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Efficiency and Goodput Analysis of Dly-ACK in IEEE 802.15.3

Kuang-Hao Liu, Humphrey Rutagemwa, *Student Member,IEEE*, Xuemin (Sherman) Shen, *Senior Member, IEEE* and Jon W. Mark, *Life Fellow, IEEE*

***Abstract*— An analytical model for studying the performance of the Delayed Acknowledgement (Dly-ACK) mechanism in IEEE 802.15.3 over wireless Rayleigh fading channel is developed. A three-state Markov chain is applied to approximate the correlated transmission errors. Explicit mathematical expressions for the goodput and efficiency of Dly-ACK are derived. It is found that the correlation between consecutive transmissions errors has significant impact on the goodput and efficiency of the Dly-ACK mechanism. The goodput tends to increase as the size of the Dly-ACK burst increases; however, the amount of increase depends on the underlying delay. Simulation results are given to validate the analytical results.**

***Index Terms*— IEEE 802.15.3, Dly-ACK, Markov channel model, Performance analysis**

I. Introduction

Wireless Personal Area Networks (WPANs) aim at providing low-power, low-cost, and short-range connectivity to fulfill the requirement of mobile users. Many applications can benefit from WPAN with its ability of rapidly forming ad hoc connections and providing satisfactory quality of service (QoS) for multimedia traffic. Bluetooth is the first enabling technology that allows WPANs to instantly connect various portable devices and online [1]. However, Bluetooth is not widely deployed because of the limited data rate (raw rate up to 1 Mbps). The IEEE 802.15.3 standard, released in September 2003, can support high data rate WPANs ($11 \sim 55$ Mbps) in the unlicensed 2.4 GHz band [2].

The IEEE 802.15.3 standard employs a semi-ad hoc configuration to allow several devices autonomously forming a piconet in which one of them is selected as the piconet coordinator (PNC). The PNC is responsible for allocating radio resource and maintaining network-wide synchronization that allows time to be slotted into a superframe structure. A superframe consists of three components: a beacon period during which control messages are broadcasted by the PNC periodically; a contention access period that allows devices to send their resource demands to the PNC; and a contention free access period for peer-to-peer data communication among devices.

To compensate for errors or lost information transmitted over error-prone wireless medium, error correction, combined with error detection and retransmission have been implemented in typical wireless data networks. There are three retransmission policies (or protocols) defined in the IEEE 802.15.3 standard: no acknowledgement (no-ACK), immediate acknowledgement (Imm-ACK), and delayed acknowledgement (Dly-ACK). For broadcast and multicast messages, the ACK policy is set to no-ACK upon transmission. Imm-ACK, functioning as a stop-and-wait protocol, is used for resource request or data transmission that requires the intended recipient to send an ACK instantly as it receives a frame[1]. If a communicating pair agrees on the use of Dly-ACK, the sender can send a group of frames where the group size is negotiated at the beginning of this session, and then wait for the ACK. Such strategy helps to reduce ACK overhead, and improves channel utilization. This improvement can be significant, especially for high data rate applications, e.g., real-time multimedia streaming. With this salient feature of supporting high rate traffic, the emerging IEEE 802.11e standard also proposes a similar scheme to enhance QoS provisioning [3], [4].

If Dly-ACK is to be a significant policy for supporting isochronous streaming, it is important to have a good understanding of its performance. Automatic repeat request (ARQ) protocols such as stop-and-wait (SW), go-back-N (GBN) and selective repeat (SR) have been extensively studied, either in traditional data networks [5] or in emerging wireless counterpart [6], [7]. Dly-ACK is similar to GBN and SR in the sense that retransmissions are only for those erroneously received frames. Unlike GBN and SR, the sender suspends its transmissions after a group of frames have been transmitted and waits for the corresponding acknowledgement, as in SW. Because of this difference, the analytical approach developed for ARQ protocols cannot be applied directly to Dly-ACK. Only a limited amount of work on analytical modeling of Dly-ACK is available in the literature; also, assuming a constant packet error rate does not reflect the characteristic of wireless transmission [4], [8]. In [4], throughput is derived by considering the effective time used for transmitting the payload. In [8], delay performance is analyzed by considering various delay components. Although some interesting findings are pointed out, the channel impairment due to fading and the potential retransmissions of the last frame in a burst are not considered. It is shown in [8] that Dly-ACK can greatly improve the channel efficiency; such improvement is more significant in higher data rates.

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[1]The term “frame” used in this paper represents the data unit, either a control or data message, at the MAC layer. A frame can be a portion of a packet if fragmentation is implemented.

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In this paper, an analytical model for studying the performance of IEEE 802.15.3 Dly-ACK protocol over wireless Rayleigh fading channel is presented. To investigate the impact of correlated packet losses due to the impairment of fading channels, the commonly accepted Finite State Markov Channel (FSMC) model [9] is adopted. While the binary FSMC [11], [12] has been widely used by virtue of its simplicity, higher accuracy of FSMC may be achieved by increasing the number of states, especially when the underlying fading process is fairly slow [10]. Considering both analytical feasibility and reasonable accuracy, a three-state Markov chain is used to approximate the correlated packet losses. By means of the Markovian analysis, explicit mathematical equations that approximate the performance of Dly-ACK, for given wireless links and protocol parameters, are derived. This framework provides a mean to assess the performance of Dly-ACK where the throughput, efficiency, delay variation, etc. can be obtained. The resultant performance is beneficial for the design of optimal transmission strategy. For instance, the reception quality of a multimedia streaming determines the amount of required retransmissions, where the induced cost (e.g., delay) may not be affordable due to heavy retransmissions. Thus, it is necessary to tune relevant protocol parameters in response to the traffic arrival pattern so that desired reception quality can be guaranteed.

The rest of this paper is organized as follows: Section II describes the salient features of the Dly-ACK scheme specified in the IEEE 802.15.3 standard. The system model is developed in Section III, and the performance analysis is given in Section IV. Section V presents the simulation results and concluding remarks are given in Section VI.

II. PROTOCOL DESCRIPTION

Fig. 1 shows the transmission process of Dly-ACK as specified in the IEEE 802.15.3 MAC standard. The Dly-ACK protocol is composed of two phases: an initialization phase and a data exchange phase. Prior to data transmissions, the communicating pair negotiates the type of acknowledgement policy to be used. The initialization procedure involves the source node sending a single data frame with the ACK policy field set to `Dly-ACK Request`. If the destination accepts the use of Dly-ACK, it responds with an acknowledgement frame immediately. As defined in the standard, this acknowledgement frame is used to acknowledge the received data frame and indicate the *burst size*. By burst size it is meant the maximum number of frames the sender may send before receiving the feedback. i.e., acknowledgement frame. The value of the burst size, which is not explicitly defined in the standard, may be determined according to the receiver buffer requirement and the delay tolerance of the underlying traffic. Once the initialization is performed the data exchange phase begins. The procedural steps of the data exchange phase are as follows:

1) The sender sends a group of frames where the number of consecutive frames equals the burst size N. Thereafter, the sender waits for the corresponding acknowledgement from the receiver.
2) In the feedback direction, if the acknowledgement is not received during an interval of retransmission interframe space (RIFS), the last data frame of the burst is repeated until the acknowledgement frame is received. The retransmission of last frame is to signal the receiver that the current burst has been finished, and the acknowledgement frame shall be launched immediately.
3) Before a burst transmission is completed, i.e., the Dly-ACK frame is received by the sender, the sender is not allowed to resume transmission. In the succeeding burst, both the erroneous and the lost frames in previous bursts have to be retransmitted if the retry limit is not exceeded.
4) Each frame is identified by a sequence number. The communicating pair is thus capable of determining when a burst finishes and which frame needs to be retransmitted.
5) The receiver can change the acknowledgement policy or the burst size after each burst by altering the associated fields in the Dly-ACK frame.

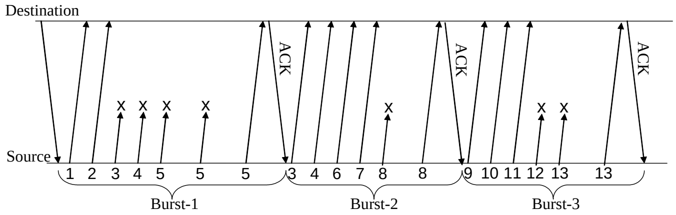

Fig. 1. Frame transmission process using Dly-ACK policy.

The operation of the data exchange phase is shown in Fig. 1, where the burst size is assumed to be 5. In the first burst (frames $1 \sim 5$), frames 3, 4 and 5 are detected to be erroneous. After transmitting the last frame (i.e., frame 5), the sender suspends its transmission and waits for the receiver's reply. Suppose the channel encounters a deep fade in the next few milliseconds, frame 5 requires three attempts to be received successfully. As frame 5 is received, the receiver indicates those frames that are successfully received (i.e.,frames 1, 2, and 5) by using a single ACK frame. In the next burst, the sender retransmits those frames lost in the previous burst (frames 3 and 4) plus new frames (frames 6, 7, and 8), as long as the number of frames transmitted does not exceed the negotiated burst size. The same procedure continues for the succeeding bursts, (frames 3, 4, 6, 7, and 8) and (frames 9, 10, 11, 12, and 13).

Therefore, the number of successful transmissions during one burst equals to the variable number of successes achieved among the first four transmitted frames plus the last transmitted frame. In addition, the last frame may be transmitted several times, while each of the the first four frames is transmitted by exact once. This observation facilitates the derivation of the protocol performance metrics, as we will demonstrate in Sec. IV.

III. SYSTEM MODELS

We focus on the peer-to-peer communication between two devices in a WPAN where the data transmission may encounter errors because of impairments of wireless links. The Dly-ACK mechanism is implemented to enhance reliability. Accordingly,

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the receiver acknowledges the reception of data via a feedback channel. The feedback channel is assumed to be error-free since the acknowledgement frames are much smaller in size than the data frames and can be protected if sufficient error-correcting codes are implemented. The consideration of feedback errors can be easily incorporated in our analytical model as commented in Sec. IV-B.

When a sender has data to send, it first negotiates the acknowledgement mode with the intended receiver. This negotiation procedure only takes place once as long as the communicating pair agrees on the current acknowledgement policy, so we exclude the negotiation procedure from our consideration and we assume the burst size is fixed. For the wireless channel, a non-line-of-sight frequency-nonselective multipath fading channel with frame transmission time shorter than the channel coherence time is assumed. Such a fading channel can be statistically described as a multiplicative complex Gaussian process with a Rayleigh distributed envelope.

A. Wireless Rayleigh Fading Channel

For a given modulation scheme, the dynamics of the fading channel can be characterized at the packet level. Various statistical models have been proposed to approximate the error process due to channel fading at the packet level [9]- [15]. One of the commonly used approaches is the Finite State Markov Channel (FSMC) model [9]. Generally the channel bit error rate (BER) is a function of signal-to-noise ratio (SNR) at the receiver where SNR takes a continuous range of values. The methodology of FSMC modeling is to partition the received SNR into n intervals according to a certain set of thresholds. Each of the intervals corresponds to a state of the Markov chain, and the error probability associated with each state can be given according to the mean received SNR and the modulation format. Therefore, several parameters involved in Markov channel modeling, such as the number of states, the SNR threshold, the transition probability matrix $\mathbf{P} = [\pi_i],\ i = 1,\ 2,\ \ldots,\ n$ need to be determined. The reader is refered to [9], [16], [17] for detailed discussions. Throughout this paper, we use n to denote the number of states in the FSMC model.

It has been shown that the first order FSMC model with three states gives a good approximation of the fading process under sufficiently slow fading (i.e., with normalized fading rate less than 0.1) [18]. Since WPANs are mainly dedicated to indoor applications with fairly slow mobility, the applied statistical model has to be able to capture the characteristics of a very slow fading process. In this paper we use a three-state Markov chain (i.e., $n = 3$ in our consideration) to model the error process of Rayleigh fading channel considering the tradeoff between accuracy and complexity. As far as partitioning method is concerned, several heuristic approaches have been proposed in [16] and further investigated in [17]. In this study, we set the SNR thresholds $\Lambda_1 = -\lambda_0 \ln(1-\pi_1)$ and $\Lambda_2 = -\lambda_0 \ln \pi_3$ such that the elements of $\mathbf{P}$ are $\pi_1 = \frac{2}{n(n+1)}$, and $\pi_i = i\pi_1$ $(i = 2,\ 3)$ [16]. Such a partitioning method allocates more states in the range of higher error probability to have a better tracking of the channels with poorer quality. Once the partitioning threshold is determined, the parameters of the Markov channel model, such as $\mathbf{P}$ and the crossover probability associated with each state, can thus be obtained either by simulation or analysis [19]. In this study, the elements of $\mathbf{P}$ are estimated from empirical data.

B. Dly-ACK Protocol Model

Our analytical model is based on a fixed burst size N. The sender will transmit N data frames consecutively, but the frame sequence may be out of order due to retransmissions. After sending the last frame in a burst, the sender suspends from transmission process and waits for ACK. The receiver will not launch ACK until the last frame is received successfully. Thus the sender will need to repeat the last frame by the end of a timeout. Taking into account the interframe space, the processing time, transmission time and the propagation delay, we set the timeout to be $2d$, where d is the maximum one-trip delay. According to the standard, the last frame is repeated until it is successfully transmitted. Without specifying a retry limit, the protocol may be unstable for extreme cases, e.g., the channel condition remains poor for a long time leading to long resequencing delay at the receiving end [20]. In terms of network throughput and efficiency, the assumption of persistent retry does not compromise the objective of capturing the interaction of the channel behavior and the protocol parameters while resulting in slightly optimistic estimates.

Let one slot correspond to the duration of one frame transmission, where the frame length is assumed constant. At the beginning of each time slot at time t, let $n(t)$ denote the number of frames pending transmissions in a burst and $c(t)$ be the current channel state. The transmission of frames can be tracked by a two-dimensional process $Y(t) = (n(t), c(t))$ where $n(t) \in \{1,\ 2,\ \ldots,\ N\}$, $c(t) \in \{1, 2, 3\}$, and t is measured in slots. By sampling $Y(t)$ at the beginning of each burst (denoted as t_k), we can obtain a new process $\{Y(t_k)\}$ which describes the transition process burst-by-burst. The process $\{Y(t_k)\}$ can be approximated by the semi-Markov process with embedded Markov chain $\{Y_k, k \geq 0\}$, in the state space $W_s \in \{(i, x) : i = N, x \in \{1, 2, 3\}\}$, defined by the transition probability matrix $\mathbf{\Psi}$ whose element $\psi_{(i,x)(j,y)}$ corresponds to the transition probability from state (i, x) to state (j, y). The element of the steady-state probability matrix $\mathbf{\Pi}$ associated with $\{Y_k\}$ can be computed by

$$\sum_{(i,x)\in W_s} \pi_{(i,x)} = 1,$$
$$\pi_{(j,y)} = \sum_{(i,x)\in W_s} \psi_{(i,x)(j,y)} \pi_{(i,x)},\ \forall (j, y) \in W_s. \tag{1}$$

The process $\{Y(t_k)\}$ is a renewal reward process in the sense that certain rewards (successful transmissions) are collected before the process is renewed (a new burst starts). Note that each burst will always start with one of the states $\{(N, 1), (N, 2), (N, 3)\}$.

IV. Performance Analysis

In this section we analyze a peer-to-peer communication system employing the Dly-ACK protocol over the Rayleigh

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fading channel in which the error process is modeled by a three-state Markov chain. We are interested in two performance metrics: goodput and efficiency. Goodput is defined as the average number of successful transmissions per unit time. The ratio of average number of successful transmissions to the average total number of transmission attempts is defined as the protocol efficiency. Throughout the analysis, we make the following assumptions: 1) there is no retry limit for frame transmissions; 2) the burst size is fixed; 3) the feedback channel is perfect. The consideration of feedback errors can be realized by augmenting an additional state that represents the channel state in the feedback direction.

By counting the rewards associated with each transition in the embedded Markov chain $\{Y_k\}$, denoted by the matrix $\mathbf{R} = \left[r_{(i,x)(j,y)}\right]$, we can track the number of successful transmissions. Similarly, the number of frames transmitted and the resultant transmission time, represented by $\mathbf{\Xi} = \left[\xi_{(i,x)(j,y)}\right]$ and $\mathbf{T} = \left[\tau_{(i,x)(j,y)}\right]$, respectively, can be obtained. The detailed derivations are given in the following subsections.

The performance metrics of interest can be obtained as follows. Let t_0, t_1 ... be the time instants when the communicating pair finishes one burst transmission, and $\Delta t_k = t_k - t_{k-1},\ k = 1, 2, \ldots$ be the time elapsed between the $(k-1)$th and kth burst. Then Δt_k forms an iid sequence since each burst duration is independent of the previous burst durations. Denote $S(t)$ the number of frames successfully transmitted by time t and $N(t)$ the total number of frames transmitted by time t. $S(t)$ can be considered as a renewal process having interarrival times Δt_k. By the renewal reward theorem [21], the long-term average efficiency η can be derived as

$$\eta = \lim_{t\to\infty} \frac{S(t)}{N(t)} = \frac{\sum_{x=1}^{3} \pi_{(N,x)} \sum_{y=1}^{3} \psi_{(N,x)(N,y)} r_{(N,x)(N,y)}}{\sum_{x=1}^{3} \pi_{(N,x)} \sum_{y=1}^{3} \psi_{(N,x)(N,y)} \xi_{(N,x)(N,y)}}, \tag{2}$$

where $\pi_{(N,x)}$ is the steady-state distribution of the chain $\{Y_k\}$ from (1). Similarly, the long-term average goodput λ is given by

$$\lambda = \lim_{t\to\infty} \frac{S(t)}{t} = \frac{\sum_{x=1}^{3} \pi_{(N,x)} \sum_{y=1}^{3} \psi_{(N,x)(N,y)} r_{(N,x)(N,y)}}{\sum_{x=1}^{3} \pi_{(N,x)} \sum_{y=1}^{3} \psi_{(N,x)(N,y)} \tau_{(N,x)(N,y)}}. \tag{3}$$

To calculate the elements of the aforementioned matrices $\mathbf{R}$, $\mathbf{\Xi}$, $\mathbf{T}$, and $\mathbf{\Psi}$ (defined in (1)), we further study the transmission process as described in Sec. II. Given the burst size equal to N, 1) for the first $N-1$ frames in the burst, the number of transmitted frames is deterministic, and the number of successfully transmitted frames is stochastic; 2) for the Nth frame (i.e., the last frame) in the burst, the number of Nth frame transmissions is stochastic, and the number of successfully transmitted frames is one. Therefore, it is convenient to decompose the burst transmission in two separate phases, and combine the results to compute the elements of $\mathbf{R}$, $\mathbf{\Xi}$, $\mathbf{T}$, and $\mathbf{\Psi}$. Phase-I covers the transmissions of the first $N-1$ frames in the burst, and phase-II covers the

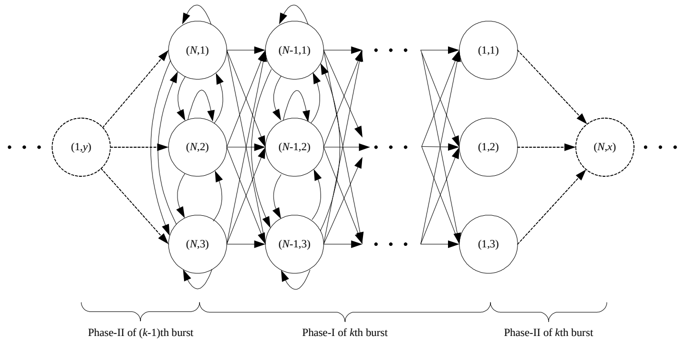

Fig. 2. State transition diagram of phase-I transmission process. N is the burst size.

transmissions of the last frame in the burst. Let $\mathbf{\Psi^{(I)}}$, $\mathbf{R^{(I)}}$, $\mathbf{\Xi^{(I)}}$, and $\mathbf{T^{(I)}}$ denote the transition probability matrix, the reward, the number of transmissions, and the transmission time associated with phase-I, respectively. Similarly, denote $\mathbf{\Psi^{(II)}}$, $\mathbf{R^{(II)}}$, $\mathbf{\Xi^{(II)}}$, and $\mathbf{T^{(II)}}$ as the transition probability matrix, the reward, the number of transmission, and the transmission time associated with phase-II. All matrices have the same dimension of $3N \times 3N$ where the elements associated with phase-II are nulls. $\mathbf{R^{(II)}}$, $\mathbf{\Xi^{(II)}}$, and $\mathbf{T^{(II)}}$ have the same structure that allows us to compute the following matrices:

$$\begin{aligned} \mathbf{\Psi} &= \mathbf{\Psi}^{(I)}\mathbf{\Psi}^{(II)}, & \mathbf{R} &= \mathbf{R}^{(I)} + \mathbf{R}^{(II)} \\ \mathbf{\Xi} &= \mathbf{\Xi}^{(I)} + \mathbf{\Xi}^{(II)}, & \mathbf{T} &= \mathbf{T}^{(I)} + \mathbf{T}^{(II)}. \end{aligned} \tag{4}$$

The derivation of each matrix is given in the sequel.

A. Phase-I

For phase-I, the transmission process can be tracked by sampling the process $\{Y(t)\}$ after every time slot. The resultant random process is a discrete two-dimensional Markov chain with state space $\{(i, x) : i \in \{1, 2, \ldots, N\}, x \in \{1, 2, 3\}\}$. The corresponding transition probability matrix $\mathbf{W}$ is given as

$$\mathbf{W} = \left[w_{(i,x)(j,y)}\right] = \begin{cases} (1-e_x)p_{xy}, & i = j+1 \\ e_x p_{xy}, & i = j \geq 2 \\ 0, & otherwise, \end{cases} \tag{5}$$

for $i, j \in \{1, 2, \ldots, N\}$, $x, y \in \{1, 2, 3\}$. Fig. 2 shows the transition diagram that models the transmission process of phase-I. Each one-step transition indicates the result of one frame transmission depending on the channel quality at the instant of sampling and the number of remaining frames in a burst.

1) Transition Probability Matrix $\mathbf{\Psi^{(I)}}$*:* Denote $Y^{(I)}(t_k)$ the state at the beginning of phase-I in the kth burst, and $Y^{(II)}(t_k + (N-1))$ the state at the beginning of phase-II. By sampling at instants t_k and $t_k + (N-1)$ of burst k, we can obtain $\left\{Y^{(I)}(t)\right\}$ corresponding to the transmission process of phase-I. Given the initial state (N, x), the probability of ending at state (j, y) can be obtained as an $(N-1)$-step transition probability of $\mathbf{W}$, i.e. $\mathbf{W}^{N-1} = \left[w_{(i,x)(j,y)}(N-1)\right]$. Consequently, the transition process from state $Y^{(I)}(t_k)$ to state $Y^{(II)}(t_k + (N-1))$ has its transition probability matrix $\mathbf{\Psi}^{(I)}$

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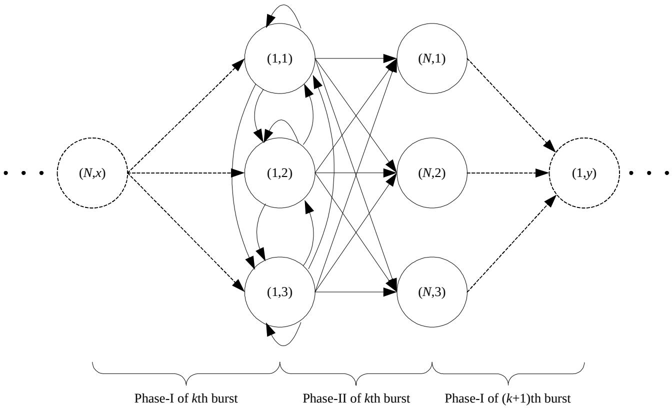

Fig. 3. State transition diagram of phase-II transmission process. N is the burst size. Note that the transition probability from state $\{(N,1),(N,2),(N,3)\}$ to state state (1,y) is one.

with element $\psi^{(I)}_{(i,x)(j,y)}$:

$$\psi^{(I)}_{(i,x)(j,y)} = \begin{cases} w_{(i,x)(j,y)}(N-1), & i = N \\ 0, & otherwise, \end{cases} \tag{6}$$

where $i, j \in \{1, 2, \ldots, N\}$, $x, y \in \{1, 2, 3\}$.

2) Expected Number of Successful Transmissions $\mathbf{R}^{(\mathbf{I})}$*:* For phase-I, a successful transmission can be interpreted as a reward being given after every successful transmission, and hence, a reward matrix $\mathbf{R}^{(I)}$ can be formed with element $r^{(I)}_{(i,x)(j,y)}$:

$$r^{(I)}_{(i,x)(j,y)} = \begin{cases} N-j, & i = N \\ 0, & otherwise, \end{cases} \tag{7}$$

where $i, j \in \{1, 2, \ldots N\}$, $x, y \in \{1, 2, 3\}$.

3) Expected Transmission Time $\mathbf{T}^{(\mathbf{I})}$ *and Number of Total Transmissions* $\mathbf{\Xi}^{(\mathbf{I})}$*:* The number of transmissions experienced in phase-I is deterministic and equals to $N-1$. Thus, we can form the matrix $\mathbf{\Xi}^{(I)}$ with element $\xi_{(i,x)(j,y)}$:

$$\xi^{(I)}_{(i,x)(j,y)} = \begin{cases} N-1, & i = N \\ 0, & otherwise, \end{cases} \tag{8}$$

where $i, j \in \{1, 2, \ldots, N\}$, $x, y \in \{1, 2, 3\}$. Since the transmission in phase-I is on a frame-by-frame basis, the expected time taken in phase-I is given by the matrix $\mathbf{T}^{(I)}$ with element $\tau^{(I)}_{(i,x)(j,y)}$:

$$\tau^{(I)}_{(i,x)(j,y)} = \begin{cases} N-1, & i = N \\ 0, & otherwise, \end{cases} \tag{9}$$

where $i, j \in \{1, 2, \ldots, N\}$, $x, y \in \{1, 2, 3\}$.

B. Phase-II

According to the IEEE 802.15.3 specification, the transmission of the last frame is repeated until it is successfully transmitted. Taking into account the channel delay, the sender repeats the last frame every round-trip delay $(2d+1)$. Here d is the channel delay counting for the time from the beginning of a transmission till it is successfully detected and decoded by the receiver.

By sampling the random process $\{Y(t)\}$ every round-trip delay $(2d+1)$, a new process is constructed with state space $W'_s \in \{(i', x') \colon i' \in \{1, N\}, x' \in \{1, 2, 3\}\}$. Here $i' = 1$ if the last frame is not successfully transmitted, and $i' = N$ if it is successfully transmitted. Fig. 3 illustrates the transition diagram of phase-II. The corresponding transition probability matrix is $\mathbf{Z} = \left[z_{(i',x')(j',y')}\right]$, where $z_{(i',x')(j',y')}$ is given by:

$$z_{(i',x')(j',y')} = \begin{cases} (1-e_{x'})p_{x'y'}(2d+1), & i'=1, j'=N \\ e_{x'}p_{x'y'}(2d+1), & i'=j'=1 \\ 0, & otherwise. \end{cases} \tag{10}$$

As shown in Fig. 3, phase-II may start in any of the initial states $(1, x')$, $x' \in \{1,\, 2,\, 3\}$, which is determined by the initial state of phase-I after experiencing $(N-1)$ transitions. Given the transmission process starts at state $(N, x), x \in \{1,\, 2,\, 3\}$ at the beginning of a burst, the probability that the transmission process is in state $(1, x')$ at the beginning of phase-II equals the $(N-1)$ transition probability from channel state x to channel state x', i.e., $p_{xx'}(N-1)$.

1) Transition Probability Matrix $\mathbf{\Psi}^{(\mathbf{II})}$*:* For phase-II, the transmission process is tracked by sampling the process $\{Y(t)\}$ after every round trip time (i.e., $2d+1$). From Fig. 3, phase-II starts with state $(1, x')$ and terminates in state (N, y') once the last frame is transmitted successfully. Let $u_{(i',x')(j',y')}$ denote the probability that the transmission process will enter absorbing state $(j', y') \in \{(N,1),(N,2),(N,3)\}$ conditioning on it starts at the state (i', x'). The probability matrix $\mathbf{U} = \left[u_{(i',x')(j',y')}\right]$ can be computed as

$$\mathbf{U} = \left[\mathbf{I} - \mathbf{Z}\right]^{-1}, \tag{11}$$

where $\mathbf{I}$ is the identity matrix and $[\;]^{-1}$ is the inverse matrix operation, and $\mathbf{Z}$ is given by (10). The elements of transition probability matrix $\mathbf{\Psi}^{(\mathbf{II})}$ are therefore given as

$$\psi^{(II)}_{(i,x')(j,y')} = \begin{cases} u_{(1,x')(N,y')}, & j = N \\ 0, & otherwise, \end{cases} \tag{12}$$

where $i, j \in \{1,\, 2,\, \ldots,\, N\}$, $x', y' \in \{1,\, 2,\, 3\}$.

2) Expected Number of Successful Transmissions $\mathbf{R}^{(\mathbf{II})}$*:* Since the last frame in a burst is retransmitted until it is successfully delivered, the expected number of successful transmissions can be described by the matrix $\mathbf{R}^{(II)}$ with element $r^{(II)}_{(i,x)(j,y)}$:

$$r^{(II)}_{(i,x)(j,y)} = \begin{cases} 1, & j = N \\ 0, & otherwise, \end{cases} \tag{13}$$

where $i, j \in \{1, 2, \ldots N\}$, $x, y \in \{1, 2, 3\}$.

3) Expected Transmission Time $\mathbf{T}^{(\mathbf{II})}$ *and Number of Total Transmissions* $\mathbf{\Xi}^{(\mathbf{II})}$*:* For phase-II, with the knowledge of initial state, the final state, and the corresponding transition probability, we can derive the average number of frames consumed in phase-II. The expected number of transmissions, $m_{(1,x')(N,y')}$, made in the transient state $(1, x')$ before the transition process enters into the absorbing state (N, y'), as

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depicted in Fig. 3, is given by (see Appendix):

$$m_{(1,x')(N,y')} = \frac{\sum_{v=1}^{3} u_{(1,x')(1,v)} u_{(1,v)(N,y')}}{u_{(1,x')(N,y')}}. \tag{14}$$

Since the state $(1, x')$ is actually conditional on the initial state of a burst (i.e., (N, x)), the expected number of transitions made in a transient state before the transition process enters into the absorbing state (N, y') is given by

$$\widetilde{m}_{(N,x)(N,y')} = \frac{\sum_{k'=1}^{3} p_{xk'}(N-1) \sum_{l'=1}^{3} u_{(1,k')(1,l')} u_{(1,l')(N,y')}}{\sum_{k'=1}^{3} p_{xk'}(N-1) u_{(1,k')(N,y')}}. \tag{15}$$

Thus, the matrix $\Xi^{(II)}$ with element $\xi^{(II)}_{(i,x)(j,y)}$ is formed by properly arranging $\widetilde{m}_{(N,x)(N,y')}$:

$$\xi^{(II)}_{(i,x)(j,y)} = \begin{cases} \widetilde{m}_{(N,x)(N,y')}, & j = N \\ 0, & otherwise. \end{cases} \tag{16}$$

On the other hand, each frame is transmitted in every round-trip time $(2d+1)$ in phase-II. The expected transition time matrix therefore can be represented as $\mathbf{T}^{(II)} = (2d+1) \cdot \Xi^{(II)}$.

V. Simulation Results

In this section, the accuracy of our analytical model is evaluated via simulation. The sensitivity of the Dly-ACK performance to burst size (i.e., transmission window) and various propagation and physical layer parameters such as normalized fading rate, received SNR and channel delay is also discussed. A peer-to-peer communication scenario using Dly-ACK is implemented. A persistent traffic is assumed at the source device, and the sender's buffer and receiver's buffer are assumed to be sufficiently large. The fading process with Rayleigh distributed envelope is generated using Jakes' model [22]. In our simulations, $500,000$ frames are generated and a warm-up period of $5,000$ frames are considered. Following the technique described in [23], the fading process is sampled frame by frame and the frame error rate (FER) corresponding to each frame is computed by considering a QPSK (quadrature phase shift keying) modulation as specified in the standard. This result is dumped into a trace file. Then we run the Dly-ACK protocol over a channel whose error process is generated from the trace file. For the analytical part, the parameters of the three-state Markov channel model are first computed according to the trace file. Then the efficiency and goodput are computed using the equations derived in Section IV.

A. The Accuracy of Three-State Markov Channel Model

We first demonstrate the accuracy of the three-state Markov channel model. For this purpose, we compare the performance of Dly-ACK protocol between three-state and two-state Markov channel models, using a simulated Rayleigh fading channel as benchmark. Fig. 4 shows the result for the scenario: $\mathrm{SNR} = 15$ dB, burst size $N = 5$ frames, and channel delay $d = 3$ slots. The normalized fading rates shown in

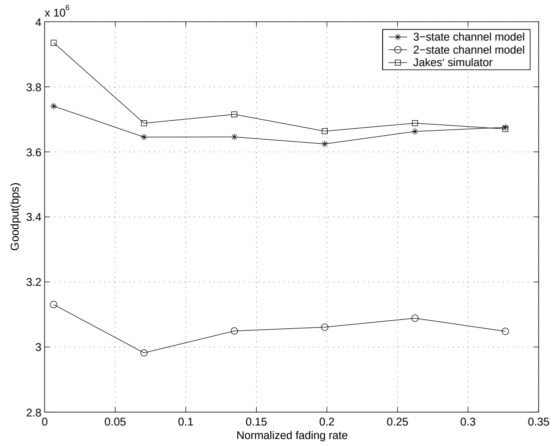

Fig. 4. The accuracy of three-state Markov channel model.

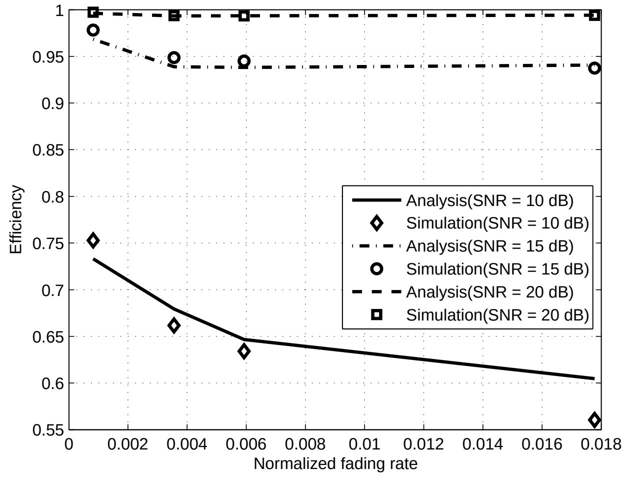

Fig. 5. Efficiency versus $f_d T$.

Fig. 4 are typical in wireless environment, but the scenario of interest only covers very small values. It can be seen that the goodput for the three-state channel model approximates that of the Rayleigh fading channel very well, whereas the two-state channel model shows a large discrepancy.

B. Effect of the Normalized Fading Rate

Multipath fading is a common phenomenon in wireless communications [24]. The envelope of the received signal is a function of the velocity v of the user and the carrier frequency f_c of the transmitted signal. With a time-varying channel, the error patterns can be correlated or uncorrelated. The degree of correlation is typically measured in normalized fading rate given by the product of the Doppler frequency $f_d = v/\lambda$ ($\lambda = c/f_c$ is the wavelength of the transmitted carrier frequency where c is the speed of light) and the transmission time of the data unit T. The fading process is considered slow if $f_d T \leq 0.1$ and consequently consecutive packet losses are correlated. The fading process is considered fast fading if $f_d T \geq 0.2$ and therefore packet losses are uncorrelated. Considering that WPANs are dedicated to indoor applications, we choose the velocity of 5 km/hr, corresponding to 1.38 m/s.

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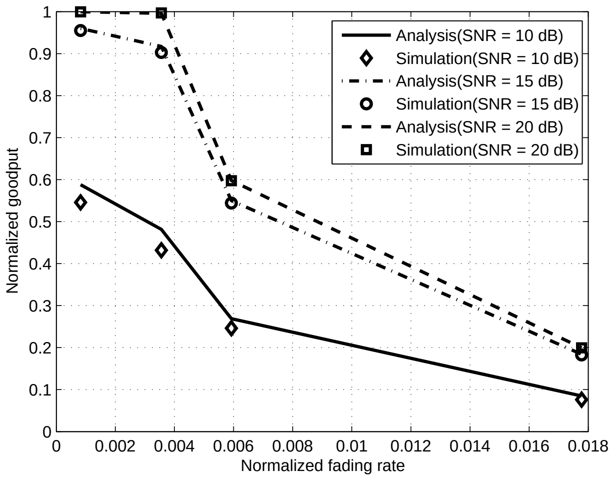

Fig. 6. Normalized goodput versus $f_d T$.

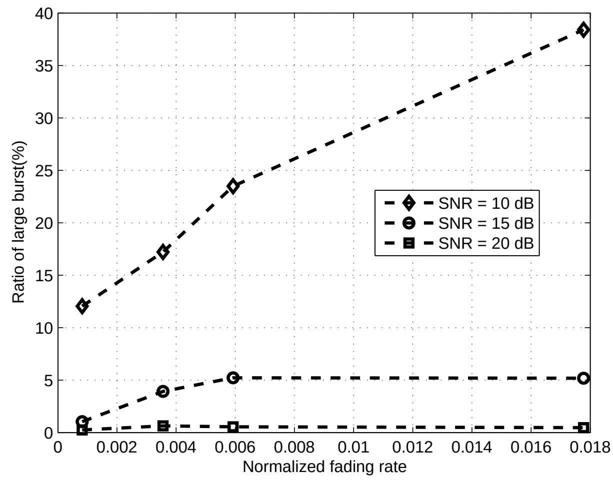

Fig. 7. Ratio of large burst versus $f_d T$.

The effect of normalized fading rate $f_d T$ to the Dly-ACK policy is investigated by manipulating the data rate and the frame size. The resultant normalized fading rate is located in the range of $[0.0008, 0.0178]$. The response of efficiency and normalized goodput to normalized fading rate can be observed in Fig. 5 and Fig. 6, respectively. For $\text{SNR} = 10$ dB, which can be interpreted as a relatively poor channel, goodput is sensitive to the change of fading rate and it reveals a downward trend at the range of normalized fading rate of interest. Since the number of retransmissions in phase-II dominates the efficiency of Dly-ACK protocol, we define the burst with size larger than the prescribed size N as *large burst* and probe the frequency of large burst per simulation run. It can be seen that when the fading rate increases the proportion of bursts that need more than N transmission attempts to receive the ACK also increases, conditioned on the same SNR. We further examine the amount of retransmissions in phase-II by showing the average size of large burst size in Fig. 8. An intuitive notion is the average size increases as the correlation of errors increases. It is shown in Fig. 8 that the proportion of frames being retransmitted is larger for small $f_d T$ than for higher $f_d T$. This is due to the fact that, once the last frame in a burst runs into an error, the next transmission is very likely to be failed because of the correlated errors. By jointly considering Figs. 7 and 8, we can see as the frame errors are less correlated, a frame falls into the retransmission group more frequently, but the duration it stays in a group of errors diminishes. Meanwhile, a more notable variation in Fig. 7 than that in Fig. 8 indicates that the sender spends more time in idle when the error pattern is less correlated. From the above observations we can conclude that the performance of Dly-ACK degrades as the channel error is less correlated. In other words, increasing the frame transmission time or movement speed, corresponding to increasing the normalized fading rate, result in lower goodput and protocol efficiency.

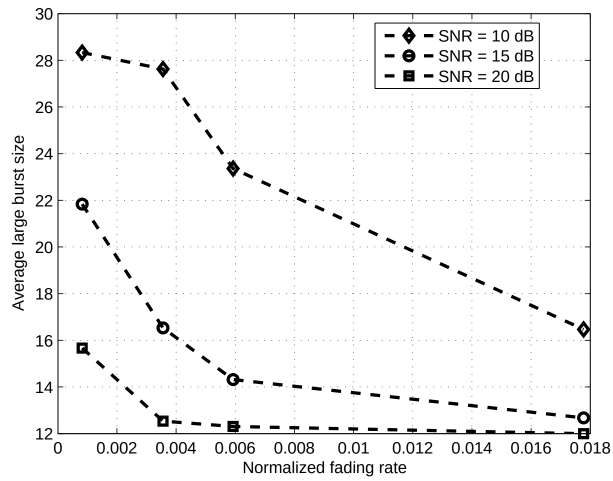

Fig. 8. Average size of large burst versus $f_d T$.

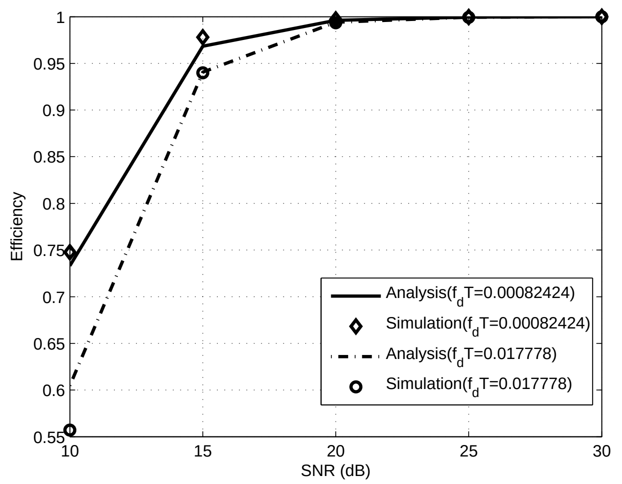

Fig. 9. Efficiency versus SNR for $f_d T = 0.00008$ and 0.01778.

C. Effect of the SNR

The impacts of SNR are investigated in Figs. 9 and 10 by setting $N = 5$ and $d = 3$ slots. Higher SNR leads to lower

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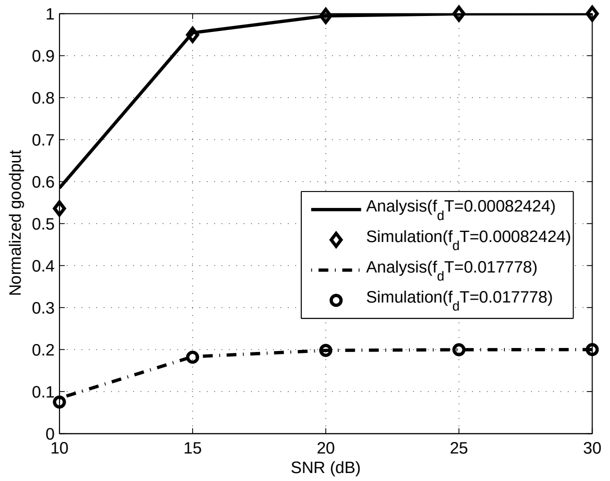

Fig. 10. Normalized goodput versus SNR for $f_dT = 0.00008$ and 0.01778.

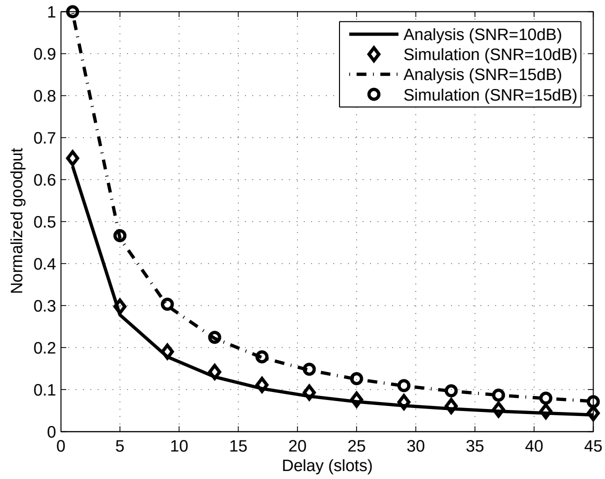

Fig. 11. Normalized goodput versus delay for SNR=15 dB and 25 dB.

error rate and, hence, efficiency and goodput increase as more successful transmissions can be achieved. Both performance measures reach their limits when the applied SNR is sufficiently large to produce very low error probability. Moreover, the channel with lower f_dT is more vulnerable to the low SNR compared to the one with higher f_dT. This phenomenon can also be explained by Figs. 7 and 8, where the sender using Dly-ACK spends more time in the idle state as the frame errors are less correlated.

D. Effect of the Channel Delay

Fig. 11 shows the response of normalized goodput to channel delay d for different values of SNR with $N = 5$. It can be seen that a longer channel delay prolongs the burst duration, and thus degrades the goodput. It can also be observed that the impact of channel delay on goodput is higher in a low SNR environment ($\text{SNR} = 10$ dB) than in a higher SNR environment ($\text{SNR} = 15$ dB). For example, when the channel delay is 5 slots long, the goodput for $\text{SNR} = 15$ dB is about 35% higher than the goodput for $\text{SNR} = 10$ dB. When the channel delay is increased to 9 slots long, the difference is decreased to 10%.

E. Effect of the Burst Size

To explore the impact of burst size on Dly-ACK goodput, we set $d = 3$ slots, $\text{SNR} = 15$ dB; the result is shown in Fig. 12. It can be seen that the normalized goodput increases when the burst size increases. The reason is that, by considering the same error rate, increasing the burst size simply concentrates the error events in bursts and, in turn, the retransmission process becomes more efficient. In addition, the effect of normalized fading rate to goodput in the lower f_dT and the higher f_dT situations is also shown in Fig. 12. When $N = 1$, both error patterns result in nearly identical goodput. In fact, the special case of $N = 1$ is equivalent to the Imm-ACK operating in a stop-and-wait manner. Therefore, the correlation of error process has minor impact. As the

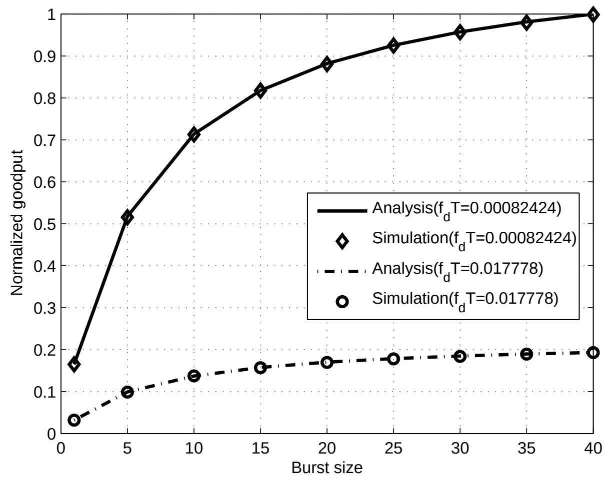

Fig. 12. Normalized goodput versus burst size for $f_dT = 0.00008$ and 0.01778.

delay increases, on the other hand, idle time increases, and the goodput drops. To compensate the performance loss due to channel delay, one of the strategies is to increase the burst size. From Fig. 13, a goodput of 50% of the highest value under investigation can be achieved when the burst size is $N = 5$ with channel delay $d = 3$ slots. When the protocol encounters longer channel delay, say 23 slots long, the performance is reduced by nearly 40%. The same goodput is attained when the burst size is increased to $N = 20$.

VI. CONCLUSION

We have proposed an analytical model for studying the efficiency and goodput performance of the IEEE 802.15.3 Dly-ACK protocol in the presence of correlated transmission errors. Simulation results have demonstrated the accuracy of the proposed analytical model. It is observed that the Dly-ACK protocol performs better in a correlated error environment than in a less correlated error environment. Also, the goodput of Dly-ACK can be improved by increasing the burst size.

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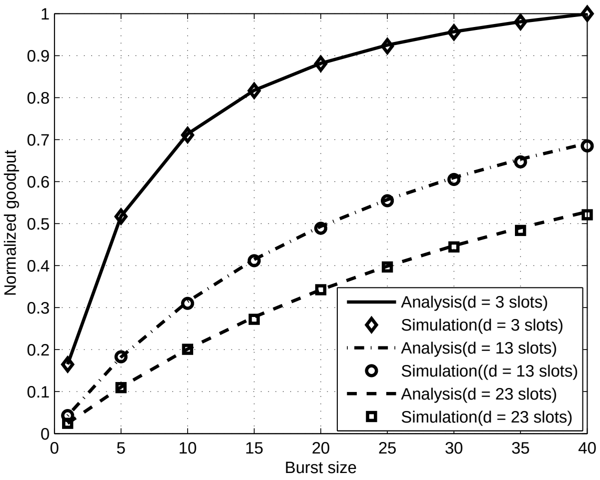

Fig. 13. Normalized goodput versus burst size for different delays.

However, the resultant inter-packet delay may be unacceptable to time-sensitive applications. Research on analyzing the delay performance of the Dly-ACK protocol over fading channels and on determining the burst size that results in optimal goodput for given channel condition and QoS requirement is underway. Furthermore, several WPANs may coexist in the vicinity and introduce unavoidable interference. The extension of the proposed research to the circumstance when multiple WPANs overlap their coverages is also underway.

APPENDIX
DERIVATION OF EQUATION (14)

From Fig. 3, a frame is transmitted for each transition. Therefore, the expected number of frame transmissions is equal to expected number of transitions. Define an indicator variable I which equals one when the system is in state $(1, v)$ at time k. This can be presented as

$$I_{(1,x')(1,v)|(N,y')}(k) = \begin{cases} 1, & s(k) = (1, v) \\ 0, & otherwise, \end{cases} \tag{17}$$

where $s(0) = (1, x')$ and $s(\infty) = (N, y')$. The expected value of the indicator variable in (17) is

$$\begin{aligned} &\bar{I}_{(1,x')(1,v)|(N,y')} = \\ &\Pr\{s(k) = (1, v)|s(0) = (1, x'), s(\infty) = (N, y')\}. \end{aligned} \tag{18}$$

By Bayes' theorem, the right-hand-side of (18) can be written as (19) at the top of the next page. From Markov property one can write (20). Let $J_{(1,x')(1,v)|(N,y')}$ denote the number of times that state $(1, v)$ is visited for an infinite number of transitions. Then, the expected number of times that state $(1, v)$ is visited can be written as

$$\begin{aligned} \bar{J}_{(1,x')(1,v)|(N,y')}(k) &= \overline{\left(\sum_{k=0}^{\infty} I_{(1,x')(1,v)|(N,y')}(k)\right)} \\ &= \sum_{k=0}^{\infty} \bar{I}_{(1,x')(1,v)|(N,y')}(k). \end{aligned} \tag{21}$$

By considering the transmission matrix $\mathbf{U} = \left[u_{(i',x')(j',y')}\right]$ defined in (11), and (20) and (21), we can write

$$\bar{J}_{(1,x')(1,v)|(N,y')}(k) = \frac{u_{(1,x')(1,v)}u_{(1,v)(N,y')}}{u_{(1,x')(N,y')}}. \tag{22}$$

The expected total number of times that the transient state $\{(1, 1), (1, 2), (1, 3)\}$ are visited, if the transmission process is started in state $(1, x')$ and ended in state (N, y') is

$$\begin{aligned} m_{(1,x')(N,y')} &= \sum_{k=1}^{3} \bar{J}_{(1,x')(1,v)|(N,y')} \\ &= \frac{u_{(1,x')(1,v)}u_{(1,v)(N,y')}}{u_{(1,x')(N,y')}}. \end{aligned}$$

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$$\frac{\Pr\{s(\infty)=(N,y')|s(k)=(1,v),s(0)=(1,x')\}\Pr\{s(k)=(1,v)|s(0)=(1,x')\}}{\Pr\{s(\infty)=(N,y')|s(0)=(1,x')\}}. \tag{19}$$

$$\bar{I}_{(1,x')(1,v)|(N,y')}(k)=\frac{\Pr\{s(k)=(1,v)|s(0)=(1,x')\}\Pr\{s(\infty)=(N,y')|s(k)=(1,v)\}}{\Pr\{s(\infty)=(N,y')|s(0)=(1,x')\}}. \tag{20}$$

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Kuang-Hao Liu received the B.S. degree in applied mathematics from National Chiao-Tung University, Hsinchu, Taiwan, in 1998, and M.S. Degree in electrical engineering from National Chun-Hsing University, Taichung, Taiwan, in 2000. From 2000 to 2002, he was a software engineer with Siemens Telecom. System Ld., Taiwan. He is currently working toward the Ph.D. Degree in the Department of Electrical and Computer Engineering at University of Waterloo, Canada. His research interests include Ultra Wideband communications, resource allocation problems, and performance analysis of network protocols.

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Humphrey Rutagemwa (S'03) received the B.Sc. degree in electronics and communications with First Class Honors from the University of Dar es Salaam, Tanzania, in 1998 and the M.Sc. degree in electrical and computer engineering from the University of Waterloo, Canada, in 2002. At present, he is a Ph.D. candidate in the Department of Electrical and Computer Engineering at the University of Waterloo. From 1999 to 2000 he was a System Engineer with the CRDB Bank Limited. Since 2003, he has been working as a Research Assistant at the Centre for Wireless Communications, University of Waterloo, Canada. His current research interests include modeling and performance evaluation, cross-layer design and optimization, and vehicular communications networks.

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Xuemin (Sherman) Shen (M'97-SM'02) received a B.Sc. (1982) degree from Dalian Maritime University, China, and M.Sc. (1987) and Ph.D. (1990) degrees from Rutgers University, New Jersey, all in electrical engineering. Currently, Dr. Shen is with the Department of Electrical and Computer Engineering, University of Waterloo, Canada, where he is a professor and the Associate Chair for Graduate Studies. His research focuses on mobility and resource management in interconnected wireless/wired networks, UWB wireless communications systems, wireless security, and ad hoc and sensor networks. He is a co-author of three books, and has published more than 300 papers and book chapters in wireless communications and networks, control, and filtering. He serves as Technical Program Chair for many conferences including IEEE Globecom'07. He also serves as Editor/Associate Editor/Guest Editor for IEEE Transactions on Wireless Communications; IEEE Transactions on Vehicular Technology; Computer Networks; ACM/Wireless Networks; IEEE JSAC, IEEE Wireless Communications, and IEEE Communications Magazine, etc. Dr. Shen received the Outstanding Performance Award from the University of Waterloo in 2002 and 2004, for outstanding contribution in teaching, scholarship and service, and the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, for demonstrated excellence of scientific and academic contributions. Dr. Shen is a senior member of the IEEE, and a registered Professional Engineer of Ontario, Canada.

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Jon W. Mark (M'62-SM'80-F'88-LF'03) received the B.A.Sc. degree from the University of Toronto in 1962, and the M.Eng. and Ph.D. degrees from McMaster University in 1968 and 1970, respectively, all in electrical engineering. From 1962 to 1970, he was an engineer and then a senior engineer at Canadian Westinghouse Co. Ltd., Hamilton, Ontario, Canada. In September 1970 he joined the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, where he is currently a Distinguished Professor Emeritus. He served as the Department Chairman during the period July 1984-June 1990. In 1996 he established the Centre for Wireless Communications (CWC) at the University of Waterloo and is currently serving as its founding Director. Dr. Mark had been on sabbatical leave at the following places: IBM Thomas J. Watson Research Center, Yorktown Heights, NY, as a Visiting Research Scientist (1976-77); AT&T Bell Laboratories, Murray Hill, NJ, as a Resident Consultant (1982-83): Laboratoire MASI, Universite Pierre et Marie Curie, Paris France, as an Invited Professor (1990-91); and Department of Electrical Engineering, National University of Singapore, as a Visiting Professor (1994-95). He has previously worked in the areas of adaptive equalization, image and video coding, spread spectrum communications, computer communication networks, ATM switch design and traffic management. His current research interests are in broadband wireless communications, resource and mobility management, and cross domain interworking. He recently co-authored the text entitled *Wireless Communications and Networking*, Prentice-Hall 2003. A Life Fellow of IEEE, Dr. Mark is the recipient of the 2000 Canadian Award for Telecommunications Research and the 2000 Award of Merit of the Education Foundation of the Federation of Chinese Canadian Professionals. He was an editor of IEEE Transactions on Communications (1983-1990), a member of the Inter-Society Steering Committee of the IEEE/ACM Transactions on Networking (1992-2003), a member of the IEEE Communications Society Awards Committee (1995-1998), an editor of Wireless Networks (1993-2004), and an associate editor of Telecommunication Systems (1994-2004).