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SIZE BASED THROUGHPUT OPTIMIZATION OF DLY-ACK OVER THE IEEE 802.15.3 NETWORKS

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Abstract—In this paper we study on the one hand under delayed-acknowledgement (Dly-ACK) mechanisms the option of using ACK Request to improve system robustness, and on the other hand the incorporation of effective retransmission schemes such as hybrid automatic repeat request (HARQ) to improve system throughput for an IEEE 802.15.3 compliant system. An expression of throughput is derived in terms of system parameters and channel conditions. A constrained optimization problem for system throughput is formulated. It is then solved numerically due to the high degree of nonlinearity in the payload size. Our results indicate that under poor channel conditions, the optimal throughput under HARQ scheme is significantly higher than that with ARQ, and larger payload size is proposed to further improve the performance.

1. INTRODUCTION

The development of wireless personal area network (WPAN) aims at wireless connectivity of high data rate, low complexity, low power consumption and low cost. The IEEE 802.15.3 standard [1] supports data rates of 11–55 Mbps and a time-division multiple access (TDMA) based medium access control (MAC) protocol is used to support the quality of service (QoS) efficiently. One of the potential applications and extensions is envisioned in the My personal Adaptive Global Net (MAGNET) project where WPANs are the constituent blocks, called clusters, to form a larger personal network (PN), and PNs can communicate with each other by forming PN Federations [2]. Moreover, the IEEE 802.15.3a standards [3, 4] make use of the emerging ultra-wideband (UWB) technology and can support high data rate up to 480 Mbps, which can satisfy most of the multimedia applications such as high-definition television (HDTV) data, video and images transmission, thus opening the door for wireless home entertainment networks (e.g., [5–7]). However, along with these promising potentials come the technical challenges, among which is to utilize the resources in the most efficient way in face of the adverse wireless channel. Characterization of wireless channel conditions is an important task and has been carried out extensively (e.g., [8–19]). In [20], a procedure of link level simulation for indoor applications of wireless local-area networks (WLANs) was proposed. The problem of synchronization for UWB orthogonal frequency division multiplexing (UWB-OFDM) systems was considered in [21].

The acknowledgment (ACK) mechanisms play an important role in the reliable transmission of data. According to the IEEE 802.15.3 standard, three ACK mechanisms are defined during channel time allocation (CTA) in the MAC: No-ACK, Immediate-ACK (Imm-ACK), and Delayed-ACK (Dly-ACK). Under the ACK-enabled mechanisms, frames received with errors can be retransmitted. The payload size has a strong influence on the system performance in terms of throughput. Under error channel conditions, the larger the payload size, the more likely that the frame is corrupted. Yet a short payload size may render MAC associated overhead such as MAC header, ACK, short interframe space (SIFS) appreciable to effectively reduce the system throughput. This clearly presents a trade-off situation, which calls for an identification of the optimal payload size to maximize the system throughput.

These ACK mechanisms also behave differently. Under the Imm-ACK mechanism, since the receiving device needs to acknowledge each frame after correct reception, the associated overhead may hinder efficient channel utilization for high data rate applications. On the other hand, under the Dly-ACK mechanism, instead of acknowledging every frame immediately, the receiving device sends ACK only after a burst of frames is received, thus reduces the associated overhead. It has been shown that Dly-ACK can significantly improve the throughput performance [22, 23]. Yet in [22], performance was analyzed without consideration of retry limit for the last frame in a burst or the empty frame. In [23], retransmissions were considered of the last frame in a transmitting burst, with infinite retry number implied, which may raise stability issue [24]. Moreover, the data frame with size much longer than that of an empty data frame is more prone to transmission error. An alternative option is thus proposed in the standard such that an ACK Request is transmitted by the sending device after the transmission of a burst of data frames is finished, with the purpose of making the system more robust [25].

It is well known that the throughput of automatic repeat request (ARQ) schemes can be improved by keeping the erroneous received packets and using them for detection, also called packet combining, or Type-I Hybrid ARQ (HARQ). A more efficient approach is the Type-II HARQ which introduces memory not only at the receiver but also at the transmitter so that the transmitter sends only incremental parity bits at each ARQ request [26]. Due to its ability to achieve high system throughput, HARQ is considered one of the key technologies for the third generation (3G) wireless communication systems (CDMA 2000 1xEV, WCDMA, HSDPA, etc.). Yet in IEEE 802.15.3 physical (PHY) layer the trellis coded modulation (TCM) is used [1], which prevents the use of efficient code combining scheme due to concerns over complexity in the receiver, which is thus usually proposed with the packet combining Type-I HARQ [27].

It is thus desirable to investigate on the one hand under Dly-ACK mechanisms the option of using ACK Request to improve system robustness, and on the other hand the incorporation of effective retransmission schemes such as Type-I HARQ to improve system throughput. These considerations provide motivations for the current work.

The rest of the paper is organized as follows. In Section 2, we first briefly describe the IEEE 802.15.3 MAC and Dly-ACK mechanism, then proceed to formulate the throughput optimization problem. Section 3 presents the performance of Dly-ACK mechanism in combination with ARQ and HARQ schemes. Section 4 concludes the paper.

2. MODELING

In this section we consider the system throughput under Dly-ACK mechanism in combination with HARQ. We shall start with a brief description of the superframe of the IEEE 802.15.3 MAC. As shown in Fig. 1, the superframe is composed of three parts: a beacon, an optional CAP and a contention free period (CFP). Beacon frame is used by the piconet coordinator (PNC) to broadcast control information to entire piconet. In CAP, the command frames and asynchronous data frames are transmitted adopting a carrier sense multiple access/collision avoidance (CSMA/CA) mechanism. The CFP is composed of CTAs (including management channel time allocations (MCTAs)), which are used for commands, isochronous streams and asynchronous data connections with TDMA-based protocol.

From Fig. 1, it is seen that under the Dly-ACK mechanism K frames are grouped as burst transmitted by sender. In the destination device, the ACKs of the individual frame is combined into one response frame that is sent when receiving a requested frame from the source device. A minimum interframe space (MIFS) is used to separate two successive frames and a SIFS is an interval used between the transmitted frame and ACK.

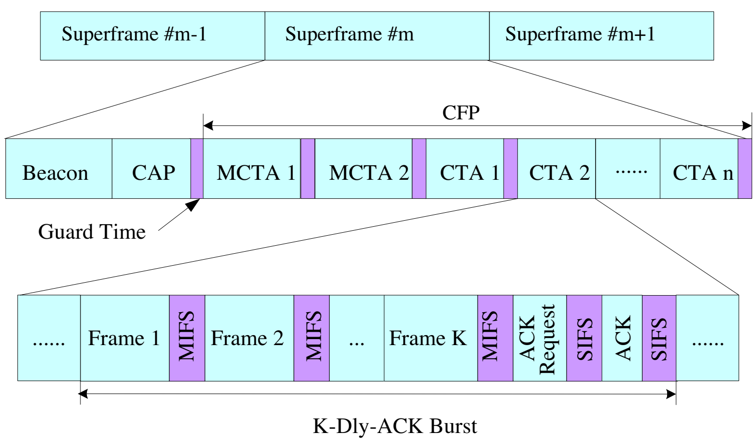

Figure 1. Superframe structure and Dly-ACK format in the IEEE 802.15.3.

In the analysis we assume a slowly varying channel so that the channel status remains almost the same during several retransmission stages (the retry limits of data frame and ACK frame have to be specified for both practicality and stability considerations). This assumption is believed to be valid for the WPAN where a device is expected to remain static or semi-static. We also assume that there are enough data to be transmitted at the sending device, buffer size of a device is sufficiently large, and transmission of the header of packet is ideal. These are standard assumptions.

Under Dly-ACK mechanism, a frame transmission is successful only when the data frame, the ACK request frame and the ACK frame are all received successfully. Each payload in the burst has its own ACK part, so effectively each payload may be treated individually. Such observation allows us to represent the transmission process by using the state diagram as shown in Fig. 2.

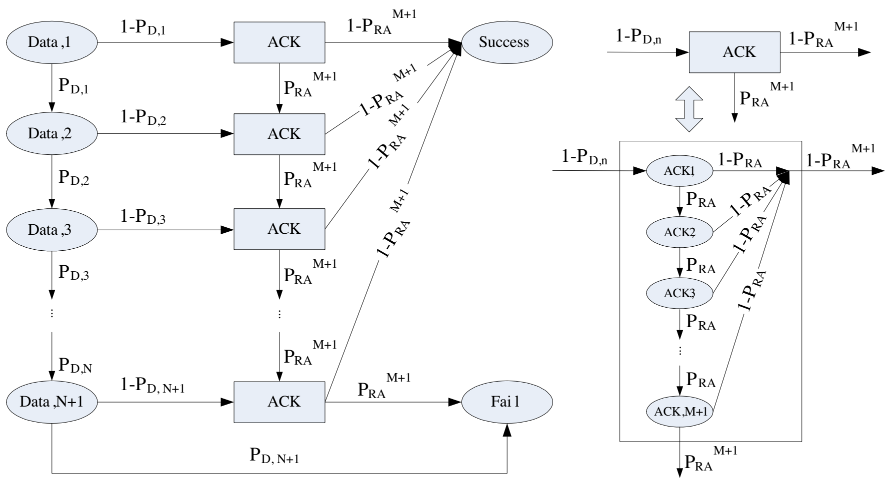

Figure 2. Data transmission process for Dly-ACK mechanism.

The transmission state at a transmitting Device (DEV) may be any of the states-(Data, k) with $k \geq 1$, ACK, Success, and Failure. A description of the state diagram is as follows. Assuming the transmission state is in data-related state (Data, k) with $k \geq 1$ and the frame is transmitted or retransmitted, four possible events can occur: i) If the payload is corrupted, the receiving DEV can store the received incorrect payload bits and perform a combining with previously stored incorrect payload bits to produce a better SNR for detection; ii) If payload is transmitted correctly, the transmission state enters the (ACK) state, where a number of ACK attempts are made in accordance with the IEEE 802.15.3 standard. In this case since the receiving DEV already knows that the correct payload has been received so there is nothing new to be modified but just to wait for the transmitting DEV to correctly receive an ACK; iii) If payload is transmitted correctly and the ACK is correctly received, the transmission is finished and is marked with Success; iv) If payload is transmitted for the $(N+1)$th time where N is the maximally permissible retransmission number, and either payload transmission is corrupted or ACK is not correctly received, the transmission is marked with Failure and the data is dropped.

The structure of this state diagram is quite general and can be used to represent the transmission states under both ARQ and HARQ mechanisms. Yet there is a slight difference in that under ARQ the same frame is simply retransmitted till detection succeeds, so the signal to noise ratio (SNR) at the receiver remains the same which implies that the data-related states (Data, k) with $k \geq 1$ can be combined into a single one.

Let us define

t_p to be the transmission time of the preamble, the PHY header and the header check sequence (HCS);

L_H, L_R, L_A, L_D, and L_F to be the length of the MAC header, ACK Request, ACK, payload, and frame check sequence (FCS), respectively;

R_B to be the base rate which is used for transmission of the Beacon, MAC header, ACK Request and ACK;

R_D to be the data rate which is used for transmission of data and the FCS;

$1 - P_{D,n}(n \geq 1)$ to be the probability of correct detection of payload at n-th transmission;

$1 - P_R$ and $1 - P_A$ to be the probability of correct transmission of ACK Request and ACK, respectively;

$P_{e,B}(\gamma)$ and $P_{e,D}(\gamma)$ to be the bit error rate (BER) for R_B and R_D under SNR γ at the receiving DEV, respectively;

$D_{\max}$ and $R_{\max}$ to be the permissible maximum number of retransmission for Data and ACK Request, respectively.

The relationships among above probabilities are given by

$$P_{D,n} = 1 - (1 - P_{e,D}(\gamma(n)))^{L_D + L_F} \tag{1}$$

$$P_R = 1 - (1 - P_{e,B}(\gamma))^{L_R} \tag{2}$$

$$P_A = 1 - (1 - P_{e,B}(\gamma))^{L_A} \tag{3}$$

The BERs $P_{e,B}(\gamma)$ and $P_{e,D}(\gamma(n))$ can be obtained through simulation in PHY layer, and we omit details here. For the ARQ mechanism, the receiving SNR remains the same after successive retransmissions, thus the value of $\gamma(n)$ is constant for all n. However, if a packet combining HARQ is used instead, the effective receiving SNR is improved after each retransmission, hence $\gamma(n)$ can be specifically written as $\gamma(n) = n\gamma$ [28]. This SNR improvement indicates that the detection capability is improved after each retransmission, i.e., the probability of correct detection increases with n.

As mentioned above, a data frame is considered to be transmitted successfully if the data frame, ACK Request frame and ACK frame are successfully transmitted. According to Fig. 2, the probability of successful transmission after the first time data transmission can be readily expressed as

$$(1 - P_{D,1}) \left(1 - P_{RA}^{R_{\max}+1}\right) \tag{4}$$

where for notational convenience P_{RA} is defined as

$$P_{RA} = 1 - (1 - P_R)(1 - P_A) = 1 - (1 - P_{e,B}(\gamma))^{L_R+L_A} \tag{5}$$

Similarly, the probability of successful transmission after the first retransmission attempt is

$$(1-P_{D,1})\, P_{RA}^{R_{\max}+1} \left(1-P_{RA}^{R_{\max}+1}\right) + P_{D,1}\,(1-P_{D,2}) \left(1-P_{RA}^{R_{\max}+1}\right) \tag{6}$$

In general, the probability for a transmission to be considered successful under maximum number of retransmission $D_{\max}$ can be expressed as

$$P_{\text{success}} = \sum_{n=1}^{D_{\max}+1} \sum_{k=1}^{n} P_{RA}^{(n-k)(R_{\max}+1)} \left(1-P_{RA}^{R_{\max}+1}\right)(1-P_{D,k}) \prod_{q=1}^{k-1} P_{D,q} \tag{7}$$

These probabilities are helpful in calculating the expected transmission time. As shown in Fig. 1, when Dly-ACK mechanism is adopted in CTAs, an ACK Request frame will be sent by the sender after the transmission of K frames. We define T_D and T_A to be the time used for data transmission and ACK response, respectively, where T_A is normalized by K frames. In view of the ACK frame format, they are given by

$$T_D = t_p + \text{MIFS} + \frac{L_D + L_F}{R_D} + \frac{L_H}{R_B} \tag{8}$$

$$T_A = \frac{1}{K}\left(2t_p + 2\text{SIFS} + \frac{L_R + L_A}{R_B}\right) \tag{9}$$

The expected time for a transmission to succeed after the first data transmission is

$$\begin{aligned}
&(1 - P_{D,1}) \left(T_D \left(1 - P_{RA}^{R_{\max}+1}\right) + T_A \left((1 - P_{RA}) + 2P_{RA}(1 - P_{RA})\right.\right.\\
&\quad \left.\left. + \ldots + (R_{\max}+1)\, P_{RA}^{R_{\max}}(1 - P_{RA})\right)\right)\\
&= (1 - P_{D,1}) \left(T_D \left(1 - P_{RA}^{R_{\max}+1}\right) + T_{S,A}\right)
\end{aligned} \tag{10}$$

where (see Fig. 2)

$$
\begin{aligned}
T_{S,A} &= T_A\left((1-P_{RA}) + 2P_{RA}(1-P_{RA}) \right.\\
&\qquad \left. + \ldots + (R_{\max}+1)\, P_{RA}^{R_{\max}}(1-P_{RA})\right)\\
&= T_A \frac{1+(R_{\max}+1)\, P_{RA}^{R_{\max}+2} - (R_{\max}+2)\, P_{RA}^{R_{\max}+1}}{1-P_{RA}}
\end{aligned} \tag{11}
$$

Similarly, the expected time for a transmission to succeed after the first data retransmission is

$$
\begin{aligned}
&(1-P_{D,1})\, P_{RA}^{R_{\max}+1}\left(\left(2T_D + (R_{\max}+1)\, T_A\right)\left(1-P_{RA}^{R_{\max}+1}\right) + T_{S,A}\right)\\
&+ P_{D,1}(1-P_{D,2})\left(\left(2T_D + T_{S,A} + T_{F,A}\right)\left(1-P_{RA}^{R_{\max}+1}\right) + T_{S,A}\right)
\end{aligned} \tag{12}
$$

where

$$
T_{F,A} = (R_{\max}+1)\, T_A P_{RA}^{R_{\max}+1} \tag{13}
$$

The compound term $(T_{S,A}+T_{F,A})$ in (12) represents the expected time used regardless of whether the acknowledgement process is successful. It can be simplified as

$$
\begin{aligned}
T_{S,A}+T_{F,A} &= T_A \frac{1+(R_{\max}+1)\, P_{RA}^{R_{\max}+2} - (R_{\max}+2)\, P_{RA}^{R_{\max}+1}}{1-P_{RA}}\\
&\quad + (R_{\max}+1)\, T_A P_{RA}^{R_{\max}+1}\\
&= T_A \frac{1-P_{RA}^{R_{\max}+1}}{1-P_{RA}}
\end{aligned} \tag{14}
$$

In general, the expected time for a transmission to be successful under maximum number of retransmission $D_{\max}$ can be expressed as

$$
\begin{aligned}
T_{\text{success}} &= \sum_{n=1}^{D_{\max}+1} \sum_{k=1}^{n} P_{RA}^{(n-k)(R_{\max}+1)} \left(\left(nT_D + (n-k)\,(R_{\max}+1)\, T_A \right.\right.\\
&\qquad \left. + (k-1)\,(T_{S,A}+T_{F,A})\right)\left(1-P_{RA}^{R_{\max}+1}\right) + T_{S,A}\Big)\\
&\qquad \cdot \left((1-P_{D,k}) \prod_{q=1}^{k-1} P_{D,q}\right)
\end{aligned} \tag{15}
$$

Similarly, the expected time for a transmission to be considered failure is obtained as

$$
T_{\text{fail}} = \sum_{n=1}^{D_{\max}+1} P_{RA}^{(D_{\max}+2-n)(R_{\max}+1)} \left((D_{\max}+1)\, T_D + (D_{\max}+2-n)\right.
$$

$$\cdot (R_{\max}+1)\, T_A + (n-1)\,(T_{S,A}+T_{F,A}))$$
$$\cdot \left((1-P_{D,n}) \prod_{q=1}^{n-1} P_{D,q}\right) + (D_{\max}+1)$$
$$\cdot (T_D + T_{S,A} + T_{F,A}) \prod_{m=1}^{D_{\max}+1} P_{D,m} \tag{16}$$

The normalized throughput is defined similar to [25] as

$$S = \frac{\frac{L_D}{R_D} P_{\text{success}}}{E[\text{slot}]} = \frac{\frac{L_D}{R_D} P_{\text{success}}}{T_{\text{success}} + T_{\text{fail}}} \tag{17}$$

The main goal is to obtain the optimal payload size that maximizes the normalized throughput S by solving the following constrained optimization problem

$$\begin{array}{ll} \max & S \\ s.t. & 0 \le L_D \le L_{\max} \end{array} \tag{18}$$

where $L_{\max}$ is the maximum payload size specified by PHY layer. As clearly manifested in the above development, the expression of normalized throughput S for Dly-ACK mechanism is complex in form and is highly nonlinear in the payload size L_D. Hence it is very difficult to obtain an analytical solution to the optimization problem. Instead, we resort to numerical techniques in our endeavor.

3. NUMERICAL SIMULATIONS

In the section, we demonstrate the performance of throughput optimization, with an emphasis on the improvement obtained by incorporating the HARQ mechanism. All the parameters used in the simulations follow the IEEE 802.15.3 standard, which are listed in Table 1. In order to compute the BER, we consider a quadrature phase shift keying (QPSK) modulation as specified in the IEEE 802.15.3 standard. For simplicity, we ignore error correcting coding. This treatment may render the HARQ in use not in the strict sense, but the key feature that we want to extract from the HARQ mechanism is the linear increase in receiving SNR with number of retransmission, which we can obtain equivalently by coherently adding all the received frames before detection in the absence of coding. Thus we choose the BER mapping rule of additive white Gaussian noise (AWGN) channel

Table 1. Simulation parameters.

SIFS	10 µs
MIFS	2 µs
L_H	10 bytes
L_R	10 bytes
L_A	$(10 + 2K + 7)$ bytes
L_F	4 bytes
t_p	9.4 µs
$L_{\max}$	2044 bytes
R_B	22 Mbps
R_D	22 Mbps

in our simulation. Unless stated otherwise, the maximum number of data retransmission and ACK retransmission are all set to be 2.

The effect of payload size on throughput is illustrated in Fig. 3, where the BER is 10^{-4}, which is used for estimating the SNR under an AWGN channel, and the delay burst sizes of the Dly-ACK mechanism are 5 and 10. There exists an optimal payload size which results in the highest throughput for both HARQ and pure ARQ cases. This is because at smaller payload size, the cost of overhead (such

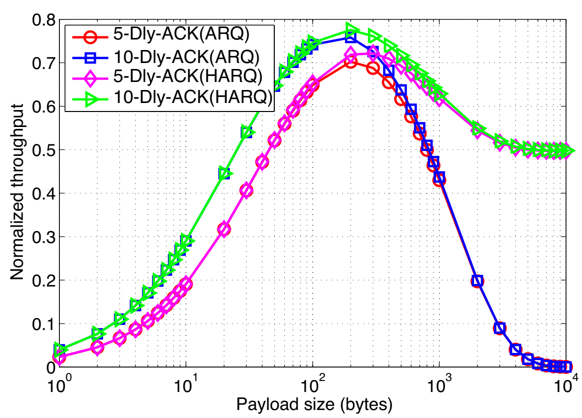

Figure 3. Normalized throughput versus payload size for ARQ and HARQ schemes.

as MIFS, SIFS, ACK Request, ACK etc.) is appreciable, while at larger payload size, the probability of successful transmission of frames decreases. For the same delay burst size, the optimal payload sizes for ARQ and HARQ are approximately the same, yet the achieved optimal throughput of HARQ is slightly better than that of ARQ. At larger payload size, ARQ drops drastically while HARQ shows more gracious degradation behavior. In practical system, the maximum length of physical layer is restricted to a preset value. For instance, the maximum payload size is specified as 2044 bytes in the IEEE 802.15.3 standard. In order to conform to the standard, in the simulations to follow we limit payload size not to exceed the maximum value.

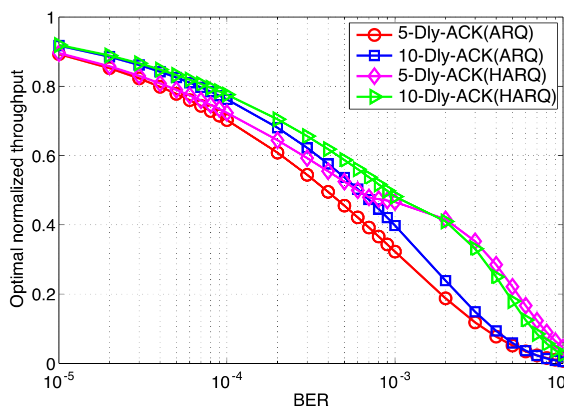

Figure 4. Optimal throughput versus BER for ARQ and HARQ schemes.

Figure 4 shows the optimal throughput performance over the BER. We observe that the optimal normalized throughput when HARQ is incorporated is higher than that with pure ARQ, in particular when BER is large ($10^{-4} \sim 10^{-2}$), where a performance gain up to 100% is achieved at BER of 0.002. Such performance improvement strongly demonstrates that HARQ is an effective means to alleviate throughput degradation in face of poor channel condition. The performance also shows dependence on delay burst size of the Dly-ACK mechanism. In general, the larger the delay burst size, the better throughput thanks to reduction of overhead transmission. Yet such correspondence does not hold when BER is sufficiently large, as illustrated by the cross-over of performances of different delay burst sizes (5 and 10 in this case) at BER of 0.002 in Fig. 4. There are two reasons behind this phenomenon: 1) the size of ACK frame increases with the bust size in Dly-ACK mechanism, leading to higher probability of unsuccessful transmission; 2) failure of acknowledge process means more data frames have to be retransmitted while large burst size is adopted. Thus the throughput of the case using larger delay burst size is much more sensitive to the errors of ACK Request and ACK frames, and such sensitivity manifests itself at poor channel conditions.

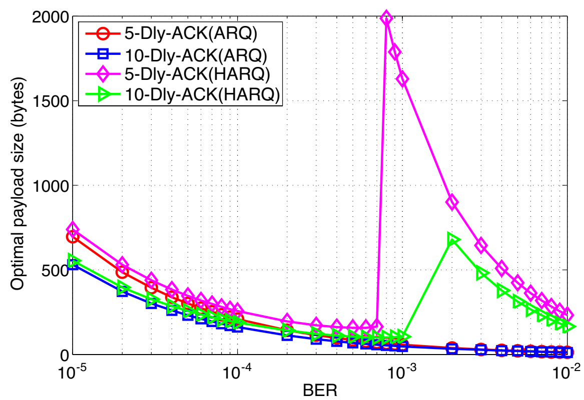

Figure 5. Optimal payload size versus BER for ARQ and HARQ schemes.

Figure 5 shows the optimal payload size as a function of the BER. It is seen that for HARQ-enabled Dly-ACK mechanisms, their optimal payload sizes are larger than those with pure ARQ. These optimal sizes monotonically decrease when the channel condition becomes worse. Yet this trend is broken at BER of around 7×10^{-4} and 2×10^{-3} for delay burst size of 10 and 5 respectively. This phenomenon results from the high degree of nonlinearity of the throughput S in the payload size as indicated in (17). Within the range of payload considered at a specific BER, there are multiple local optimal values for S. Change of relative magnitude of these local optimal values will result in a change in the corresponding optimal payload size.

Data retransmissions are widely adopted for reliable wireless communication. To examine the impact of data and ACK retry limits on throughput performance when HARQ is adopted, we change the permissible number of retransmissions from null up to four for data and ACK, as shown in Fig. 6 and Fig. 7, respectively. In the simulations we only allow either data or ACK to be able to retransmit for the purpose of separating effects. In Fig. 6, it is seen that when BER is low ($10^{-5} \sim 10^{-4}$), the optimal normalized throughput is almost independent of the number of retransmissions, which is expected since in such benevolent case, it is highly probable for the first time transmission to be correct. When the BER increases, the optimal normalized throughput begins to show its dependence on the number of retransmissions, with larger value for more retransmission. However, the performance gain becomes marginal when $D_{\max} > 2$. Similar observations apply to the ACK retransmittion effect (Fig. 7). Yet comparison of these two figures indicates that data retransmission leads to more throughput improvement.

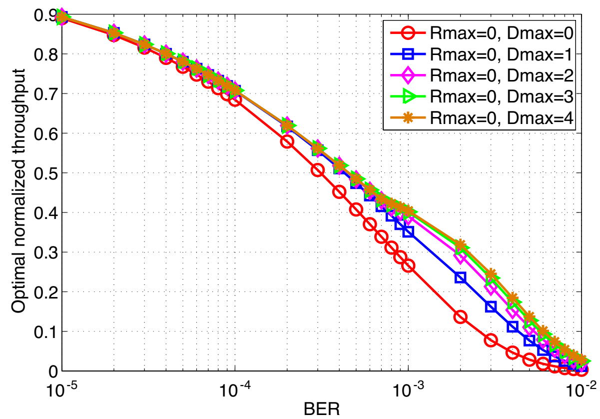

Figure 6. Optimal throughput versus BER for different data retransmission limits.

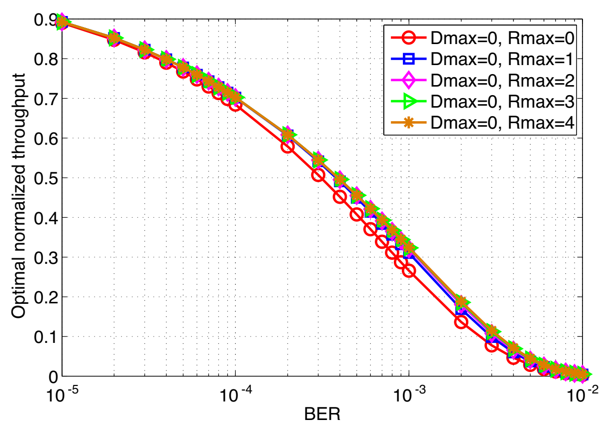

Figure 7. Optimal throughput versus BER for different Dly-ACK retransmission limits.

4. CONCLUSION

In this paper we investigated on the one hand under Dly-ACK mechanisms the option of using ACK Request to improve system robustness, and on the other hand the incorporation of effective retransmission schemes such as Type-I HARQ to improve system throughput for a IEEE 802.15.3 compliant system. A constrained optimization problem for system throughput was formulated. It was then solved numerically due to the high degree of nonlinearity in the payload size.

Our main findings are as follows: 1) For the same delay burst size, the achieved optimal throughput of HARQ is slightly better than that of ARQ. At larger payload size, ARQ drops drastically while HARQ shows more gracious degradation behavior; 2) the optimal normalized throughput when HARQ is incorporated is higher than that with pure ARQ, in particular when BER is large ($10^{-4} \sim 10^{-2}$), where a performance gain up to 100% is achieved at BER of 0.002. Such performance improvement strongly demonstrates that HARQ is an effective means to alleviate throughput degradation in face of poor channel condition; 3) The performance also shows dependence on delay burst size of the Dly-ACK mechanism. In general, the larger the delay burst size, the better throughput thanks to reduction of overhead transmission. Yet when BER is sufficiently large, a reverse of the trend is observed; 4) For HARQ-enabled Dly-ACK mechanisms, their optimal payload sizes are slightly larger than those with pure ARQ when channel condition is benevolent, yet can be much larger under very poor channel condition; 5) it is reasonable to set the permissible maximum number of retransmission of data frame to be three and of ACK frame to be one.

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REFERENCES

1. IEEE Standard 802.15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs), Sept. 2003.

2. IST-2004-507102, My personal Adaptive Global NET (MAGNET). http://www.ist-magnet.org.
3. IEEE P802.15-04/0137r1, DS-UWB physical layer submission to 802.15 Task Group 3a, Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), 2004.
4. IEEE P802.15-03/268r3, multi-band OFDM physical layer proposal for IEEE 802.15 Task Group 3a, Project: IEEE P802.15Working Group for Wireless Personal Area Networks (WPANs), 2004.
5. Kim, J., S. Lee, Y. Jeon, and S. Choi, "Residential HDTV distribution system using UWB and IEEE 1394," *IEEE Trans. Consum. Electron.*, Vol. 52, 116–122, Jan. 2006.
6. Lee, C. S., D. J. Cho, Y. H. You, and H. K. Song, "A solution to improvement of DS-UWB system in the wireless home entertainment network," *IEEE Trans. Consum. Electron.*, Vol. 51, 529–533, May 2005.
7. Park, H. J., M. J. Kim, Y. J. So, Y. H. You, and H. K. Song, "UWB communication system for home entertainment network," *IEEE Trans. Consum. Electron.*, Vol. 49, 302–311, May 2003.
8. Noori, N. and H. Oraizi, "Evaluation of mimo channel capacity in indoor environments using vector parabolic equation method," *Progress In Electromagnetics Research B*, Vol. 4, 13–25, 2008.
9. Hu, C.-F., J.-D. Xu, N. Li, and L. Zhang, "Indoor accurate RCS measurement technique on UHF band," *Progress In Electromagnetics Research*, PIER 81, 279–289, 2008.
10. Xiao, S., J. Chen, B.-Z. Wang, and X.-F. Liu, "A numerical study on time-reversal electromagnetic wave for indoor ultrawideband signal transmission," *Progress In Electromagnetics Research*, PIER 77, 329–342, 2007.
11. Martinez, D., F. Las-Heras, and R. G. Ayestaran, "Fast methods for evaluating the electric field level in 2D-indoor environments," *Progress In Electromagnetics Research*, PIER 69, 247–255, 2007.
12. Abouda, A. A. and S. G. Haggman, "Effect of mutual coupling on capacity of MIMO wireless channels in high SNR scenario," *Progress In Electromagnetics Research*, PIER 65, 27–40, 2006.
13. Abouda, A. A., H. M. El-Sallabi, and S. G. Haggman, "Effect of antenna array geometry and ula azimuthal orientation on MIMO channel properties in urban city street grid," *Progress In Electromagnetics Research*, PIER 64, 257–278, 2006.
14. Yarkoni, N. and N. Blaunstein, "Prediction of propagation characteristics in indoor radio communication environments,"

Progress In Electromagnetics Research, PIER 59, 151–174, 2006.

15. Hua, J., L. Meng, and Z. Xu, "A new method for SNR and Doppler shift estimation in wireless propagations," *Journal of Electromagnetic Waves and Applications*, Vol. 21, 2431–2441, 2008.
16. Jeong, Y.-S. and J.-H. Lee, "Estimation of time delay using conventional beamforming-based algorithm for UWB systems," *Journal of Electromagnetic Waves and Applications*, Vol. 21, 2413–2420, 2008.
17. Liu, Y.-J., Y.-R. Zhang, and W. Cao, "A novel approach to the refraction propagation characteristics of UWB signal waveforms," *Journal of Electromagnetic Waves and Applications*, Vol. 21, 1939–1950, 2007.
18. Gopikrishna, M., D. D. Krishna, A. R. Chandran, and C. K. Aanandan, "Square monopole antenna for ultra wide band communication applications," *Journal of Electromagnetic Waves and Applications*, Vol. 21, 1525–1537, 2007.
19. Abouda, A. A., H. M. El-Sallabi, L. Vuokko, and S. G. Haggman, "Spatial smoothing effect on Kronecker MIMO channel model in urban microcells," *Journal of Electromagnetic Waves and Applications*, Vol. 21, 681–696, 2007.
20. Roozbahani, M. G., E. Jedari, and A. A. Shishegar, "A new link-level simulation procedure of wideband MIMO radio channel for performance evaluation of indoor WLANs," *Progress In Electromagnetics Research*, PIER 83, 13–24, 2008.
21. Kim, J.-H., Y.-H. You, K.-I. Lee, and J.-H. Yi, "Pilot-less synchronization receiver for UWB-based wireless application," *Progress In Electromagnetics Research*, PIER 83, 119–131, 2008.
22. Chen, H., Z. Guo, R. Y. Yao, X. Shen, and Y. Li, "Performance analysis of delayed acknowledgment scheme in UWB-based high-rate WPAN," *IEEE Trans. Veh. Technol.*, Vol. 55, 606–621, Mar. 2006.
23. Liu, K. H., H. Rutagemwa, X. Shen, and J. W. Mark, "Efficiency and goodput analysis of Dly-ACK in IEEE 802.15.3," *IEEE Trans. Veh. Technol.*, Vol. 56, 3888–3898, Nov. 2007.
24. Shacham, N. and D. Towsley, "Resequencing delay and buffer occupancy in selective repeat ARQ with multiple receivers," *IEEE Trans. Commun.*, Vol. 39, 928–937, June 1991.
25. Xiao, Y., X. Shen, and H. Jiang, "Optimal ACK mechanisms of the IEEE 802.15.3 MAC for ultra-wideband systems," *IEEE J. Sel. Areas Commun.*, Vol. 24, 836–842, Apr. 2006.

26. Caire, G. and D. Tuninetti, "The throughput of hybrid-ARQ protocols for the Gaussian collision channel," *IEEE Trans. Inf. Theory*, Vol. 47, 1971–1988, July 2001.
27. Bosisio, R., U. Spagnolini, and Y. Bar-Ness, "Multilevel type-II HARQ with adaptive modulation control," *Prop. IEEE WCNC'06*, Vol. 4, 2082–2087, Apr. 3–6, 2006.
28. Zheng, H. and H. Viswanathan, "Optimizing the ARQ performance in downlink packet data systems with scheduling," *IEEE Trans. Wireless Commun.*, Vol. 4, 495–506, Mar. 2005.