Optimal ACK Mechanisms of the IEEE 802.15.3 MAC for Ultra-Wideband Systems

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***Abstract*—Ultra-wideband (UWB) transmission is an emerging wireless technology for future short-range indoor and outdoor multimedia applications. To coordinate the access to the wireless medium among the competing devices, the IEEE 802.15.3 medium access control (MAC) is proposed for short-range high-speed wireless personal area networks (WPANs) in the IEEE 802.15.3a task group. In the MAC, three acknowledgment (ACK) mechanisms are adopted during channel time allocation for error control over the error-prone wireless channel: No-ACK, Immediate-ACK (Imm-ACK), and Delayed-ACK (Dly-ACK). Frames received with errors can be retransmitted in the Imm-ACK and Dly-ACK mechanisms. However, how to optimally use these ACK mechanisms during channel time allocation is still an open issue.**

In this paper, we investigate how to configure the ACK mechanism parameters in order to achieve optimal throughput performance. We first formulate the throughput optimization problem for a contention-free channel time allocation under error channel condition. We then apply the three ACK mechanisms in the contention access period, to optimize the channel throughput. Simulation results demonstrate the effectiveness of our investigation.

***Index Terms*—Bit-error rate (BER), error channel, IEEE 802.15.3, medium access control (MAC), ultra-wideband (UWB).**

I. Introduction

ULTRA-WIDEBAND (UWB) is an emerging simple and low-cost radio technology, and has been considered as one of the promising technologies to provide multimedia services in both indoor and outdoor applications, from wireless personal area networks (WPANs) to wireless ad hoc networks. The ultra-wide bandwidth and ultra-low transmission power density make the UWB technology attractive for high-rate ($>$ 100 Mb/s) short-range ($<$ 10 m) or low-rate ($<$ a few Mb/s) moderate/long-range (100–300 m) wireless communications [1], [2]. UWB transmission has a large processing gain for robust operations in the presence of narrowband interference, covert operations, and fine time resolution for accurate position sensing [1]. It promises to revolutionize home media networking, taking over such tasks as transmitting video, voice, images, and data among high-definition television (HDTV) receivers, TV sets, computers, printers, digital cameras, etc., around a house/office [3], [4]. UWB can also be applied in industrial automation and control, medical monitoring, and vehicular radar systems. As a significant breakthrough for R&D on UWB, the U.S. Federal Communications Commission (FCC) has allowed UWB indoor applications using the frequency band from 3.1 to 10.6 GHz on an unlicensed basis [5]. Industrial standards for UWB include the IEEE 802.15.3a (high data rate up to 480 Mb/s) [6], [7] and IEEE 802.15.4a (very low data rate up to 1 Mb/s) [8]. UWB technology has also been introduced to some Department of Defense (DoD) systems, due to its enhanced ability in secured communications (because of the transmission over ultra-wide bandwidth).

In a UWB network, the wireless medium is shared among mobile devices. Therefore, the multiple access to the channel should be coordinated by a medium access control (MAC) mechanism in an effective and orderly manner. One major stream of the UWB MAC research is the IEEE 802.15.3, proposed in the IEEE 802.15.3a task group. Since wireless channel is usually error prone, error control techniques should be applied in MAC to provide a certain level of reliable delivery for the network higher layers. Accordingly, the IEEE 802.15.3 standard adopts three acknowledgment (ACK) mechanisms, No-ACK, Immediate-ACK (Imm-ACK), and Delayed-ACK (Dly-ACK) under UWB error channel condition. Corrupted frames can be retransmitted in the Imm-ACK and Dly-ACK mechanisms. However, it is still an open issue how to configure the parameters in the ACK mechanisms in order to achieve optimal system throughput performance. This paper is intended to contribute to the MAC parameter optimization in the UWB-based IEEE 802.15.3 wireless networks. We demonstrate that, for a given contention-free channel time allocation to a station, the throughput with the three ACK mechanisms can be represented by the same format. Accordingly, we formulate a throughput optimization problem under error channel condition, and derive a closed-form solution for the optimal throughput. We also apply the three ACK mechanisms in contention access period (CAP), analyze the throughput performance, and determine the optimal throughput numerically.

II. IEEE 802.15.3 MAC

The 802.15.3 MAC [9] adopts the notion of piconets. Each piconet has a number of data devices (DEVs) to communicate with each other on a peer-to-peer basis. Among the DEVs, one is selected to act as the piconet coordinator (PNC), providing timing, access control, and resource allocation in the piconet via the transmission of a beacon. As shown in Fig. 1, time is partitioned into superframes, each of which is further divided into a beacon period, an optional CAP based on carrier sense multiple-access/collision avoidance (CSMA/CA) and a backoff procedure, and a channel time allocation period (CTAP) based

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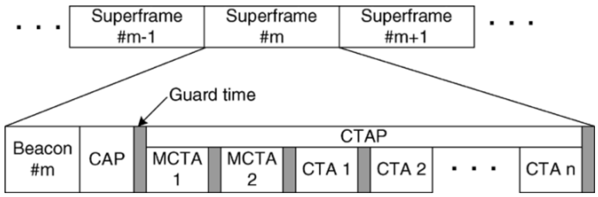

Fig. 1. The basic superframe in IEEE 802.15.3.

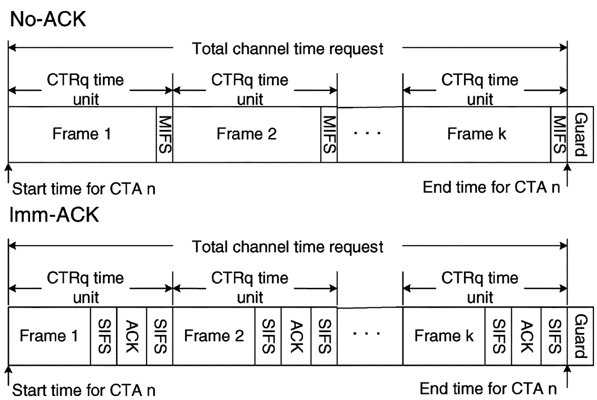

Fig. 2. A CTA under different ACK mechanisms.

on time-division multiple access (TDMA), which consists of a number of channel time allocations (CTAs) including management CTAs (MCTAs). The PNC is responsible for an effective and efficient resource allocation in each CTA.

IEEE 802.15.3 defines three types of acknowledgment mechanisms for CTAs: the No-ACK, Imm-ACK and Dly-ACK mechanisms. For the Imm-ACK and Dly-ACK mechanisms, retransmission is adopted to recover corrupted frames in previous transmissions. For the No-ACK mechanism, ACK is not sent after a reception. The No-ACK mechanism is useful for frames that do not require guaranteed delivery, where the retransmitted frame would arrive too late or where an upper layer protocol is handling the ACK and retransmission. In the Imm-ACK mechanism, each frame is individually ACKed following the reception of the frame. The Dly-ACK mechanism allows the source to send multiple frames without waiting for individual ACKs. Instead, the ACKs of the individual frames are grouped into a single response frame to be sent to the source DEV.

For the Imm-ACK and Dly-ACK mechanisms, frames start transmission after a short interframe space (SIFS) at the end of the previous frame transmission. When either the No-ACK mechanism or the Dly-ACK mechanism is used, a minimum interframe space (MIFS) is used in the CTA between a frame and the next successive frame transmitted over the medium.

Fig. 2 shows a CTA with the No-ACK mechanism and the Imm-ACK mechanism, respectively. For the Dly-ACK, the CTA is similar to that for the No-ACK mechanism except that after a burst of frames is received, the whole burst is acknowledged by one ACK frame. The sender retransmits (in the next burst) the frames not acknowledged in the previous ACK frames.

In our research, for the Dly-ACK mechanism, after the burst of data frames is transmitted, the sender sends a delay-request frame (separated by an MIFS) to trigger the ACK from the receiver since it makes the system more robust.

On the other hand, during the CAP, CSMA/CA is used. The DEV or the PNC shall not transmit a frame if such a transmission as well as the ACK frame will go beyond the CAP. A DEV with a frame to transmit first senses the medium for idle for a random length of time, called backoff time. The PNC can send a command after an SIFS following the ACK of a frame in the CAP or following a frame with ACK policy field set to No-ACK in the CAP. In this way, the PNC is not required to perform the backoff procedure before transmitting its frame.

The backoff procedure has the following parameters: retry_count is an integer that takes values in the range 0 to 3, inclusively; backoff_window(retry_count) takes values [7, 15, 31, 63]; pBackoffSlot is a physical-layer (PHY) dependent parameter based on the amount of time it takes to sense the channel; bw_random(retry_count) is a random integer uniformly selected over the interval [0,backoff_window(retry_count)]. A DEV begins the backoff procedure after an idle duration of a backoff interframe space (BIFS), except that at the beginning of the CAP, the DEV begins the backoff procedure after an SIFS idle duration following the beacon frame. The retry_count is zero for the first transmission attempt of a frame. For each backoff stage, the DEV chooses a backoff counter as bw_random(retry_count) and the backoff counter is decremented only when the medium is idle for the entire duration of pBackoffSlot. Whenever the channel is busy, the backoff counter is suspended, and resumed if the channel is sensed idle again for the duration of a BIFS period. When the backoff counter reaches zero, the DEV transmits the frame. The backoff counter is suspended outside of the CAP duration or if there is no enough time remaining in the CAP for the DEV to send the frame. The backoff counter is also maintained across superframes and is not reset with each beacon. If the total time has exceeded the transmission timeout specified for the frame because it was queued for transmission, the backoff counter shall be reset and the attempted transmission shall be cancelled. When a frame is transmitted and the expected ACK is not correctly received by the DEV, the retry_count shall be incremented but shall not be set to more than 3, otherwise, the frame is dropped [9].

III. Throughput Optimization for a CTA

In this section, we define a throughput optimization problem for a contention-free CTA and provide its solution under the three ACK mechanisms. In our analysis, the CAP or MCTAs are not considered for simplicity.

We assume a Gaussian wireless channel model and the channel bit error rate (BER), denoted as p_e ($0 < p_e < 1$), can be calculated via pervious frames. How to obtain p_e is out of the scope of this paper. The optimization problem is to maximize the throughput within a CTA under error channel condition, specifically defined as follows.

Throughput Optimization Problem: Given a BER for the channel and a fixed CTA allocated to a station, the optimization problem is defined as how to maximize the throughput, S, during the fixed CTA period via arranging the transmitted payload size under the Imm-ACK, the No-ACK, and the Dly-ACK mechanisms, where S is defined as the successfully transmitted and/or acknowledged data.

Let $t_{\rm CTA}$ denote a fixed/allocated CTA for a station. Assume that the station has enough data to transmit. For an ideal error-free channel condition, a larger frame has a better throughput. However, for error-prone channel condition, a larger frame is more likely to be corrupted. Therefore, our objective is to obtain the optimal payload size in order to maximize the throughput during $t_{\rm CTA}$ under the three different ACK mechanisms.

Let L_o and L denote the MAC overhead (header and trailer) size and the payload size in bits in a frame, respectively; t_p denote the transmission time of the preamble and the PHY header; L_a denote the ACK frame size in bits; L_r denote the delay-request frame size in bits in the Dly-ACK mechanism; K denote the number of data frame transmissions during $t_{\rm CTA}$; R_b and R_d denote the base rate and the data rate, respectively. The base rate is used for transmissions of MAC header/trailer, the beacon frame, the delay-request frame and ACK, while the data rate is used for transmissions of payloads of data frames.

For a frame with a length x in bits, the probability that the frame is successfully transmitted can be calculated as $(1-p_e)^x$.

The probability that a data frame is considered (by the sender) to be transmitted successfully is denoted by p_s, where the meanings of a successfully transmitted frame differ for different ACK mechanisms. A data frame is considered to be successfully transmitted if: 1) both the data frame and the ACK are successfully transmitted in the Imm-ACK mechanism; 2) the data frame is successfully transmitted in the No-ACK mechanism; or 3) the data frame, the delay-request frame, and the ACK frame are all successfully transmitted in the Dly-ACK mechanism. We use I_ACK, No_ACK, and D_ACK to denote the Imm-ACK mechanism, the No-ACK mechanism, and the Dly-ACK mechanism, respectively. Then, we have

$$\begin{aligned} p_{s,I\_ACK} &= (1-p_e)^{L_o+L+L_a} \\ p_{s,No\_ACK} &= (1-p_e)^{L_o+L} \\ p_{s,D\_ACK} &= (1-p_e)^{L_o+L+L_r+L_a}. \end{aligned} \tag{1}$$

Note that p_{s,D_ACK} should be used with care since other transmitted frames may also be related with L_r+L_a. For notation simplicity, we define a function $f(x,y,L,p_e)$ as follows:

$$f(x,y,L,p_e) = \frac{xL(1-p_e)^L}{L+y}. \tag{2}$$

Then, we have the normalized throughput for the three ACK mechanisms as

$$\begin{aligned} S_{I\_ACK} &= \frac{K\frac{L}{R_d}p_{s,I\_ACK}}{K\left(2t_p+\frac{L_o}{R_b}+\frac{L}{R_d}+2\mathrm{SIFS}+\frac{L_a}{R_b}\right)} \\ &= \frac{AL(1-p_e)^L}{L+B} = f(A,B,L,p_e) \\ A &= (1-p_e)^{L_o+L_a} \\ B &= R_d\left(2t_p+\frac{L_o+L_a}{R_b}+2\mathrm{SIFS}\right) \\ S_{No\_ACK} &= \frac{K\frac{L}{R_d}p_{s,No\_ACK}}{K\left(t_p+\frac{L_o}{R_b}+\frac{L}{R_d}+\mathrm{MIFS}\right)} \\ &= \frac{CL(1-p_e)^L}{L+D} = f(C,D,L,p_e) \\ C &= (1-p_e)^{L_o} \\ D &= R_d\left(t_p+\frac{L_o}{R_b}+\mathrm{MIFS}\right) \\ S_{D\_ACK} &= \frac{(1-p_e)^{L_r+L_a}\sum_{i=1}^{K}\frac{L}{R_d}(1-p_e)^{L_o+L}}{K\left(t_p+\frac{L_o}{R_b}+\frac{L}{R_d}+\mathrm{MIFS}\right)+2t_p+2\mathrm{SIFS}+\frac{L_r}{R_b}+\frac{L_a}{R_b}} \\ &= \frac{K\frac{L}{R_d}p_{s,D\_ACK}}{K\left(t_p+\frac{L_o}{R_b}+\frac{L}{R_d}+\mathrm{MIFS}\right)+2t_p+2\mathrm{SIFS}+\frac{L_r}{R_b}+\frac{L_a}{R_b}} \\ &= \frac{EL(1-p_e)^L}{L+F} = f(E,F,L,p_e) \\ E &= (1-p_e)^{L_o+L_r+L_a} \\ F &= R_d\left(t_p+\frac{L_o}{R_b}+\mathrm{MIFS}+\frac{L_r+L_a}{KR_b}+\frac{2t_p+2\mathrm{SIFS}}{K}\right). \end{aligned}$$

It can be seen that, throughputs for the three ACK mechanisms have the same format: $f(A,B,L,p_e)$, $f(C,D,L,p_e)$, and $f(E,F,L,p_e)$ for the Imm-ACK, No-ACK, and Dly-ACK mechanisms, respectively. Therefore, to optimize these throughputs, we only need to study the function $f(x,y,L,p_e)$. Since $\lim_{L\to\infty}(xL/(L+y)) = x$ and $\lim_{L\to\infty}(1-p_e)^L = 0$, $\forall p_e \in (0,1)$, we have

$$\lim_{L\to\infty} f(x,y,L,p_e) = 0. \tag{3}$$

Equation (3) indicates that for all ACK mechanisms, if the payload is too large, the throughput is very small as long as $0 < p_e < 1$ holds.

On the other hand, since $y > 0$, we have

$$\lim_{L\to 0} f(x,y,L,p_e) = 0. \tag{4}$$

Equation (4) shows that for all ACK mechanisms, the throughput performance with very small payload size is not good. Therefore, from (3) and (4), it is expected that an optimal payload size exists to maximize the throughput, which is determined as follows.

Take the first derivative of (2)

$$\frac{\partial f(x,y,L,p_e)}{\partial L} = \frac{[x(1-p_e)^L+xL(1-p_e)^L\ln(1-p_e)](L+y)-xL(1-p_e)^L}{(L+y)^2}.$$

Let $\partial f(x,y,L,p_e)/\partial L = 0$, we have

$$L = \frac{-y\ln(1-p_e)\pm\sqrt{[y\ln(1-p_e)]^2-4y\ln(1-p_e)}}{2\ln(1-p_e)}. \tag{5}$$

Since $\ln(1-p_e) < 0$, among the two roots in (5), we choose the positive one and define it as

$$R(y) = \frac{-y\ln(1-p_e)-\sqrt{[y\ln(1-p_e)]^2-4y\ln(1-p_e)}}{2\ln(1-p_e)}. \tag{6}$$

One further consideration is that a $t_{\rm CTA}$ period may not hold an L value in (6). In other words, there is a maximum L value for a fixed $t_{\rm CTA}$ period, when $K=1$ holds.

For the three ACK mechanisms, the maximum L values for a fixed t_{CTA} period can be determined as

$$L_{I\_ACK}^{\max} = R_d\left(t_{\mathrm{CTA}} - 2\mathrm{SIFS} - 2t_p - \frac{L_o + L_a}{R_b}\right)$$
$$L_{No\_ACK}^{\max} = R_d\left(t_{\mathrm{CTA}} - \mathrm{MIFS} - t_p - \frac{L_o}{R_b}\right)$$
$$L_{D\_ACK}^{\max} = R_d\left(t_{\mathrm{CTA}} - \mathrm{MIFS} - 2\mathrm{SIFS} - 3t_p - \frac{L_o + L_r + L_a}{R_b}\right).$$

Therefore, the optimal payload sizes for the Imm-ACK mechanism, the No-ACK mechanism, and the Dly-ACK mechanism are given as follows:

$$L_{I\_ACK}^{*} = \min(R(B), L_{I\_ACK}^{\max})$$
$$L_{No\_ACK}^{*} = \min(R(D), L_{No\_ACK}^{\max})$$
$$L_{D\_ACK}^{*} = \min(R(F), L_{D\_ACK}^{\max}).$$

IV. Optimal ACK Schemes in CAP

In this section, we use the three ACK mechanisms in the CAP with a contention-based CSMA/CA. We study how to optimize the channel throughput using these ACK mechanisms under error channel condition.

When the Imm-ACK mechanism is used in CAP, each node adopts CSMA/CA with binary exponential backoff. Whenever a node cannot receive successfully the ACK, it will double its backoff window until the retry limit is reached. When the No-ACK mechanism is used, each node will use a fixed backoff window as it has no knowledge whether or not the transmitted data frame is successfully received. If the Dly-ACK mechanism is used, as long as the backoff timer of a node reaches zero, the node will first send a number (K) of data frames each separated by an MIFS and a delay-request frame separated by an MIFS, and wait for the ACK. If a burst transmission (of K data frames) is considered successful, the sender will reset the backoff window to the initial value; otherwise, the backoff window will be doubled. In this context, there are two definitions at the sender to determine whether or not the burst transmission is successful.

- The sender may consider a burst transmission being successful if the ACK can be received successfully. In other words, regardless of the reception status of the transmitted K data frames, a burst transmission is considered successful as long as the delay-request frame and the ACK frame are received successfully, and the unsuccessfully transmitted data frames will be retransmitted during next burst transmission.
- The sender may consider a burst transmission being successful if the ACK is received successfully and it acknowledges the successful reception of all the transmitted K data frames. In other words, a burst transmission is successful only when all the data frames, the delay-request frame, and the ACK frame are received successfully. If an ACK is received successfully, but some of the transmitted data frames are not, the sender will double its backoff window but not retransmit the positively acknowledged data frames.

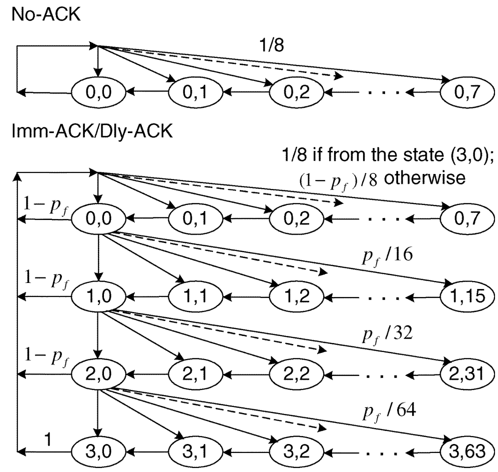

Fig. 3. The state transition diagram for the Imm-ACK/Dly-ACK and No-ACK mechanisms in CAP.

We use the first definition for the Dly-ACK mechanism. However, our analysis can be easily extended to the case with the second definition. We assume that all the mobile nodes use the same payload size L and burst size K in the Dly-ACK mechanism. We also assume that each station always has frames ready to send. Let W_0 denote the initial backoff window size, i.e., 8 (7+1) for convenience, and j the backoff stage, where $j = 0$, 1, 2, 3 for the Imm-ACK mechanism and the Dly-ACK mechanism, and $j = 0$ for the No-ACK mechanism. Let W_j denote current backoff window size in the jth retry/retransmission (or the jth backoff stage). We have $W_0 = 8$, $W_1 = 16$, $W_2 = 32$, and $W_3 = 64$. Similar to Bianchi's model and its enhanced models [10]–[12], $b(t)$ is defined as a random process representing the value of backoff counter at time t, and $s(t)$ is defined as the random process representing the backoff stage j. The backoff counter is uniformly chosen in the range $(0, 1, \ldots, W_j - 1)$. Let p denote the probability that a transmitted frame collides. p is also equal to the probability that a station in the backoff stage senses the channel busy. Let p_f denote failure probability that a (burst) transmission is considered unsuccessful. We have approximately

$$p_f = \begin{cases} 1 - (1-p)p_{s,I\_ACK}, & \text{for } I\_ACK \\ 1 - (1-p)(1-p_e)^{L_r + L_a}, & \text{for } D\_ACK \end{cases}. \tag{7}$$

The bidimensional random process $\{s(t), b(t)\}$ is a discrete-time Markov chain under the assumption that the probability p and the probability p_f are both independent to the backoff procedure [10]. Therefore, the state of each station is described by $\{j, k\}$, where j stands for the backoff stage, and k stands for the backoff timer value.

Fig. 3 illustrates the state transition diagrams for the No-ACK mechanism, and Imm-ACK/Dly-ACK mechanisms, respectively. Only one state is used for the No-ACK mechanism. The retry-limit L_{retry} is 3 for Imm-ACK/Dly-ACK, and 0 for No-ACK. When the retry-limit is reached, the unsuccessfully transmitted frame(s) are dropped by the sender.

Let $b_{j,k} = \lim_{t\to\infty} \Pr\{s(t) = j, b(t) = k\}$ be the stationary distribution of the Markov chain [10]. Let τ be the probability that a station transmits during a generic slot time. A station transmits when its backoff counter reaches zero, i.e., the station is at any of states $\{j, 0\}$. Let n denote the number of stations. Then, we have

$$\tau = \sum_{j=0}^{L_{\text{retry}}} b_{j,0} \tag{8}$$

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

Let p_b denote the probability that the channel is busy, i.e., at least one station transmits during a slot time. Let P_s denote the probability that a successful transmission occurs in a slot time. We have

$$p_b = 1 - (1-\tau)^n \tag{10}$$

$$P_s = \begin{cases} n\tau(1-\tau)^{n-1} p_{s,No\_ACK}, & \text{for } No\_ACK \\ n\tau(1-\tau)^{n-1} p_{s,I\_ACK}, & \text{for } I\_ACK \\ n\tau(1-\tau)^{n-1}(1-p_e)^{L_r+L_a}, & \text{for } D\_ACK \end{cases}. \tag{11}$$

Let δ denote the duration of a slot time, T_s the time for a transmission considered successful (indicated by a successful reception of the ACK), T_f the time for a transmission considered failed (indicated by the unsuccessful ACK reception). Then, T_s and T_f are given by the first equation at the bottom of the page, where t_{ACK_TO} is the TIMEOUT value waiting for an ACK. Then, we have the normalized saturation throughput, as shown in (12) at the bottom of the page.

To optimize the throughput, we take the first derivative of S with L, set it to zero: $\partial S/\partial L = 0$, and obtain the optimal payload size L^* numerically.

V. Performance Evaluation

For the IEEE 802.15.3 MAC, we adopt following parameters unless stated otherwise: BIFS $= 9.4\ \mu$s, $\delta = 6\ \mu$s, MIFS $=$ SIFS $= 8\ \mu$s, $t_p = 9.4\ \mu$s, $R_b = 54$ Mb/s, $L_o = L_a = L_r = 14$ bytes. In the following subsections, we demonstrate the performance of the throughput optimization in a CTA, and the optimal ACK mechanisms in the CAP, respectively.

A. Throughput Optimization in a CTA

Fig. 4 shows the throughput for different payload sizes in the Imm-ACK and No-ACK mechanisms, where "No" means "the No-ACK mechanism," "I" means "the Imm-ACK mechanism," "Analy" means "Analytical," and "Sim" means "Simulation." It can be seen that, the simulation results match well with our analysis. As expected, an optimal payload size exists for a given BER. The optimal payload size increases as the BER decreases. It can also be seen that the No-ACK mechanism has better throughputs than the Imm-ACK mechanism.

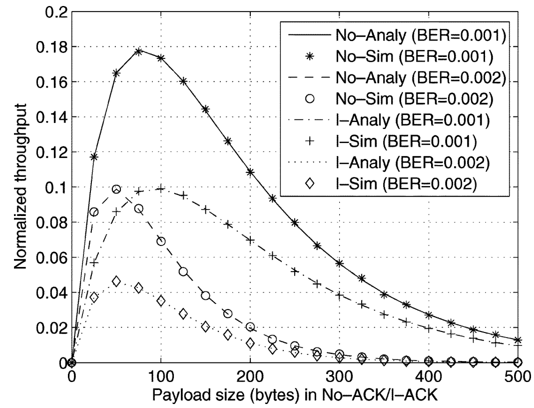

Fig. 4. Throughput versus payload size in Imm-ACK and No-ACK.

Fig. 5 shows throughput for different payload sizes in the Dly-ACK mechanism. It can be seen that an optimal payload size exists for a given BER, and the optimal payload size increases as the BER decreases.

Fig. 6 shows throughput for different burst size K values in the Dly-ACK mechanism with payload size $L = 300$ bytes for each data frame. It can be seen that the normalized throughput increases as K increases.

Figs. 7 and 8 show optimal payload and throughput for different BER values in the three ACK mechanisms, respectively, where "D" means "the Dly-ACK mechanism." A burst size $K = 4$ is used for Dly-ACK. As the BER increases, both the optimal payload size and the optimal throughput decrease. The No-ACK mechanism has larger throughputs and smaller optimal payload sizes than the Dly-ACK mechanism, and the Dly-ACK mechanism has larger throughputs and smaller optimal payload sizes

$$T_s = \begin{cases} t_p + \frac{L_o}{R_b} + \frac{L}{R_d} + \text{BIFS}, & \text{for } No\_ACK \\ 2t_p + \frac{L_o}{R_b} + \frac{L}{R_d} + \text{SIFS} + \frac{L_a}{R_b} + \text{BIFS}, & \text{for } I\_ACK \\ K\left(t_p + \frac{L_o}{R_b} + \frac{L}{R_d} + \text{MIFS}\right) + 2t_p + \text{SIFS} + \frac{L_r + L_a}{R_b} + \text{BIFS}, & \text{for } D\_ACK \end{cases}$$

$$T_f = \begin{cases} t_p + \frac{L_o}{R_b} + \frac{L}{R_d} + \text{BIFS}, & \text{for } No\_ACK \\ t_p + \frac{L_o}{R_b} + \frac{L}{R_d} + t_{ACK\_\text{TO}} + \text{BIFS}, & \text{for } I\_ACK \\ K\left(t_p + \frac{L_o}{R_b} + \frac{L}{R_d} + \text{MIFS}\right) + t_p + \frac{L_r}{R_b} + t_{ACK\_\text{TO}} + \text{BIFS}, & \text{for } D\_ACK \end{cases}$$

$$S = \begin{cases} \frac{P_s \frac{L}{R_d}}{(1-p_b)\delta + P_s T_s + (p_b - P_s) T_f}, & \text{for } No\_ACK \\ \frac{P_s \frac{L}{R_d}}{(1-p_b)\delta + P_s T_s + (p_b - P_s) T_f}, & \text{for } I\_ACK \\ \frac{P_s \sum_{i=1}^{K} \frac{L}{R_d}(1-p_e)^{L_o+L}}{(1-p_b)\delta + P_s T_s + (p_b - P_s) T_f} = \frac{P_s K \frac{L}{R_d}(1-p_e)^{L_o+L}}{(1-p_b)\delta + P_s T_s + (p_b - P_s) T_f}, & \text{for } D\_ACK \end{cases} \tag{12}$$

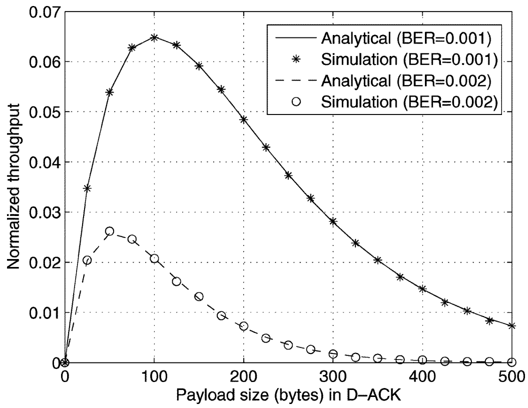

Fig. 5. Dly-ACK throughput versus payload size with burst size $K = 1$.

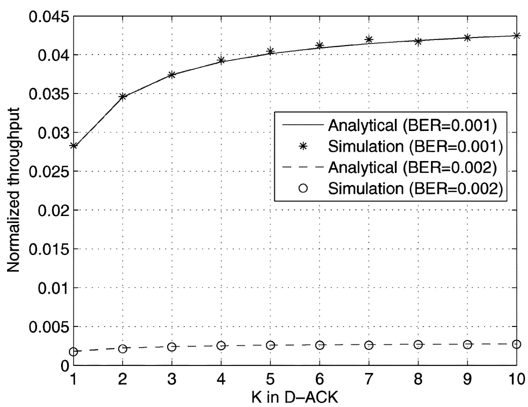

Fig. 6. Dly-ACK throughput versus K with payload size $L = 300$ bytes.

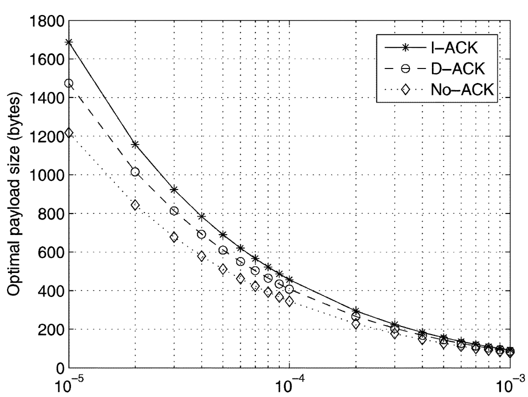

Fig. 7. Optimal payload size versus BER in CTA.

than the Imm-ACK mechanism. The good match between the simulations and our analysis demonstrates the accuracy of our analytical model.

B. Optimal ACK Schemes in the CAP

Fig. 9 shows the normalized throughput over different payload size when the number of active stations is 10 and the BER is 0.0001. A burst size $K = 5$ is used for Dly-ACK in CAP. For the No-ACK mechanism, we evaluate two cases: the backoff window size value $W_0 = 8$ and $W_0 = 16$. We can see that the simulations match well with our analysis. For each ACK mechanism, with the increase of the payload size, the normalized throughput first increases, then decreases after the

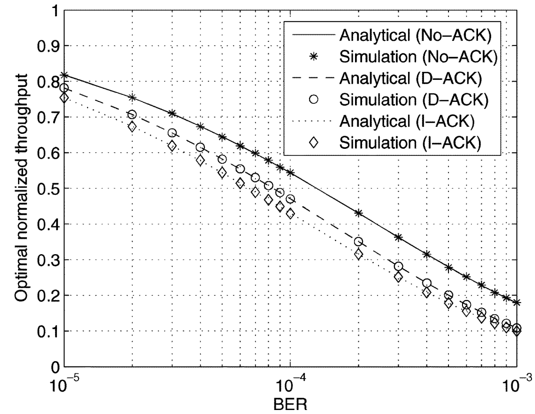

Fig. 8. Optimal throughput versus BER in CTA.

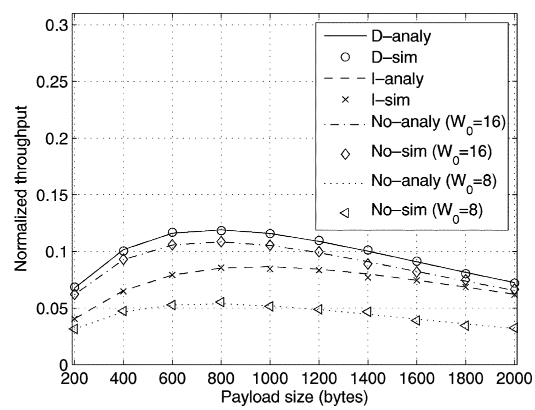

Fig. 9. Throughput versus payload size with ten active stations, R_d = 432 Mb/s, and $p_e = 0.0001$.

maximal point. This can be explained as follows. In CAP, the time to transmit the payload is only a small portion of the total time used (including the time to transmit the payload, the interframe spaces, time for PHY and MAC overhead, and the ACK transmission time for the Imm-ACK/Dly-ACK mechanism). Therefore, when the payload size increases, the transmission efficiency can be increase, but the frame error probability also increases. The increase of the curves in Fig. 9 is because the effect of increased transmission efficiency is more significant than the effect of increased frame error probability, and the decrease of the curves is due to the dominant effect of increased frame error probability when payload size further increases. The optimal payload size for the four simulated cases is in the neighborhood of 800 bytes.

From Fig. 9, it can be seen that the performance of the No-ACK mechanism is sensitive to the backoff window size setting. As there is no binary exponential backoff, the collision probability largely depends on the number of active stations and the backoff window size. Network designers should pay attention when using the No-ACK mechanism in CAP. The throughput of the Dly-ACK mechanism is larger than that of the Imm-ACK mechanism, due to the reduced overhead.

Fig. 10 shows the normalized throughput of different ACK mechanisms for different number of active stations. It can be seen that throughput decreases as the number of active stations increases. The decreasing degree in the No-ACK mechanism is steeper than those in the Imm-ACK and Dly-ACK mechanisms.

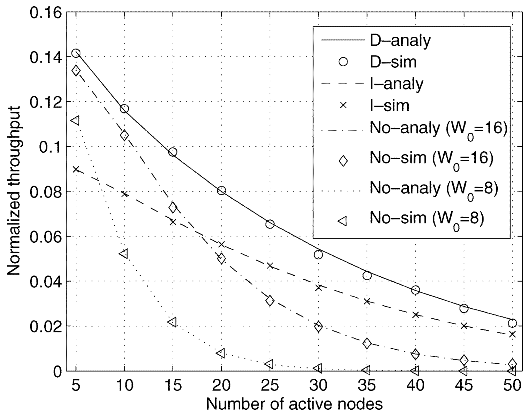

Fig. 10. Throughput versus number of active stations with payload size 600 bytes, $R_d = 432$ Mb/s, and $p_e = 0.0001$.

This is because no binary exponential backoff is adopted in the No-ACK mechanism.

VI. Conclusion

We have extensively studied the optimal No-ACK, Imm-ACK, and Dly-ACK mechanisms (adopted by IEEE 802.15.3) in contention-free CTA and contention-based CAP. For a given ACK mechanism and error channel condition (represented by BER), the optimal payload size (in terms of maximal throughput) can be determined analytically (for CTA) or numerically (for CAP). This research should provide helpful insight to the implementation of UWB-based IEEE 802.15.3 wireless networks.

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