaptively or change the burst size of Dly-ACK according to the transmitter queue status. The second is a retransmission counter to enable the destination DEV to deliver the MAC data frames to upper layer timely and orderly. In [8], the authors mainly focused on optimization of channel capacity. Both papers [4, 8] laid a good foundation in simulation and analytical works of IEEE802.15.3 MAC protocol. Similarly, in [14] the authors formulated a throughput optimization problem under error channel condition and derive a closed form solution for the optimal throughput. Also, in [2] the authors presented the throughput analysis of mm-wave WPAN and introduced a private channel release time mechanism to increase the throughput of mm-wave WPAN.

The work presented in [14] is close to our work but their analysis scope is limited only in terms of throughput analysis, while our work span covers the delay, throughput, and channel utilization with different ACK policies under frame aggregation and error channel condition. The paper is outlined as follows. In section 3, we present the designing and analysis of WPAN MAC from protocol architecture's point of view and finally, conclusions and future work are drawn in section 4.

3. WPAN MAC: Design and Analysis

In this section, we present the designing and analysis of IEEE802.15.3 MAC to answer several questions like optimization of payload, optimization of ACK policies, and effect of aggregation, under various parameters.

3.1. Analytical Model

We use ground work of [1, 14] to present our analysis work. Table 1 shows the notations that we used for the analytical model.

Table 1. Parameters notations.

T_{SIFS}	Short Inter Frame Space (SIFS) time
T_{DIFS}	Distributed Coordinate Function Inter Frame Space (DIFS) time
T_{MIFS}	Minimum Inter Frame Space (MIFS) time
CW_{min}	Minimum back-off window size
T_{pre}	Transmission time of the physical preamble
T_{PHY}	Transmission time of the PHY header
$L_{MAC\text{-}H}$	MAC overhead in bytes
L_{ACK}	ACK size in bytes
L_{Data}	Payload size in bytes
$T_{MAC\text{-}H}$	Transmission time of MAC overhead
T_{Data}	Transmission time for the payload
$L_{MAC\text{-}HS}$	MAC Sub-header bytes
$T_{f\text{-}CAP}$	The time for a transmission considered failed during CAP
$T_{s\text{-}CAP}$	The time for a transmission considered successful during CAP
$T_{f\text{-}CTA}$	The time for a transmission considered failed during CAT
$T_{s\text{-}CTA}$	The time for a transmission considered successful during CAT
$T_{ACK\text{-}TO}$	The time-out value waiting for an ACK

The theoretical throughput is given by:

$$Th = \frac{Transmitted\ Data}{Transmission\ Cycle\ Duration} \tag{1}$$

We assume a Gaussian wireless channel model. The channel Bit Error Rate (BER), denoted as p_e $(0 < p_e < 1)$, can be calculated via previous frames or some other mechanism. How to obtain p_e is way out of the scope of this paper. From [1], a frame with a length L in bits, the probability that the frame is successfully transmitted can be calculated as[1]:

$$p_{s=} (1 - p_e)^L \tag{2}$$

Here, for simplicity we assume that a data frame is considered to be successfully transmitted if both data frame and ACK are successfully transmitted in different ACK mechanism policies. We use Imm-ACK, No-ACK, Dly-ACK, and K-Dly-AGG-ACK to denote the immediate acknowledgement, No acknowledgement, delay acknowledgement, and delay acknowledgement with aggregation, respectively. Then we can define p_s for different ACK mechanisms as follows:

$$\begin{aligned}
p_{s-\text{Imm-ACK}} &= (1 - p_e)^{(L_{Data} + L_{MAC-H} + L_{ACK-Imm})*8} \\
p_{s-\text{No-ACK}} &= (1 - p_e)^{(L_{Data} + L_{MAC-H})*8} \\
p_{s-\text{Dly-ACK}} &= (1 - p_e)^{(L_{Data} + L_{MAC-H} + L_{ACK-Dly})K*8} \\
p_{s-K\text{-Dly-ACK-AGG}} &= (1 - p_e)^{(L_{Data} + L_{MAC-H} + L_{MAC-Hs} + L_{ACK-Dly})K*8}
\end{aligned} \tag{3}$$

A successful transmission time during CTA is given by:

$$T_{s-CTA} = \begin{cases}
(T_{MIFS} + T_{Data} + T_{MAC-H} + T_{pre} + T_{PHY}) & for No-ACK \\
(2*T_{SIFS} + T_{Data} + T_{MAC-H} + 2*T_{pre} + T_{PHY} + T_{MAC-ACK} + T_{PHY-ACK} + T_{Imm-ACK}) & for Imm-ACK \\
(K(T_{MIFS} + T_{Data} + T_{MAC-H} + T_{pre} + T_{PHY}) + T_{SIFS} + T_{MAC-ACK} + T_{PHY-ACK} + T_{Dly-ACK} + T_{pre}) & for Dly-ACK \\
(K*T_{Data} + T_{MAC-H} + T_{MAC-HS} + 2*T_{pre} + T_{PHY} + T_{SIFS} + T_{MAC-ACK} + T_{PHY-ACK} + T_{Dly-ACK-AGG}) & for K-Dly-ACK-AGG
\end{cases} \tag{4}$$

From (2, 3, and 4), the normalized throughput during CTA is given by:

$$Th_{CTA} = \begin{cases}
\frac{p_{s-No-ACK} L_{Data} * 8}{T_{s-CTA}} & for\ No-ACK \\
\frac{p_{s-Imm-ACK} L_{Data} * 8}{T_{s-CTA}} & for\ Imm-ACK \\
\frac{p_{s-Dly-ACK} K * L_{Data} * 8}{T_{s-CTA}} & for\ Dly-ACK \\
\frac{p_{s-K-Dly-ACK-AGG} K * L_{Data} * 8}{T_{s-CTA}} & for\ K-Dly-ACK-AGG
\end{cases} \tag{5}$$

Based on the analytical model presented in [13], the upper theoretical throughput limit during CTA is given by:

$$Th_{UL-CTA} = \begin{cases}
\frac{K * L_{Data} * 8}{2 * T_{PHY} + 2 * T_{pre} + T_{MIFS} + T_{DIFS}} & for\ K-ACK-AGG \\
\frac{L_{Data} * 8}{T_{PHY} + T_{pre} + T_{MIFS} + T_{DIFS}} & for\ No-ACK \\
\frac{K * L_{Data} * 8}{T_{PHY} + T_{pre} + T_{MIFS} + T_{DIFS}} & for\ K-No-ACK-AGG
\end{cases} \tag{6}$$

To demonstrate the effect of K-Dly-ACK and K-Dly-ACK-AGG on bandwidth utilization, we define a metric named maximum effective bandwidth (MEB) based on [13], which is a fraction of time the channel is used to successfully transmit data frames versus the total channel time. The maximum effective bandwidth utilization during a CTA/CAP slot is given by:

$$MEB_{CTA} = \begin{cases}
K.\frac{L_{Data} p_{s-Dly-ACK}}{T_{s-CTA}} & for\ Dly-ACK \\
K.\frac{L_{Data} p_{s-K-Dly-ACK-AGG}}{T_{s-CTA}} & for\ K-Dly-ACK-AGG
\end{cases}$$

$$MEB_{CAP} = \begin{cases}
K.\frac{L_{Data} n\psi(1-\psi)^{n-1} p_{s-\text{Dly-ACK}}}{T_{s-CAP}} & for\ Dly-ACK \\
K.\frac{L_{Data} n\psi(1-\psi)^{n-1} p_{s-K-Dly-ACK-AGG}}{T_{s-CAP}} & for\ K-Dly-ACK-AGG
\end{cases} \tag{7}$$

Here, we study how to optimize the channel throughput using different ACK policies under error channel condition. During CAP, if Imm-ACK mechanism is used, every node acquires CSMA/CA with binary exponential backoff. During NO-ACK mechanism every node start with some fixed backoff window value without any knowledge of success/failure of transmitted data frames. When Dly-ACK mechanism is used, a node will randomly select some back of window value and send a number (K) of data frames each separated by an MIFS with Dly-ACK request information in MAC header once its backoff timer reaches zero, and will wait for an ACK. If a burst transmission of K data frames is assumed to be successful, then the sender will reset the backoff window to the initial value; otherwise, the backoff window will be doubled. K-Dly-ACK-AGG follows the same backoff procedure as Dly-ACK. From [1], the failure probability of a transmission during CAP is given by:

$$p_f = \begin{cases}
1 - (1 - p) p_{s-Imm-ACK} & for\ Imm-ACK \\
1 - (1 - p) p_{s-Dly-ACK} & for\ Dly-ACK \\
1 - (1 - p) p_{s-K-Dly-ACK-AGG} & for\ K-Dly-ACK-AGG
\end{cases} \tag{8}$$

For n number of stations, the probability of a transmitted frame collision is given by:

$$p = 1 - (1 - \psi)^{n-1} \tag{9}$$

Where ψ, probability of a station to transmit during a generic (i.e., randomly chosen) slot time is also depends on number of retry limit. This ‘slot time’ is contention window slot and it is different from the data transmission slot. Usually, data transmission slot is

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[1] Readers are advised to have a look at Table 1 while referring equations for parameters notations.

quite long compared to contention window slot. Then, the probability of the busy channel is given by:

$$p_b = 1 - (1 - \psi)^n \qquad (10)$$

From (9) and (10), the probability of a successful transmission occurs in a slot time is given by:

$$P_S = \begin{cases} n\psi(1-\psi)^{n-1} p_{s-No-ACK} & for\ No-ACK \\ n\psi(1-\psi)^{n-1} p_{s-Imm-ACK} & for\ Imm-ACK \\ n\psi(1-\psi)^{n-1} p_{s-Dly-ACK} & for\ Dly-ACK \\ n\psi(1-\psi)^{n-1} p_{s-K-Dly-ACK-AGG} & for\ K-Dly-ACK-AGG \end{cases} \qquad (11)$$

A successful transmission time during CAP is given by:

$$T_{s-CAP} = \begin{cases} \left(\overline{CW} + T_{MIFS} + T_{Data} + T_{MAC-H} + T_{pre} + T_{PHY}\right) & for\ No-ACK \\ \left(\overline{CW} + 2*T_{SIFS} + T_{Data} + T_{MAC-H} + 2*T_{pre} + T_{PHY} + T_{MAC-ACK} + T_{PHY-ACK} + T_{Imm-ACK}\right) & for\ Imm-ACK \\ \left(\overline{CW} + K(T_{MIFS} + T_{Data} + T_{MAC-H} + T_{pre} + T_{PHY}) + T_{SIFS} + T_{MAC-ACK} + T_{PHY-ACK} + T_{Dly-ACK} + T_{pre}\right) & for\ Dly-ACK \\ \left(\overline{CW} + KT_{Data} + T_{MAC-H} + T_{MAC-HS} + 2*T_{pre} + T_{PHY} + T_{SIFS} + T_{MAC-ACK} + T_{PHY-ACK} + T_{Dly-ACK-AGG}\right) & for\ K-Dly-ACK-AGG \end{cases} \qquad (12)$$

Where $\overline{CW}$ represents the average back-off time. The average back-off defines the back-off duration for "light loaded networks", i.e., when each station has access to the channel after the first back-off attempt and is given by:

$$\overline{CW} = \frac{CW_{\min}.T_{slot}}{2} \qquad (13)$$

A failure transmission time during CTA is given by:

$$T_{f-CTA} = \begin{cases} \left(T_{MIFS} + T_{Data} + T_{MAC-H} + T_{pre} + T_{PHY}\right) & for\ No-ACK \\ \left(T_{SIFS} + T_{Data} + T_{MAC-H} + T_{pre} + T_{PHY} + T_{ACK-To}\right) & for\ Imm-ACK \\ \left(K(T_{MIFS} + T_{Data} + T_{MAC-H} + T_{pre} + T_{PHY}) + T_{ACK-To} + T_{SIFS}\right) & for\ Dly-ACK \\ \left(K*T_{Data} + T_{MAC-H} + T_{MAC-HS} + T_{pre} + T_{PHY} + T_{ACK-To} + T_{SIFS}\right) & for\ K-Dly-ACK-AGG \end{cases} \qquad (14)$$

From (11, 12, and 14), the throughput during CAP is given by:

$$Th_{CAP} = \begin{cases} \dfrac{P_S L_{Data} * 8}{(1-p_b)\delta + P_S T_{s-CAP} + (p_b - P_S)T_{f-CAP}} & for\ No-ACK \\ \dfrac{P_S L_{Data} * 8}{(1-p_b)\delta + P_S T_{s-CAP} + (p_b - P_S)T_{f-CAP}} & for\ Imm-ACK \\ \dfrac{P_S K L_{Data} * 8}{(1-p_b)\delta + P_S T_{s-CAP} + (p_b - P_S)T_{f-CAP}} & for\ Dly-ACK \\ \dfrac{P_S K L_{Data} * 8}{(1-p_b)\delta + P_S T_{s-CAP} + (p_b - P_S)T_{f-CAP}} & for\ K-Dly-ACK-AGG \end{cases} \qquad (15)$$

From [13], the upper theoretical throughput limit during CAP is given by:

$$Th_{UL-CAP} = \begin{cases} \dfrac{KL_{Data} * 8}{\overline{CW} + 2*T_{PHY} + 2*T_{pre} + T_{MIFS} + T_{DIFS}} & for\ ACK-AGG \\ \dfrac{L_{Data} * 8}{\overline{CW} + T_{PHY} + T_{pre} + T_{MIFS} + T_{DIFS}} & for\ No-ACK \\ \dfrac{KL_{Data} * 8}{\overline{CW} + T_{PHY} + T_{pre} + T_{MIFS} + T_{DIFS}} & for\ K-No-ACK-AGG \end{cases} \qquad (16)$$

From (1), we can also calculate the average access delay during CTA/CAP.

3.2. Performance Evaluation

In this subsection, we present the performance evaluation of WPAN MAC in terms of throughput, efficient bandwidth utilization, and delay with different ACK policies under the error channel condition. For the performance evaluation we carried out simulation in Matlab [7]. The main parameters for our simulation are based on [6] and listed in Table 2. For the simulation results we do not consider the technology adopted at the Physical layer, however the physical layer determines some network parameter values like inter-frame spaces, etc. Whenever necessary we choose the values of the physical layer dependent parameters by referring to [6]. Also, we do not consider any specific scheduling algorithm to allocate the channel time slots as it is outside the scope of this paper. To design a simple but effective scheduling algorithm is still an open issue. The results obtained here are the average values of our collected data.

Table 2. Parameters values.

Parameters	Values
SIFS	2.5 usec
MIFS	1 usec
Preamble and PLCP Header	9 usec
CW_{min}	8
Payload Size	1~5 KB
ACK Policy	3 basic +Dly-ACK-AGG policies
Data Rate	1~2 Gbps
Control Signal Rate	48 Mbps
Nodes	1~30

Figures 3 and 4 show the throughput for different payload size with different ACK polices without aggregation, for CTA and CAP, respectively. We assume an ideal channel condition for these results. Here, we can observe that No-ACK gives the superior results as most of the CTA and CAP time is utilized for data transfer. However, No-ACK policy is not suitable for every application due to its limited communication reliability compared to other ACK policies.

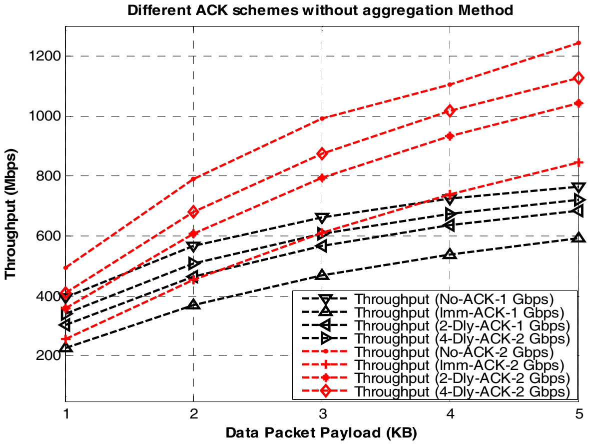

Figure 3. Throughput versus payload size with different ACK policies without aggregation.

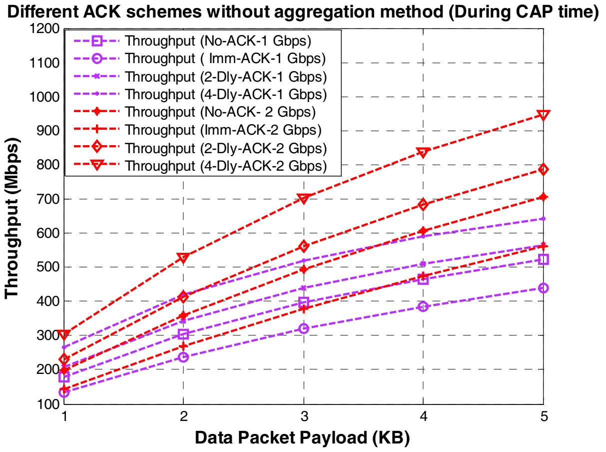

Figure 4. Throughput versus payload size without aggregation.

As a WPAN designer it is always required to design the system with higher data rate or high throughput. One way to achieve this requirement is to increase the data rate; However, that also has some limitations. It is worth to note that the theoretical upper limit exits on throughput due to space limitation we couldn't show the results.

Even if we increase the data rate to infinite without reducing the overhead, we can get only the bounded throughput. So to reduce the overhead and to increase the throughput, with maximum available practical data rate [6] we adopt the frame aggregation method for WPAN. Now, Figures 8 and 9 show the similar results but with aggregation method applied to different ACK policies in CTA and CAP, respectively. Here, No-ACK with aggregation (No-ACK-AGG) is nothing but the simple frame aggregation technique with maximum K burst size [9].

The K-Dly-ACK-AGG[2] policy can achieve somewhat close results to No-ACK policy, as it reduces the unnecessary inter-frame time as well as the header size Due to space limitation we couldn't show the results. From aforementioned discussion it is easy to conclude that aggregation method gives higher throughputs at higher data size but we found it other way around.

Figures 5 and 6 show the percentage gain in throughput using an aggregation method for different payload size for CTA and CAP, respectively. We can observe that as payload size increases, percentage gain in throughput reduces; Reason is being that at lower payload size we can send more data packets in a given CTA/CAP duration but also increases overhead. With aggregation methods we can reduce overhead to a large extend but can't get the same benefit at higher payload size. So there is an open issue for a designer to choose an appropriate data packet size with needed gain in throughput.

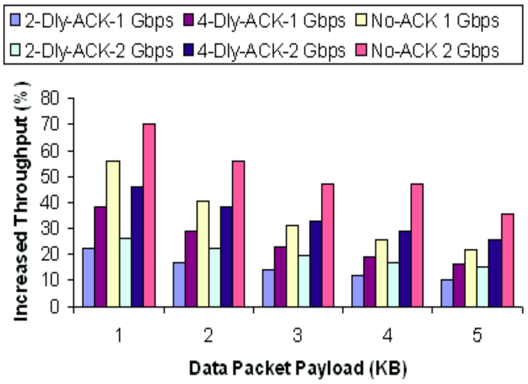

Figure 5. Increased in throughput.

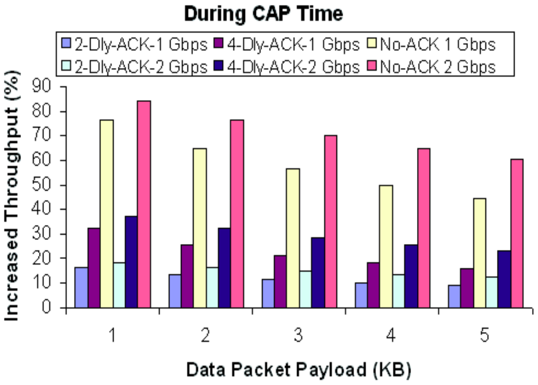

Figure 6. Increased in throughput.

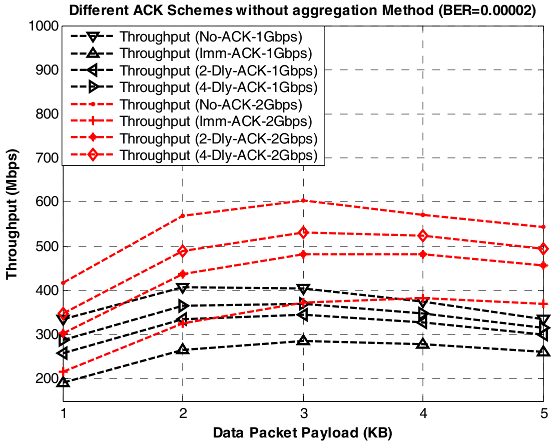

Figure 7. Throughput versus payload size with different ACK policies without aggregation.

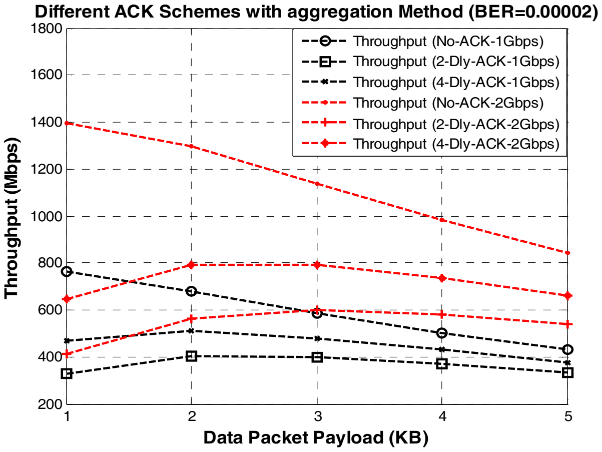

Figure 8. Throughput versus payload size without aggregation.

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[2] In the rest of the paper we keep using terms "*K*-Dly-ACK-AGG" and "DLY-ACK with aggregation" interchangeably.

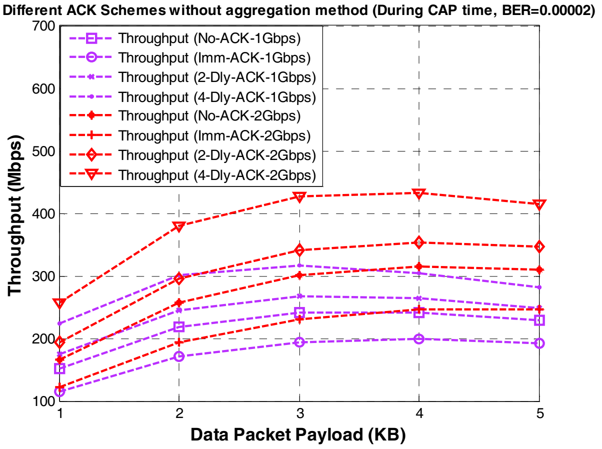

Figure 9. Throughput versus payload size with different ACK policies with aggregation.

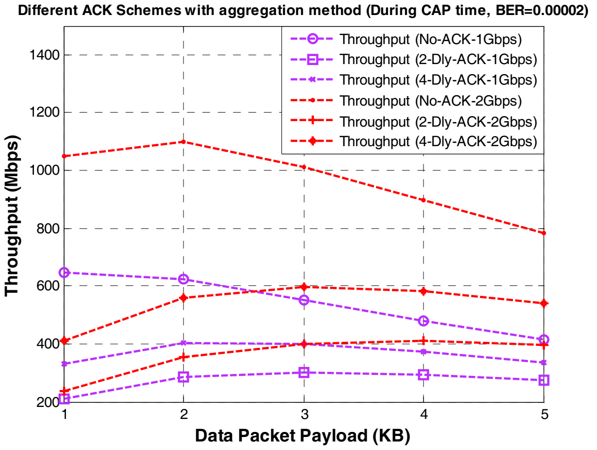

Figure 10. Throughput versus payload size with aggregation.

From Figures 3 and 4, we can observe the value of throughput at different payload sizes but still these results are not sufficient to find the optimum payload size with given ACK policies.

So, we obtained the same results under Gaussian wireless channel model with different BER rates. However, only a part of the results are presented here to reduce the number of graphs in order to maintain the lucidity of the paper. Figures 7, 8, 9, and 10 show the throughput for different payload sizes under different BER values during CTA and CAP duration, with and without aggregation, respectively.

It can be seen that an optimal payload size exists for a given BER value, and the optimal payload size increases as BER values decreases. As shown in the mentioned Figures the throughput first increases, and then decreases with increasing payload size even with the aggregation in error prone channel.

This is because without the protection of FCS in individual payload frame, a single bit error may corrupt the whole frame which will waste lots of medium time usage and counteract the efficiency produced by an increased payload size. So, the initial increase of the curves in Figures show the effect of increased transmission efficiency over the effect of increased frame error probability, while decrees in the curves show the opposite results. From the above mentioned Figures we can find out the optimum payload size value for a given BER value As shown in the results *K*-Dly-ACK with aggregation policy give the best results after No-ACK policy. For all our throughput results during CAP time we select light-load network scenario. However, it is very interesting to note that during CAP duration Figures 8 and 10, throughput performance depends on the number of active stations and back off window size.

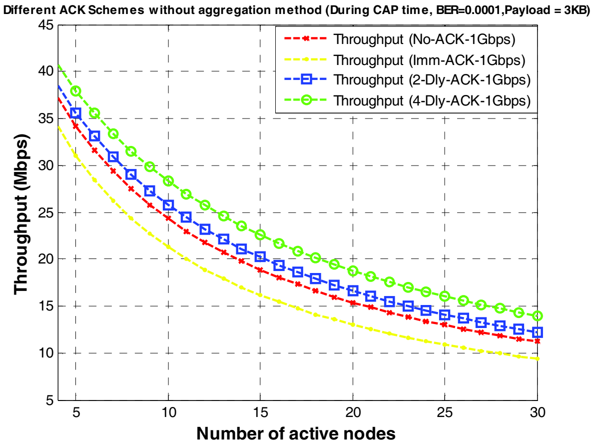

Figure 11. Throughput versus number of active nodes (without aggregation).

Figure 11 further investigate this observation. As shown in the Figure 11 the throughput under a given BER value, with and without aggregation, respectively, decreases as the number of active nodes increases due to increase in collision probability and channel access time. From the aforementioned results we only get the optimal payload size for a fixed BER value which might not be a sufficient result for a WPAN designer. So, to check the performance of a given network under the range of BER values with different payload sizes, we obtained the subsequent results as shown in Figures 12 and 13. As we mentioned earlier for the sake of clarity in the paper, here, we omitted several results with different payload sizes.

Figures 12 and 13 show the normalized throughput for different BER values with different ACK policies when payload size is set to 3KB in CTA and CAP, respectively. As the BER value increases the optimal payload size and the optimal throughput decreases. From the Figure we can observe that the No-ACK policy with aggregation has larger throughput over large range of BER values than any other ACK policies, because No-ACK policy with aggregation gives maximum usage of CTA and CAP duration. Also, we can notice that at higher value of BER throughput reaches to zero, at this value payload size is too big for the given system.

To control the decrement in throughput we need dynamic payload size adjusting mechanism that we left to our future research investigation. Along with an optimum payload size it is also important for a WPAN designer to find an optimum K burst size for frame aggregation policy. So to find the effect of K-Dly-ACK on bandwidth utilization as well as to find the optimal value of burst size for K-Dly-ACK and K-Dly-ACK-AGG policies, we define the MEB metric in 7. Here, Imm-ACK is a special case of K-Dly-ACK (where K=1) so we do not need to define it separately.

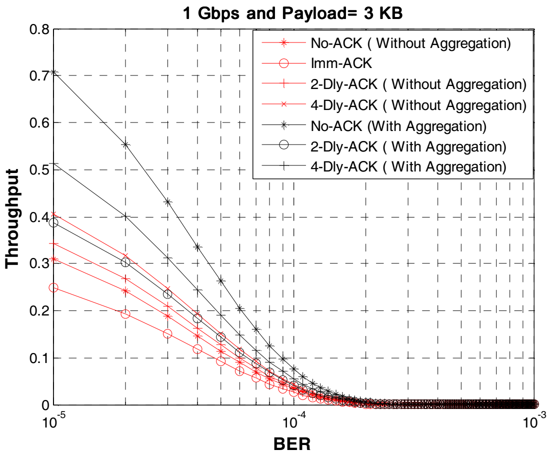

Figure 12. Throughput versus BER value with different ACK policies (3KB).

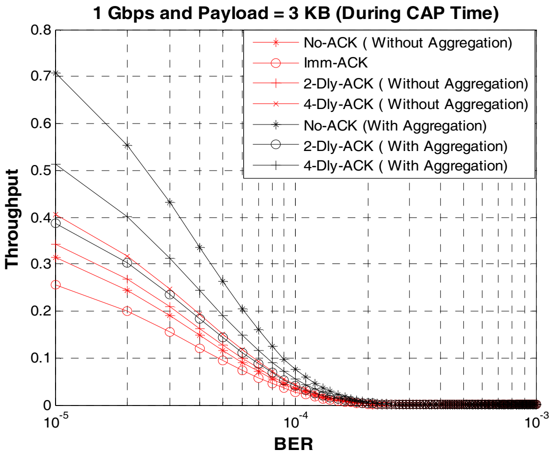

Figure 13. Throughput versus BER value with different ACK policies.

Figures 14 and 15 show the MEB for different burst values for a given BER value, for CTA and CAP, respectively. From the Figures we see that when the burst size increases, bandwidth utilization can be increase initially, but the BER probability also increases and so the bandwidth utilization. From the figures we can find the optimum value for K for different payload sizes under a given BER value, From these figures we can observe that burst size=4 gives good results in fairly all payload values. Here, aggregation method clearly shows it advantage over non aggregation method even at higher value of BER. Again, it is an open trade off between MEB and payload size that a WPAN designer has to decide according to his application requirements. This result also support for our motivation on dynamic adjusting payload size requirement for the WPAN MAC design.

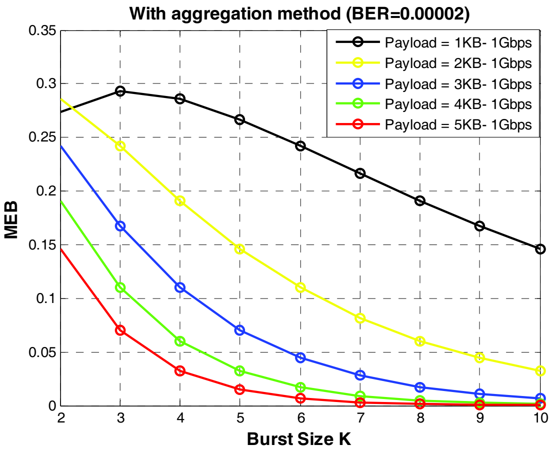

Figure 14. MEB versus burst size (with aggregation).

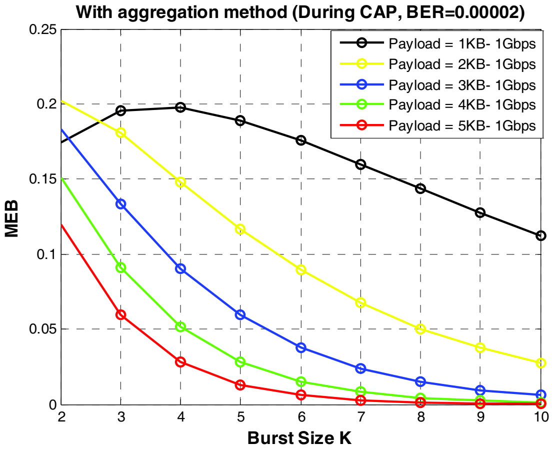

Figure 15. MEB versus burst size with aggregation.

Figures 16 and 17 show the access delay performance for different size with aggregation method, under different BER values for CTA and CAP, respectively. Here, we define the access delay as the time from the moment a packet is ready to be transmitted to the moment the packet starts its successful transmission. For a WPAN designer it is very important to know the maximum possible delay limit for a given network. *K*-Dly-ACK-AGG policy gives the maximum delay limit compared to other ACK policies as it transmit large payload size with aggregation.

Figure 16 shows access delay during CTA period where we do not need to consider any back off and channel access delay, however, during CAP period, the obtained results shown in Figure 17, are largely depends on back off window size and number of active stations. As the number of burst size increases, access delay also increases linearly with it. To reduce the back off and channel access time we would like to use geometrically increasing distribution over uniform distribution for back off algorithm in WPAN MAC. We left this improvement for the future version of this paper.

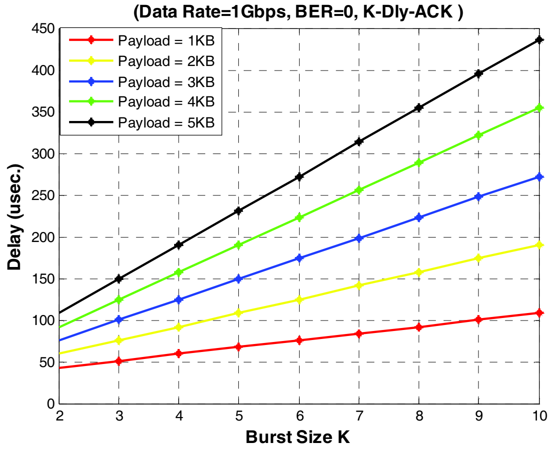

Figure 16. Access delay versus burst size.

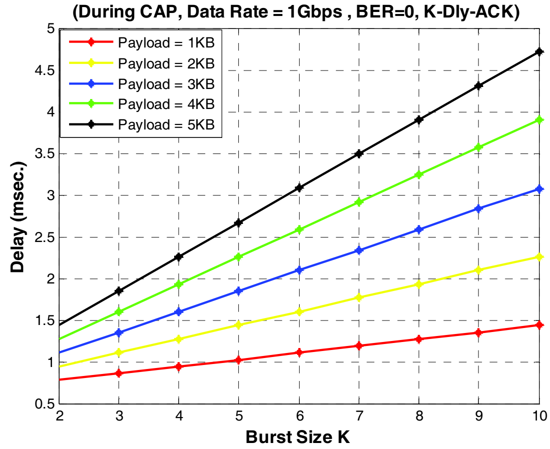

Figure 17. Access delay versus burst size.

4. Conclusions and Future Work

In this paper, we discussed the designing and analysis of WPAN MAC (IEEE 802.15.3) from protocol architecture's point of view. We have extensively studied the different ACK policies in CTA and CAP under different BER values. We also showed the advantage of frame aggregation adopted ACK policy over basic ACK policies. The optimal payload size as well as optimal burst size can be determined analytically from the presented analysis.

Finally, based on our results we come across the two major future research directions: One, to introduce dynamic payload size adjustment mechanism using a cross layer design with physical layer, and second to use geometrical-increasing distribution for back off algorithm during CAP to reduce the collision probability and access delay.

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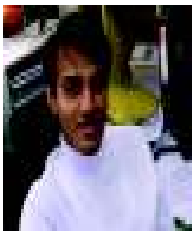

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