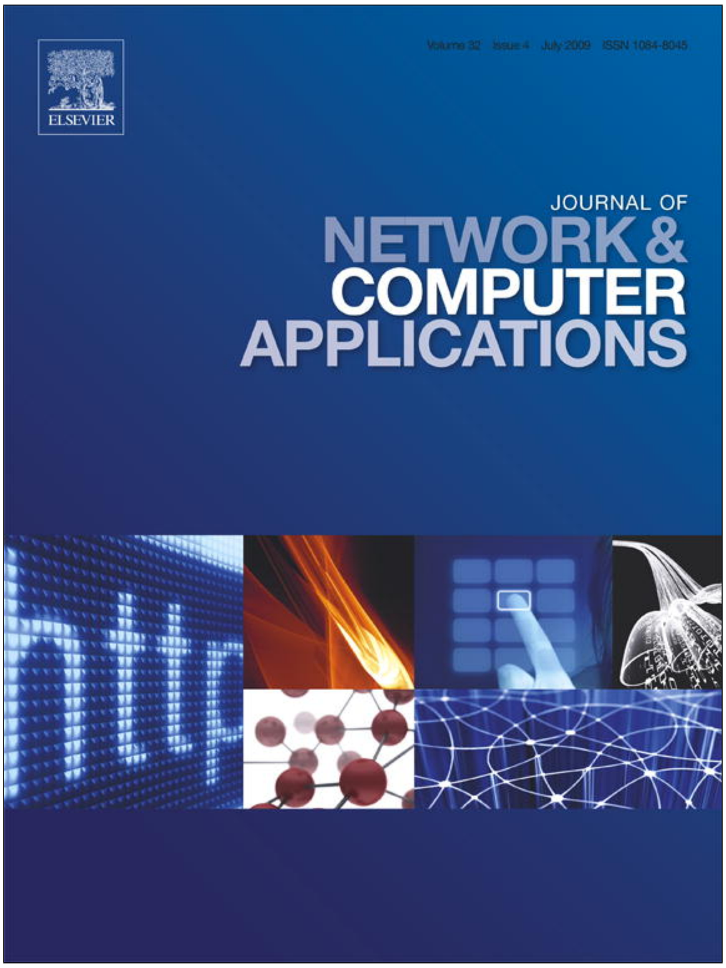
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Performance evaluation of wireless sensor network with hybrid channel access mechanism

Prasan Kumar Sahoo [a,c,*], Jang-Ping Sheu [b], Yu-Chia Chang [a]

[a] Department of Computer Science and Information Engineering, National Central University, Chungli 32054, Taiwan, ROC
[b] Department of Computer Science, National Tsing Hua University, Hinchu 30013, Taiwan, ROC
[c] Department of Information Management, Vanung University, Chungli 32061, Taiwan, ROC

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ABSTRACT

In this paper, a hybrid channel access mechanism is proposed for the wireless sensor network that considers the channel access procedure of IEEE 802.15.4 and combines the binary exponential backoff mechanism of IEEE 802.11 due to packet collision of nodes after successful channel assessment. Taking the backlogged nodes due to collision, an extended linear feedback model is developed and a discrete-time Markov chain model is designed to analyze the successful and failure probabilities of the system model of the wireless sensor network. Besides, an energy consumption model for the one hop wireless sensor network is developed based on our models and hybrid channel access mechanism. Extensive performance analysis are done to study the effect of binary exponential contention window on energy consumption of the nodes and it is verified that our simulation results totally match with the theoretical results for different size of contention windows and node numbers.

1. Introduction

IEEE 802.15.4 specification (IEEE Std 802.15.4, 2003) provides a standardized base set of solutions for the devices with low data rate, low power and short-range transmissions, which can be used for the wireless sensor networks (WSNs). Due to power constraints characteristics of the sensors, it is vital to enhance longevity of the nodes in the network to prolong the network lifetime. Though, a good deal of studies have been proposed for the WSNs to be long-lived, few analytical methods are proposed along this direction. In Bianchi (2000), the author provides a framework for studying the saturation throughput of the carrier sense multiple access with collision avoidance (CSMA-CA) algorithm adopted for the IEEE Std 802.11 (1999) distributed coordination function (DCF) and a discrete-time Markov chain model is designed for the CSMA-CA backoff procedure. Following the same approach, authors in Wu et al. (2001) provide a modified model for the backoff procedure to be more close to the standard. In this model, once the retry limit for a transmission attempt is reached, the contention window (CW) is reset. The authors in Foh and Zukerman (2002), extend the model introduced in Bianchi (2000) to study the system throughput without saturated traffic condition.

A Markovian state dependent continuous time single server queue is used to represent the process of the idle stations that become active. In Tay and Chua (2001), another approximation using average values is presented for computing the collision probability, channel capacity, and maximum number of stations in a wireless system. The authors in Ni et al. (2003) propose an analytical model for the slow CW decrease scheme of the IEEE 802.11 MAC protocol. It is proposed to prevent from the plenty of collisions due to overloaded traffic. The authors in Chen et al. (2003) modify the linear feedback model in Kleinrock (1975) and Tobagi and Kleinrock (1977) for the IEEE 802.11 CSMA-CA and declare that the system throughput can be improved through the optimal CW size that they have found. From the lately published studies, we notice that researchers are diverting their attention from IEEE 802.11 to IEEE 802.15.4. In Ma et al. (2005), three topology control algorithms are proposed to construct the network topologies with small number of coordinators, while still maintaining the network connectivity. In their work, the average duty cycle is reduced and battery life is prolonged.

A first simulation based performance evaluations of the medium access protocol of IEEE 802.15.4 is done in Lu et al. (2004), focusing the beacon-enabled mode for a star topology network. The authors consider the superframe structure and thebeacon-based synchronization mechanism, which allows devices to access the channels in a contention access period or a collision free period. The authors in Bougard et al. (2005), have studied an energy-aware radio activation policy and the corresponding average power consumption and transmission reliability

* Corresponding author at: Department of Information Management, Vanung University, Chungli 32061, Taiwan, ROC.
E-mail addresses: pksahoo@msa.vnu.edu.tw (P.K. Sahoo), sheujp@cs.nthu.edu.tw (J.-P. Sheu), jimchang@axp1.csie.ncu.edu.tw (Y.-C. Chang).

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have been analyzed to optimize the physical and medium access control layers parameters. Concept of CWs is introduced in IEEE 802.11 and binary CW is used by the nodes during backoff procedure. The binary exponential CW concept of IEEE 802.11 could be used in WSN in the post collision scenarios with initial channel access mechanisms of IEEE 802.15.4. Though several works propose the analytical models for the WSNs using IEEE 802.15.4 channel access mechanisms, to the best of our knowledge, no analytical model evaluates the performance of the network based on the number of backlogged nodes with exponential backoff windows. Besides, no work studies the effect of backoff and halting procedures in the channel access mechanism of IEEE 802.15.4, if collision occurs. Hence, in this paper, we propose a hybrid CSMA-CA mechanism for the WSNs that combines the initial channel assessment procedure of IEEE 802.15.4 and binary exponential CWs of IEEE 802.11 in the post collision situation without violating any one of those standards.

The remainder of the paper is organized as follows. Related work and motivations behind our work are presented in Section 2. System model related to our performance analysis is introduced in Section 3. The analytical model designed for evaluating the expected energy consumption of WSN is described in Section 4. Performance analysis and numerical results of our energy consumption model are shown in Section 5 and concluding remarks are made in Section 6 of the paper.

2. Related work and motivations

Due to the technical constraints of the sensors, performance analysis in terms of energy consumption and throughput is highly essential in WSNs. The performance analysis in a beacon-enabled IEEE 802.15.4 network is made in Misic and Misic (2005) under two duty cycle management distributed algorithms. The authors evaluate both policies using theory of discrete-time Markov chains and M/G/1/K queues with vacations. In Misic et al. (2004), the same authors, model the WPAN with uplink transmissions, considering the devices with buffers of finite size, where packets may be rejected, if the buffer is full. They combine the theory of discrete-time Markov chains and the theory of M/G/1/K queues in order to obtain the access probability for a device, taking the probability of idle medium, probability distribution of packet service times, and probability distribution of the packet queue size at the device. In Shi et al. (2005), authors have numerically simulated the performance of relative location for both single-hop and multi-hop networks. However, they have not considered the energy consumption issues of the network during such estimations of relative locations and thereby node locations.

A new Markov chain model of 802.15.4 is proposed in Park et al. (2005) and the throughput and energy consumption in saturation conditions are analyzed. The performance analysis of low rate wireless technology for medical applications are done in Golmie and Cypher () and a comprehensive performance study of IEEE 802.15.4 is made in Zheng and Lee (2004). The authors in Lee (2005), have compared the IEEE 802.15.4 standard with IEEE 802.11 in terms of overhead and resource consumption. In Angrisanil et al. (2007), the authors have investigated experimentally the coexistence problems of IEEE 802.11b and IEEE 802.15.4 wireless networks. The main goal of their work is to deduce the correlations between interfering effects and systems configuration to be used in the design of coexisting networks. However, they have not make any performance study about such coexistence issues. The authors in Xiao and Zeng (2007) have proposed an adaptive message passing MAC protocol for WSN. The proposed MAC protocol modifies the message passing mechanism of SMAC to make the size of the small fragment adjusted according to different traffic load by using the information of the control packet and achieves a significant decrease in energy consumption. However, this work does not propose any hybrid MAC mechanism using both IEEE 802.11 and IEEE 802.15.4.

The packet error rate of the IEEE 802.15.4 under the interference of the IEEE 802.11b is analyzed (Shin et al., 2005) using the bit error rate and the collision time. The bit error rate is obtained from signal to interference and noise ratio. In this work, the power spectral density of the IEEE 802.11b is considered in order to determine the in-band interference power of the IEEE 802.11b to the IEEE 802.15.4. They have not considered any performance analysis using both IEEE 802.11 and IEEE 802.15.4 MAC mechanisms. In Lee (2005) and Howitt et al. (2005), the authors have established the realistic environment for the preliminary performance evaluation of IEEE 802.15.4 wireless networks, taking several sets of practical experiments to study the effects of direct and indirect data transmissions, CSMA-CA mechanism in the beacon-enabled mode. It is to be noted that the effect of backoff mechanism with binary exponential CWs on the performance of the sensors have not been studied yet. Hence, motivations of proposing a hybrid backoff mechanism and our analytical models are given as follows.

Motivations: In IEEE 802.15.4 CSMA-CA, the standard specifies the conditions for the successful and failure status of the channel access mechanism based on its two clear channel assessments (*CCAs*). If both CCAs of a node are successful, channel access is considered to be a success and data transmission occurs. However, if busy channel is reported at the first CCA, value of backoff exponential (*BE*) is increased by one, and a node reties till its retry limit does not exceed five times, otherwise the process terminates with a channel access failure and the packet may be rejected. However, in our work it is assumed that the packet is not rejected in a single attempt, as it may contain important sensing data.

As we know, in WSN nodes are deployed densely over certain region and, therefore, can compete the same channel simultaneously. After channel access is successful, nodes start transmitting their data and may collide with another one due to densely deployment nature of the WSNs. Hence, we feel that the nodes who fail to get the channel or fail to transmit data due to collision should go to the backlogged states and wait for re-accessing the channel. Therefore, we consider the backoff procedure of IEEE 802.11 for those collide nodes, as it includes the halting and wait mechanism, which is not available in IEEE 802.15.4. Besides, motivated with the importance of energy conservation in WSNs, we have developed the analytical models for the fixed and exponential backoff windows to study the energy efficiency issues in WSNs, taking finite number of backlogged nodes. To the best of our knowledge, this is the first analytical model to analyze the effect of fixed and exponential backoff windows in IEEE 802.15.4 MAC mechanisms.

3. System model

It is to be noted that IEEE 802.11 channel access mechanism is quite different from CSMA-CA procedure of IEEE 802.15.4. In IEEE 802.11, a node must sense the channel to determine, if other nodes are transmitting. If other nodes are not transmitting, the node must ensure that the medium is idle for the specified distributed coordination function interframe space (DIFS) duration before transmitting. If a node senses the channel to be busy, it waits until the channel become idle for DIFS period, and chooses a random backoff counter, in which a node defers channel access by a random amount of time chosen within a CW. As soon as the backoff counter becomes zero, the node can access the channel again and follows the channel access procedure. During backoff procedure, if the node detects a busy channel, it halts its backoff counter till the channel is idle for the period of DIFS. It can decrease its backoff counter again only after the channel is clear for DIFS. After each successful transmission, the receiver sends an ACK back to the sender. By receiving an ACK the sender resets its *CW* size to CW_{min}. If sender does not receive ACK, it assumes that the packet is collided with another packet, and therefore doubles its CW to retransmit the packet.

In IEEE 802.15.4, the value of backoff exponent (BE) shall be either initialized to the value of *macMinBE* or initialized to the lesser of 2 and the value of *macMinBE* by the MAC sublayer. The variable *macMinBE* means the minimum value of the backoff exponent (BE) in the CSMA-CA algorithm and as per the standard, its value can be 0 through 3. The node shall delay for a random number of complete backoff periods in the range of 0–$(2^{BE}-1)$ units and then perform the first clear channel assessment (CCA_1). If the node senses the channel to be busy, it again goes for the random backoff delay and perform the clear channel assessment (CCA_1) again, otherwise performs the second clear channel assessment (CCA_2). If both *CCAs* are successful, the MAC sublayer assumes that the channel access is a success and shall begin transmission of the frame and the procedure is terminated.

3.1. Our hybrid CSMA-CA mechanism

Consider a homogeneous and fully connected WSN with N number of nodes. As shown in Fig. 1, when a device is turned on and is ready to transmit, it first delays for a random number of backoff periods in the range of 0–$(2^{BE}-1)$ units. After the initial random backoff period is over, the device has to perform the CCA for two consecutive slots to access the channel similar to the CSMA-CA mechanism of IEEE 802.15.4. If the channel is sensed idle upon two successful *CCAs*, transmission begins immediately. Otherwise, a node defers channel access, remains in the backlogged state and waits for the random maximum $(2^{BE}-1)$ units backoff periods. During the backoff procedure, the backoff timer is halted, if channel busy is detected and resumes immediately, if the channel becomes idle. For reliable communications, the acknowledgment message is considered, which is sent out by the destination node upon successfully receiving the packet. As shown in Fig. 2, let us assume that devices A and B are turned on at the same time, and are ready to transmit data. Since, both nodes A and B sense the channel idle and transmit data at the same time, collision occurs and no node receives the acknowledgment. After the acknowledge timeouts, the *CCA* procedure is performed again. If the CCA is not a success, initial CW is doubled and the device enters to the backoff state. After the backoff procedure, the retransmission is begun. If device C is turned on when device B is transmitting, device C senses the channel busy and will not transmit until completion of the current transmission. Upon terminating the current transmission, device A continues the backoff procedure and device C performs the *CCA*. Since, the result of *CCA* for device C is idle, it goes to the random backoff procedure and starts transmitting after the backoff procedure is over.

3.2. Extended linear feedback model

Based on our hybrid CSMA-CA mechanism, we propose here an extended linear feedback model, as shown in Fig. 3. It is assumed

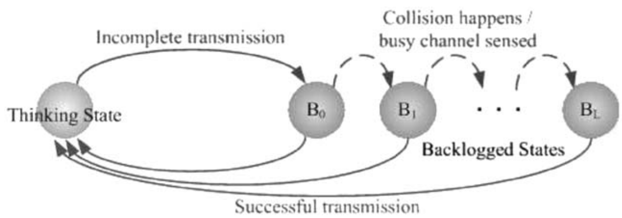

Fig. 3. The extended linear feedback model.

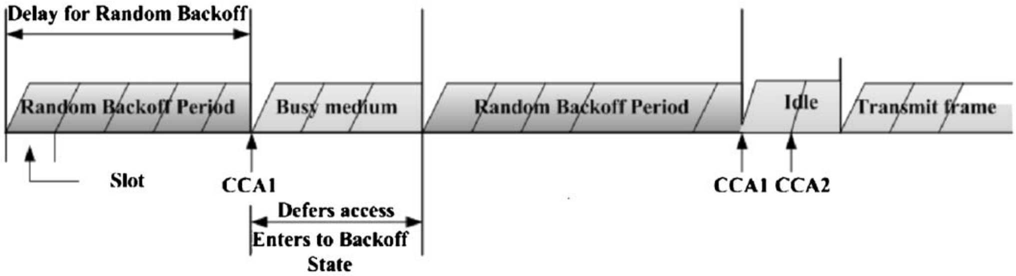

Fig. 1. Basic channel access procedure in our hybrid CSMA-CA mechanism.

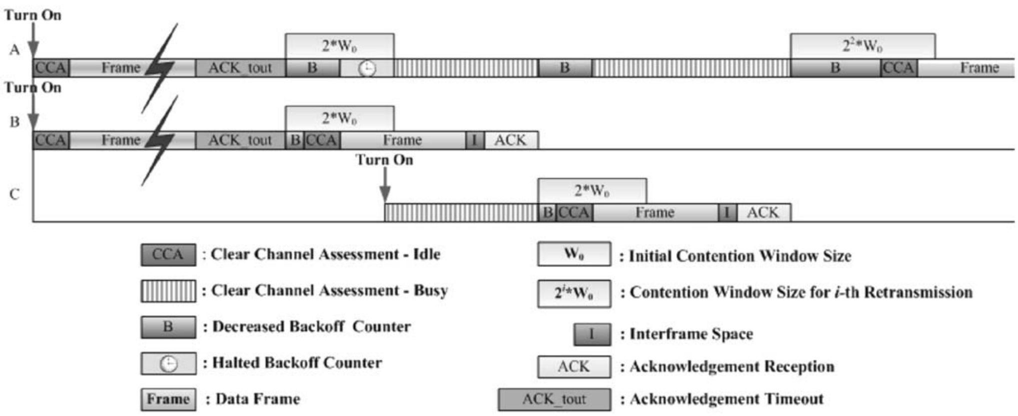

Fig. 2. Example of backoff procedure in our hybrid CSMA-CA mechanism to deal with collision.

that the nodes in the extended linear feedback model may be in *thinking* or in *backlogged* states, alternatively. Nodes in the thinking state has generated a new packet with probability g to transmit, whereas a node remains in the backlogged state, if it senses the channel busy. In our extended linear feedback model, $L+1$ number of backlogged states are considered, where L be the retry limit and is application oriented or set as a default value. In our model, we consider the binary exponential backoff mechanism, in which the CW is doubled with each retransmissions. In our feedback model, let W_0 be the initial size of the CW, which is doubled for each retransmissions. Let, maximum CW size for the m-th retransmission be W_m, which is defined as $W_m = W_0 \times 2^m$. The rescheduling delay of a backlogged packet is uniformly distributed with a mean of $W_m/2$ slots, where m is the number of retransmissions of a backlogged packet. Hence, each backlogged user senses the channel in the current slot of m-th retransmission with a probability of $\nu_m = 2/W_m$. It is to be noted that the backlogged nodes can perform retransmissions, if the channel is assessed to be idle. Once the transmission attempt is completed successfully or rejected owing to the retransmission limit, a backlogged device can immediately switch back to the thinking state.

3.3. A discrete-time Markov chain model

In this section, a discrete-time Markov chain model is designed based on our assumptions. In our model, the time is slotted for accessing the channel and all packets are allowed to transmit only at the beginning of each slot. All packets are assumed to have the same length and propagation delay between one node with another or one node with the coordinator is assumed to be same and equals to one time slot. At the end of each time slot, every sensor node is either in thinking or backlogged state. Then, the extended linear feedback model is applied to a discrete-time Markov chain to describe the transition of the system status with time. By defining the system status as the number of nodes in the backlogged state of the network system, we describe here how to apply the extended linear feedback model to a discrete-time Markov chain model.

As per our extended linear feedback model, $L+1$ number of backlogged states are present in the system represented by B_0, $B_1, \ldots, B_L$, respectively. Let us assume that $i_0, i_1, \ldots, i_L$ be the number of backlogged nodes present within the backlogged states $B_0, B_1, \ldots, B_L$, respectively and X_t denotes the total number of backlogged nodes present in those backlogged states B_m, $\forall m \in \{0, 1, \ldots, L\}$. Hence, $X_t = \sum_{m=0}^{L}(i_m)$, for all $t \in [t, t+I]$, where I is the duration of each idle period. If N represents total number of nodes in the network, the total number of backlogged nodes X_t may range from 0 to N and those $L+1$ number of backlogged states can be represented in a discrete-time Markov chain, as shown in Fig. 4. The transition from state i to j ($i \leqslant j$) implies that some thinking nodes are entering to the backlogged state. Similarly, transition from state $i+1$ to i represents that there is a successful packet transmission. In order to find out the state transition probability of the discrete-time Markov chain model, we assume that the communication channel consists of a sequence of regeneration cycles composed of idle and busyperiods. The embedded slots are defined to be the first slot of each idle period. As shown in Fig. 5, length of an idle period is I slots and length of the busy period is T slots. The only one slot Q', after end of each transmission, accounts for the propagation delay. Hence, each cycle of the communication channel occupies $I+T$ number of slots, as shown in Fig. 5. It is to be noted that the busy period has duration of T slots, if the transmission is successful, otherwise it has C slots, if it is unsuccessful due to collision. By the definition, no sensor is ready to transmit during intervals $[T+1, T+I-1]$; however, at least one node becomes ready in the last slot of the idle period, i.e., at the $(T+I)$-th slot. Nodes, those become ready at the $(T+I)$-th slot sense the channel idle and transmit at the beginning of $(T+I+1)$-th slot. If we consider an example as shown in Fig. 6, the duration of successful transmission period involves one random backoff period, two slots CCA (T_{CCA}), the time for data transmission (T_{data}), one slot interframe space (T_{slot}), and eventually the acknowledgment reception time (T_{ack}). Comparably, the collision period includes one random backoff period, two slots CCA (T_{CCA}), the time for data transmission (T_{data}), one slot interframe space (T_{slot}), and end up with the acknowledgment timeout (T_{ack_tout}). As mentioned earlier, the thinking nodes generate new packets with probability of g and we assume that the backlogged nodes in states $B_0, B_1, \ldots, B_L$ retransmit the buffered packets with probability of $\nu_0, \nu_1, \ldots, \nu_L$, respectively. Taking, $i_0, i_1, \ldots, i_L$ as the number of backlogged nodes in the backlogged states, $B_0, B_1, \ldots, B_L$, respectively, the conditional probability that at least one node is ready when the system status$X_{t+I} = i$ is given as

$$Pr\{\text{at least one node is ready}|X_{t+I} = i\} = 1 - \left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i} \quad (1)$$

Our objective in this section is to calculate the state transition probability matrix P of the discrete-time Markov chain within cycles from $t+I$ through $t+I+T$, as shown in Fig. 5. Here, P is the product of several single-slot transition matrices, which are defined later. We denote R as the state transition matrix for the last idle slot $t+I$, and Q for all remaining time slots of the busy periods from slots $t+I+1$ through $t+I+T$ for the successful transmission or $t+I+1$ through $t+I+C$ for the unsuccessful transmission due to collision in the channel, where C and T represent the number of busy slots due to collision and successful packet transmission, respectively. Since, length of the busy period

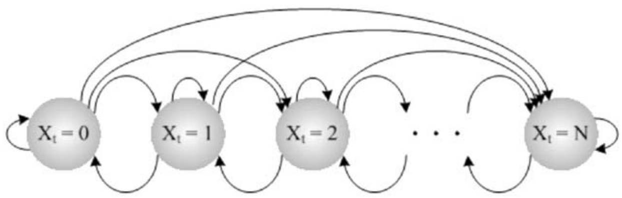

Fig. 4. A discrete-time Markov chain model for the system status.

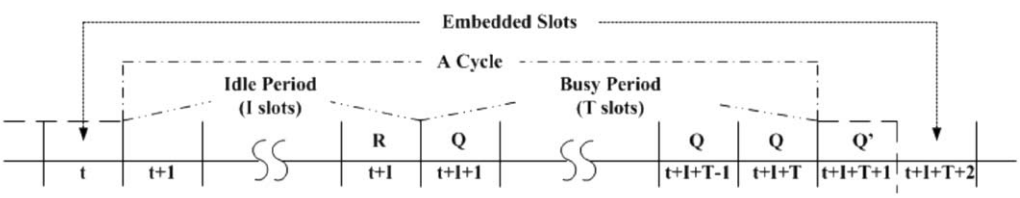

Fig. 5. Embedded slots and communication cycle of Markov chain.

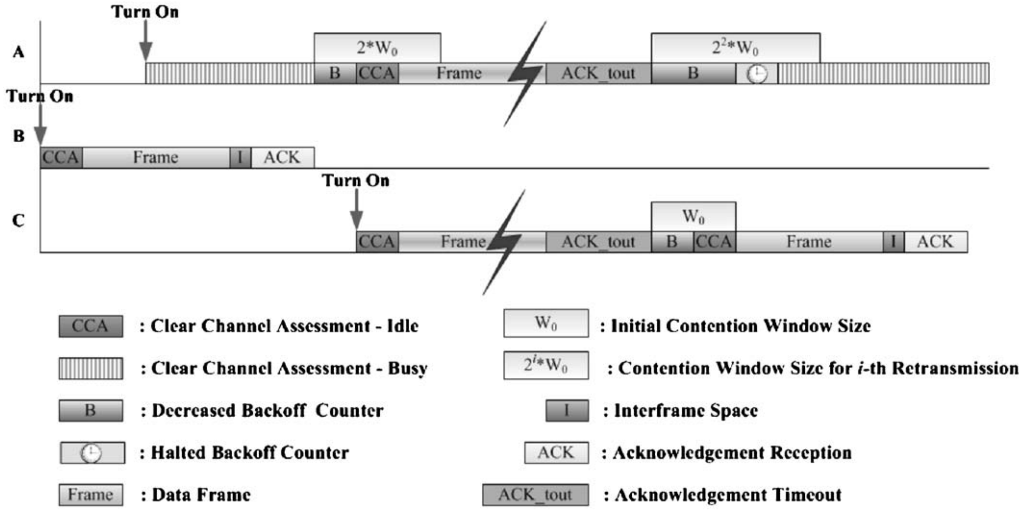

Fig. 6. An example of packet transmission.

depends on the number of nodes, which become ready in slot $t+I$, we compute the state transition probability matrix for the successful and failure transmissions, separately. Therefore, we specify the transition probability matrix $R = S+F$, where (i, k)-th element of S and F are defined as follows:

$$s_{ik} = Pr\{X_{t+I+1} = k \text{ and transmission is successful}|X_{t+I} = i\} \quad (2)$$

and

$$f_{ik} = Pr\{X_{t+I+1} = k \text{ and transmission is failed}|X_{t+I} = i\} \quad (3)$$

$Pr\{X_{t+I+1} = k$ and success$|X_{t+I} = i\}$ implies that there is only one node ready to transmit at slot $t+I$ and, therefore, the transmission is successful. Similarly, $Pr\{X_{t+I+1} = k$ and failed$|X_{t+I} = i\}$ implies that there are more than one nodes ready to transmit at slot $t+I$, for which the transmission is unsuccessful. Hence, Q represents the addition to the backlogged nodes from the rest $N-X_t$ thinking nodes at any time slot t during the busy period. On the other hand, all ready nodes within interval $[t+I+1, t+I+T]$ sense the channel busy and hold their transmissions and remain in the backlogged state. If they are already in backlogged states, those thinking nodes who have generated new packets switch to the backlogged state. Hence, for any $t \in [t+I+2, t+I+T]$, we define the one-step transition probability matrix $Q = (q_{ik})$, as follows:

$$q_{ik} = Pr\{X_{t+1} = k|X_t = i\} \quad (4)$$

If the transmission is successful, duration of the busy period is T slots and for unsuccessful transmissions, its duration is C slots. Hence, according to Kleinrock (1976) and Li and Zeng (2005), the transmission matrix P, is expressed as

$$P = SQ^T J + FQ^C \quad (5)$$

where $S = (s_{ik})$, $F = (f_{ik})$, and $Q = (q_{ik})$ are the transition matrices and are defined as follows:

$$s_{ik} = \begin{cases} 0, & k<i \\ \dfrac{\left(\sum_{m=0}^{L}\left(i_m \nu_m (1-\nu_m)^{i_m-1}\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)\right)(1-g)^{N-i}}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}, & k=i \\ \dfrac{\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(N-i)g(1-g)^{N-i-1}}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}, & k=i+1 \\ 0, & k>i+1 \end{cases} \quad (6)$$

$$f_{ik} = \begin{cases} 0, & k<i \\ \left\{\left[\dfrac{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}\right] - \left[\dfrac{\sum_{m=0}^{L}\left(i_m\nu_m(1-\nu_m)^{i_m-1}\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}\right]\right\}(1-g)^{N-i}, & k=i \\ \dfrac{\left(1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)\right)(N-i)g(1-g)^{N-i-1}}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}, & k=i+1 \\ \dfrac{\binom{N-i}{k-i} g^{k-i}(1-g)^{N-k}}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}, & k>i+1 \end{cases} \quad (7)$$

and

$$q_{ik} = \begin{cases} 0, & k<i \\ \binom{N-i}{k-i} g^{k-i}(1-g)^{N-k}, & k \geqslant i \end{cases} \quad (8)$$

where J represents the fact that a successful transmission decreases the backlog by 1. Hence, its (i, k)-th entry is defined as follows:

$$j_{ik} = \begin{cases} 1, & k=i-1 \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

Let, $\Pi = (\pi_0, \pi_1, \ldots, \pi_N)$ denotes the stationary probability distribution of X_t at the embedded points, where π_i represents the probability that there are i nodes in the backlogged state at the current slot. Then, we can have $\Pi = \Pi P$, which can be obtained from the recursive solution of $\Pi = \Pi P$.

4. Energy consumption analysis

This section presents the energy consumption analysis of each transmission attempts using our hybrid CSMA-CA mechanism as the underlying medium access control. The analysis is based on the extended linear feedback model and the state transition probabilities, as described in the previous sections.

4.1. Energy consumption model

Before we design the energy consumption model for the sensor network, let us consider an example as shown in Fig. 7, where the

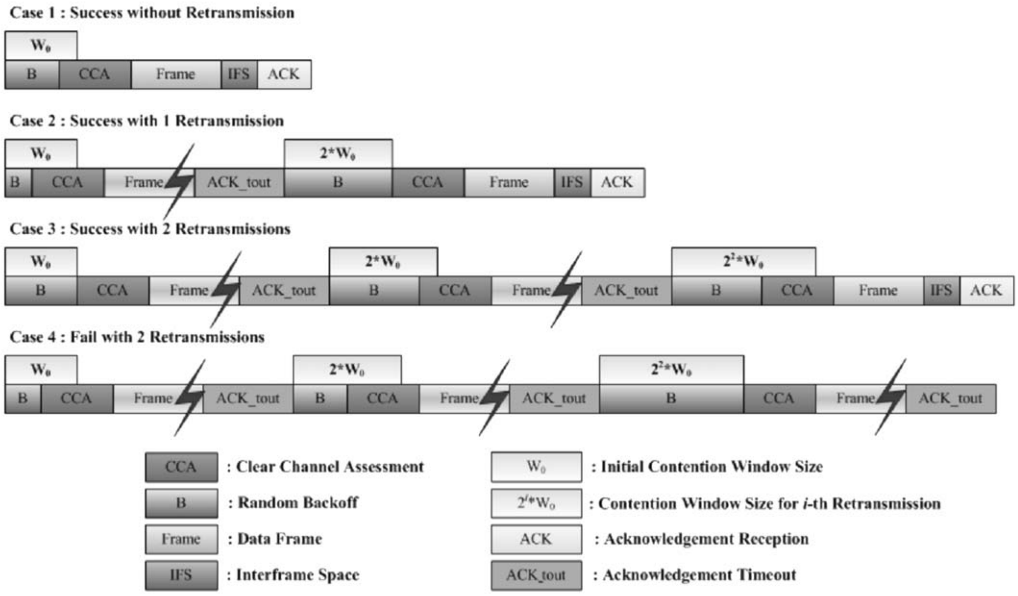

Fig. 7. Example of an energy consumption model with retry limit $L = 2$.

maximum retry limit of the packet retransmission is equal to two. Under such condition, four possible cases may arise for the failure or successful transmission. Without loss of generality, as shown in Fig. 7, Case 1 is a successful transmission attempt without any further retransmission. In Case 2, the packet is successfully transmitted after only one retransmission. Similarly in Case 3, successful transmission occurs only after two retransmissions. But, in Case 4, the transmission attempt is failed, even after two retransmissions. Based on the above example, we generalize here the energy consumption model. Let, $\bar{P_s}(m)$: be the expected successful probability of the m-th retransmission of transmission attempts, for $m \in \{1, \ldots, L\}$.

$\bar{P_s}(0)$: be the expected successful probability of the first transmission.

$\varepsilon_s(m)$: be the total energy consumption of the successful transmission attempt with m number of retransmissions.

$\varepsilon_f(m)$: be the total energy consumption of the failed transmission attempts with m number of retransmissions.

Then, the expected energy consumption for any transmission attempts, i.e. either for the successful or failure transmission due to two-retransmission attempts can be estimated as follows:

$$\begin{aligned}\bar{\varepsilon} &= \bar{P_s}(0)\varepsilon_s(0) + [1-\bar{P_s}(0)]\bar{P_s}(1)\varepsilon_s(1) \\ &\quad + [1-\bar{P_s}(0)][1-\bar{P_s}(1)]\bar{P_s}(2)\varepsilon_s(2) \\ &\quad + [1-\bar{P_s}(0)][1-\bar{P_s}(1)][1-\bar{P_s}(2)]\varepsilon_f(2) \end{aligned} \tag{10}$$

However, by generalizing the retry limit from two to L, the expected total energy consumption can be expressed as

$$\begin{aligned}\bar{\varepsilon} &= \bar{P_s}(0)\varepsilon_s(0) + \sum_{m=1}^{L}\left(\prod_{j=0}^{m-1}[1-\bar{P_s}(j)]\right)\bar{P_s}(m)\varepsilon_s(m) \\ &\quad + \left(\prod_{m=0}^{L}[1-\bar{P_s}(m)]\right)\varepsilon_f(L)\end{aligned} \tag{11}$$

It is to be noted that a transmission is completed successfully, if no other transmission is being performed simultaneously. Hence, consequently the successful probability of a transmission is equal to the probability, when only one node transmits at the same time. Since, the system status varies with time, we have the expected successful probability of the m-th retransmission of the transmission attempts as follows:

$$\bar{P_s}(m) = \sum_{i=0}^{N}\pi_i P_s(m,i) \tag{12}$$

where π_i is the probability that the system status X_t equals to i. $P_s(m,i)$ is the successful probability of the m-th retransmission of the transmission attempt while there are i number of nodes in the backlogged state. The successful probability $P_s(m,i)$ is given as follows:

$$P_s(m,i) = \begin{cases} \left[\dfrac{(N-i)g(1-g)^{N-i-1}\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}\right] \\ \quad + \left[\dfrac{\sum_{m=0}^{L}\left(i_m\nu_m(1-\nu_m)^{i_m-1}\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}\right], & m=0 \\ \dfrac{\left(\prod_{m=0}^{L}i_m\nu_m(1-\nu_m)^{i_m-1}\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}{1-\left(\prod_{m=0}^{L}(1-\nu_m)^{i_m}\right)(1-g)^{N-i}}, & 0<m\leqslant L \end{cases} \tag{13}$$

4.2. Energy consumption estimation

In this section, we analyze the energy consumption due to failure and success of each transmission during each retransmission attempts. Let us consider an example as a case study. Taking Fig. 7, it is to be estimated that the total energy consumption in Case 1 is $\varepsilon_s(0)$, which can be calculated as $\bar{\varepsilon}_{backoff}(0) + \varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ifs} + \varepsilon_{ack}$. The total energy consumption $\varepsilon_s(1)$ in Case 2, equals to $\bar{\varepsilon}_{backoff}(0) + \varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ack\_tout} + \bar{\varepsilon}_{backoff}(1) + \varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ifs} + \varepsilon_{ack}$. The total energy consumption $\varepsilon_s(2)$ in Case 3, is $2 \times (\varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ack_tout}) + \varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ifs} + \varepsilon_{ack} + \sum_{m=0}^{2}\bar{\varepsilon}_{backoff}(m)$. The total energy consumption $\varepsilon_f(2)$ in Case 4, is $3 \times (\varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ack\_tout}) + \sum_{m=0}^{2}\bar{\varepsilon}_{backoff}(m)$.Generalizing the above example for any retry limit m, the total energy consumption is given by

$$\varepsilon_s(m) = m \cdot \varepsilon_f + \varepsilon_s + \sum_{k=0}^{m} \bar{\varepsilon}_{backoff}(k) \tag{14}$$

$$\varepsilon_f(m) = (m+1) \cdot \varepsilon_f + \sum_{k=0}^{m} \bar{\varepsilon}_{backoff}(k) \tag{15}$$

where $\varepsilon_s = \varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ack}$ and $\varepsilon_f = \varepsilon_{cca} + \varepsilon_{data} + \varepsilon_{ack\_tout}$. ε_s is the energy consumption of a successful transmission excluding the energy consumption during the backoff periods. The value of ε_s comprises the energy spent for performing CCA (ε_{cca}), transmitting data frame (ε_{data}), the interframe space time (ε_{ifs}), and for receiving the acknowledgment message (ε_{ack}). On the contrary, ε_f is the energy consumption of a failed transmission excluding the energy consumption during backoff periods. The value of ε_f considers the energy spent for performing CCA (ε_{cca}), transmitting data frame (ε_{data}), and waiting for the acknowledgment timeout (ε_{ack_tout}). Let, P_{tx_mode} and P_{rx_mode} denote the power consumption in the transmitting and receiving modes, respectively. Then, the energy consumption due to individual operation could be estimated as follows:

$$\begin{aligned} \varepsilon_{cca} &= P_{rx\_mode} \times T_{cca} \\ \varepsilon_{ifs} &= P_{rx\_mode} \times T_{ifs} \\ \varepsilon_{ack} &= P_{rx\_mode} \times T_{ack} \\ \varepsilon_{ack\_tout} &= P_{rx\_mode} \times T_{ack\_tout} \\ \varepsilon_{data} &= P_{tx\_mode} \times T_{data} \end{aligned} \tag{16}$$

where T_{cca} is the time for performing the CCA. T_{ifs} is the interframe space time. T_{ack} is the duration within which an acknowledgment message is received. T_{ack_tout} is the duration of acknowledgment timeout. T_{data} is the duration of transmitting data. To be more accurate, the analysis of the expected energy spent during the backoff period ($\bar{\varepsilon}_{backoff}(m)$) in the m-th retransmission of all transmission attempts is divided into two parts: the energy consumption, while the backoff counter is decreasing ($\bar{\varepsilon}_{decrease}(m)$) and the energy consumption, while the backoff counter is halted ($\bar{\varepsilon}_{halt}(m)$) due to the busy medium. The energy consumption in both of the cases could be estimated as follows:

$$\bar{\varepsilon}_{backoff}(m) = \bar{\varepsilon}_{decrease}(m) + \bar{\varepsilon}_{halt}(m) \tag{17}$$

where energy consumption $\bar{\varepsilon}_{decrease}$ for the fixed CW is estimated as

$$\bar{\varepsilon}_{decrease}(m) = P_{rx\_mode} \times T_{slot} \times \frac{1+W_0}{2} \tag{18}$$

and $\bar{\varepsilon}_{decrease}$ for the exponentially increased CW is estimated as

$$\bar{\varepsilon}_{decrease}(m) = P_{rx\_mode} \times T_{slot} \times \frac{1+2^m W_0}{2} \tag{19}$$

where $0 \leqslant m \leqslant$ L and T_{slot} is the duration of each slot. Similarly, the energy consumption due to halting the backoff counter can be estimated as follows:

$$\bar{\varepsilon}_{halt}(m) = P_{rx\_mode} \times \bar{T}_{halt}(W) \times T_{data} \tag{20}$$

It is to be noted that each node's backoff counter is halted, if one node in the network is ahead of transmitting data with respect to another one of the network. If nodes with least value of backoff counter starts transmitting, the backoff counter of other nodes is halted and the energy consumption of the network is increased. Hence, it is essential to estimate the halting time duration for the CW size, W, to analyze the energy consumption. At the time of halt, each node must have certain size of CW, which is a random number and let the size ranges from 1 units to maximum up to W units. If repetition of the CW size occurs, maximum $N-1$ nodes can be ahead in the network. Besides, if a node in the network is ahead in forwarding data with respect to other nodes of the network, its CW size may range from 1 unit to maximum up to $(W-1)$ units. With these information, if i number of nodes in the network are ahead with respect to one node in the network, then considering the number of ahead and non-ahead nodes with repetition of CW size, the possible duration of halting time for the CW size W could be estimated as

$$\bar{T}_{halt}(W) = \sum_{i=1}^{N-1} i \left(\frac{\sum_{k=1}^{W-1} \binom{k+i-1}{i} \binom{(W-k)+(N-i-1)-1}{N-i-1}}{\binom{W+N-1}{N}} \right) \tag{21}$$

where $W = 2^m W_0 - 1, \ \forall m \in \{0, 1 \ldots, L\}$.

Considering several factors as discussed above, the total energy consumption per node for each successful and failure transmission could be estimated as given in Eqs. (14) and (15), respectively.

5. Performance analysis

In this section, we present the theoretical and simulation results for different size of fixed and binary exponential windows to compare the results and to validate our analytical models. The simulation setups and corresponding results are described as follows.

5.1. Simulation setups

In order to evaluate the energy consumption based on our hybrid model for different sizes of fixed and exponentially CWs, we consider a single-hop and fully connected WSN with a single coordinator. All nodes in the network use our hybrid CSMA-CA protocol to access the channel that is similar to IEEE 802.15.4 MAC mechanisms. The CW is considered for each collision among the nodes. For every packet is sent or received, energy consumption of packet transmissions in the network is estimated. As per a typical WSNs, nodes are assigned time slots to wake up or to go to the power saving mode. The theoretical results are obtained from our mathematical equations using MATLAB and the simulation results are obtained from the implementation of our model with PowerTOSSIM (Shnayder et al., 2004), which is a scalable simulation environment based on TOSSIM (Levis et al., 2003) for TinyOS (Hill et al., 2000) applications that provides the user accurate and per-node's energy consumption estimation. The simulations are setup according to the IEEE 802.15.4 MAC/PHY specification and radio characteristics of IEEE 802.15.4 compliant product CC2420 (http://www.chipcon.com), as listed in Table 1. Since, MICAz is a hardware representative of IEEE 802.15.4 platform for TinyOS and is widely used today, the packet length is set as a constant length of 36 bytes with reference to the maximum packet length of MICAz specification (http://www.xbow.com).

5.2. Model validation

In order to validate our analytical models, different sets of nodes are considered as the network size (N) for the MATLAB and PowerTOSSIM. The MATLAB tool evaluates the energy consumption with packet generation probability g equals to 0.0032 and 0.032, whereas PowerTOSSIM simulates the packet generation probability λ equals to 1000 and 100 ms corresponding to the packet generation probability g equals to 0.0032 and 0.032, respectively. Since, a slot time (T_{slot}) is 320 μs and g is the packet generation probability for each slot, traffic for the MATLAB and PowerTOSSIM is identical. In both MATLAB and PowerTOSSIM, our hybrid CSMA-CA mechanism with backoff windows is implemented for both fixed and exponentially increased CWs. First, the theoretical results are obtained from the MATLAB and corresponding graphs are plotted as shown in Figs. 8(a)–13(a). Later, the simulation results obtained from the PowerTOSSIM are plotted in Figs. 8(b)–13(b) alongside of each theoretical results and are compared with them to validate our models.

It is to be observed that the theoretical and simulation results are identical for the CWs size starting from 8 to 128, as shown in Figs. 8 and 9. This is because of the value of packet generation probability λ considered in the simulation. However, the nature and trend of the graphs in both cases remain same. Besides, the theoretical and simulation results as shown in Figs. 10–13 are totally identical, which justify the validation of our models. From Figs. 10 to 13, the percentage of successful transmission probability for different size of fixed and binary exponential windows are almost identical, which validates our analytical models of successful transmission probability.

Table 1
List of parameters and their values used in our simulation.

Characteristics	Value	Comments
T_s	16 μs	Symbol interval
T_B	32 μs	Byte interval
T_{slot}	320 μs	Slot duration
T_{data}	1152 μs	Data transmission duration
T_{cca}	640 μs	Clear channel assessment duration
T_{ack}	544 μs	ACK reception duration
T_{ack_tuot}	864 μs	ACK timeout
P_{rx_mode}	19.7 mA	Current consumption in receiving mode
P_{tx_mode}	17.4 mA	Current consumption in transmit mode
V	3.3 V	Typical working voltage

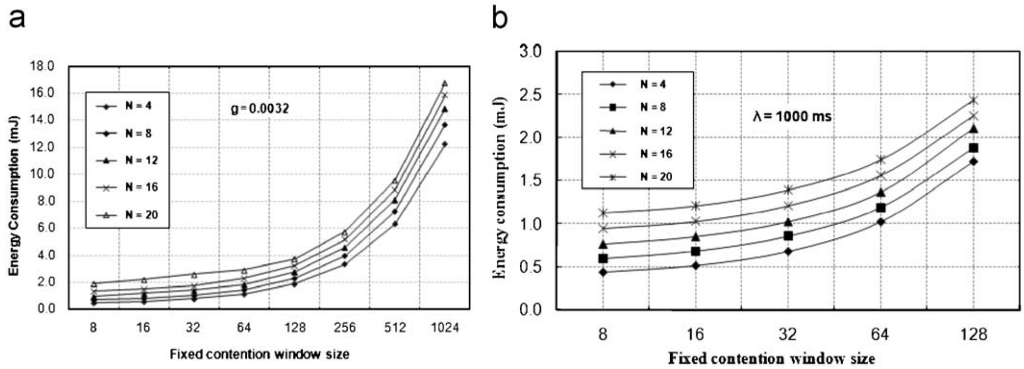

Fig. 8. Energy consumption for different size of *fixed contention window* with fixed packet generation probability and different node numbers. (a) Theoretical result. (b) Simulation result.

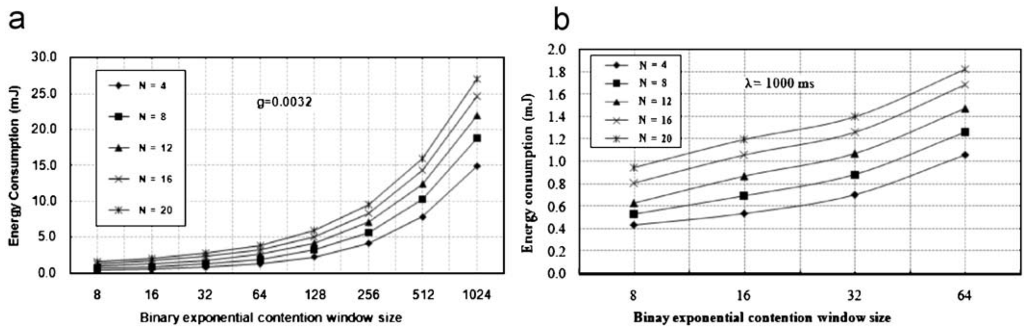

Fig. 9. Energy consumption for different size of *binary exponential contention window* with fixed packet generation probability and different node numbers. (a) Theoretical result. (b) Simulation result.

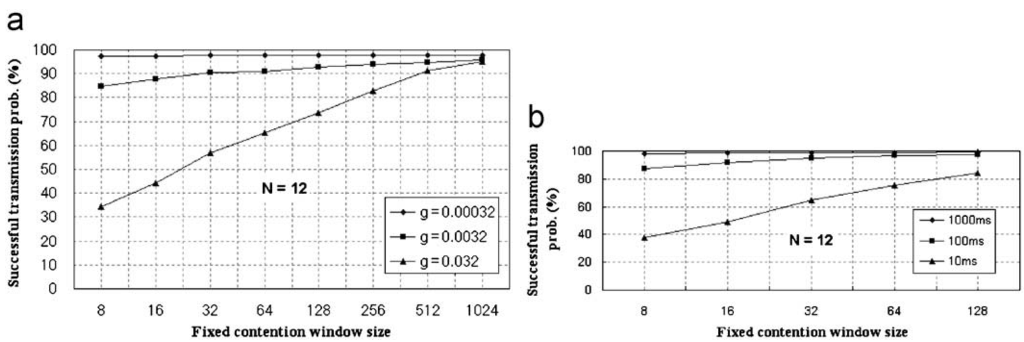

Fig. 10. Percentage of successful transmission probability for different size of *fixed contention window* with different packet generation probabilities and fixed node numbers ($N = 12$). (a) Theoretical result. (b) Simulation result.

5.3. Performance evaluation

In this section, we compare our simulation results obtained from PowerTOSSIM with the theoretical results to know, if the binary exponential backoff mechanism indeed benefits the energy conservation in WSNs. We expect to find more energy efficient strategies by studying the energy consumption of our hybrid CSMA-CA for binary exponential windows with a fixed CWs (W).

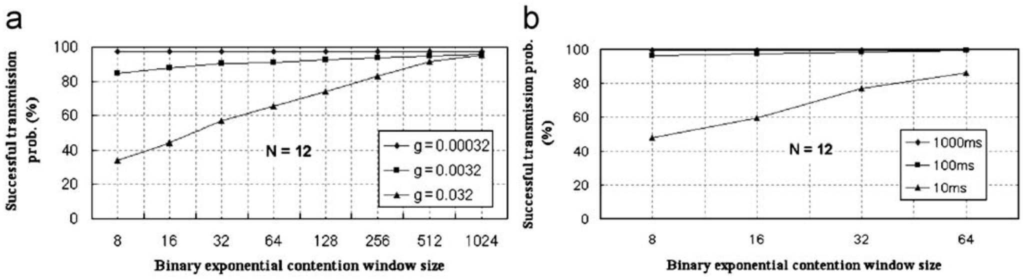

Fig. 11. Percentage of successful transmission probability for different size of *binary exponential contention window* with different packet generation probabilities and fixed node numbers ($N = 12$). (a) Theoretical result. (b) Simulation result.

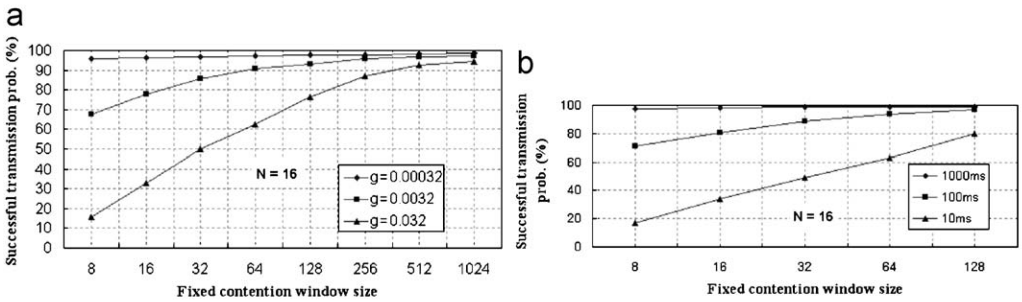

Fig. 12. Percentage of successful transmission probability for different size of *fixed contention window* with different packet generation probabilities and fixed node numbers ($N = 16$). (a) Theoretical result. (b) Simulation result.

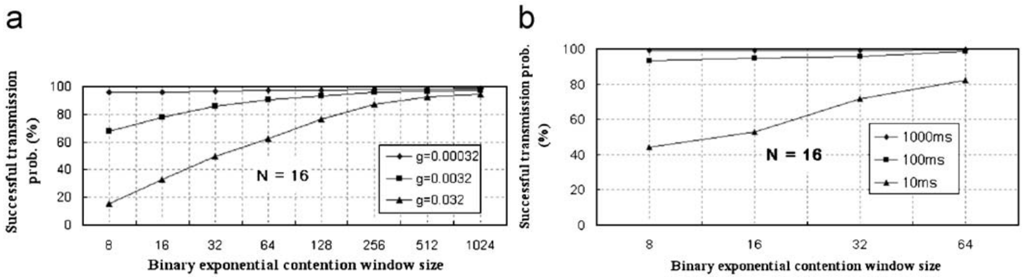

Fig. 13. Percentage of successful transmission probability for different size of *binary exponential contention window* with different packet generation probabilities and fixed node numbers ($N = 16$). (a) Theoretical result. (b) Simulation result.

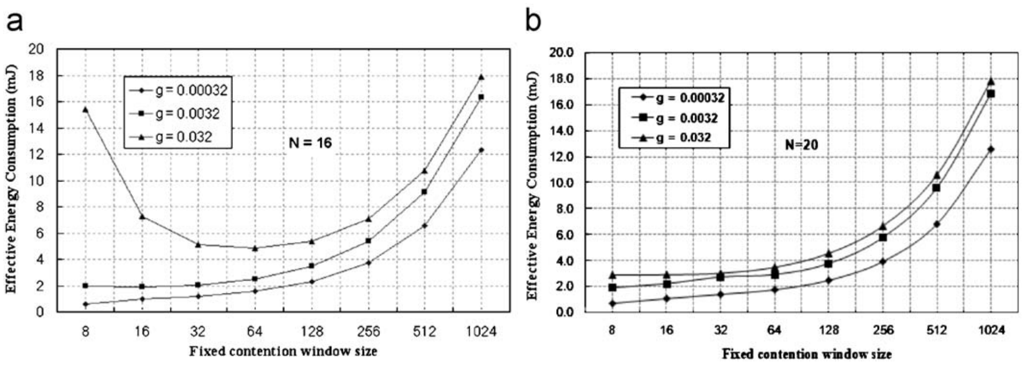

Fig. 14. Effective energy consumption vs. *fixed contention window* for different packet generation probabilities with fixed number of nodes. (a) Node numbers (N) = 16. (b) Node numbers (N) = 20.

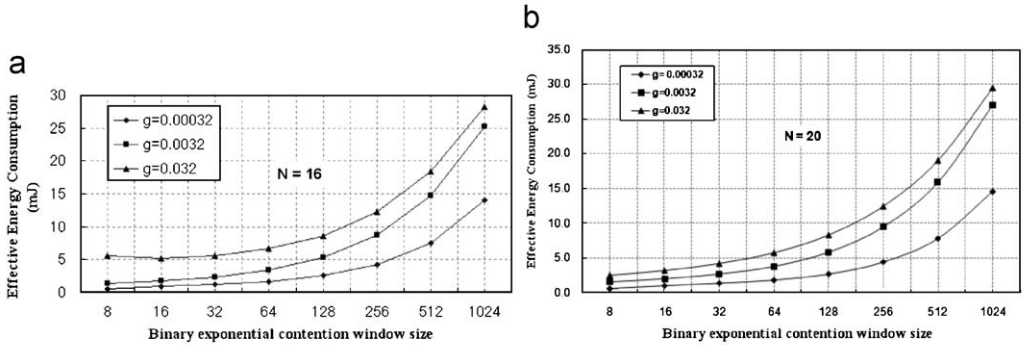

Fig. 15. Effective energy consumption vs. *binary exponential contention window* for different packet generation probabilities with fixed number of nodes. (a) Node numbers $(N) = 16$. (b) Node numbers $(N) = 20$.

Note that, the fixed backoff mechanism can be viewed as a special case for the extended linear feedback model, where the retransmission probability $\nu_m = 2/W_m$ for all $m = 0, \ldots, L$.

The simulation results displayed in Figs. 8(b) and 9(b), present the energy consumption analysis for the fixed and exponentially increased CWs with different node numbers (N). From those figures, it is found that the energy consumption increases with increase in node numbers (N), and CW size. Since, increase in node numbers (N) induces more number of CWs, the waiting time for the transmission increases and raises the probability of collision. Hence, the overall energy consumption of the network is increased. From our analysis, it is clear that the large CW size makes the nodes waiting for longer time to retransmit data and thereby causes more energy consumption. Moreover, as compared to the respective theoretical results, extraordinary high energy consumption for the packet transmissions is discovered in both cases. This is because of the simulated MICAz platform stays in receiving mode, if it has no packet to transmit. It is to be noted that MICAz spends more energy in receiving mode than in transmission mode.

Figs. 10(b) and 11(b) display the percentage of successful transmission probabilities for the fixed and exponentially increased CW size, respectively, for fixed number of nodes ($N = 12$) attached to a coordinator. In both cases, the successful probability of each transmission attempt increases with the size of CWs. It is to be noted that the successful probability slightly increases, if binary exponential window is considered in place of fixed one. Consequently, we have the idea of finding the best effective energy consumption, which is defined as the least amount of energy consumed for successfully transmitting a packet. In our opinion, though the increment of CW size always raises successful probability, as long as the increment of CW becomes adequate for staggering transmissions, additional increment can only do more harms than good for energy conservation. Further, we may view the expected energy consumption as a cost for increasing the successful probability. As shown in Figs. 12(b) and 13(b), the percentage of successful transmission probability slightly decreases, if node numbers are increased, that is from $N = 12$ to 16. This decrement is observed for both fixed and binary exponential CWs, as increase innumber of nodes increases the competition to access the channel.

Figs. 14 and 15 display the results of effective energy consumption for the fixed and exponentially increased CW size, respectively. As shown in Fig. 14, the effective energy consumption abruptly decreases for the fixed CW size. This change is well marked, if number of nodes are increased from $N = 16$ to 20, as shown in Figs. 14(a) and (b). Similar results of effective energy consumption is also found in Figs. 15(a) and (b). From this observation, we can infer that the energy consumption can be minimized by increasing the CW size, if node numbers are increased. However, higher CW size may consume more energy, as waiting time of the nodes will be more, which are observed from both Figs. 14 and 15. The interesting observations from Figs. 14 and 15 are that energy consumption due to successful transmission attempts is minimized in case of fixed CWs for increasing the node numbers, whereas energy consumption increases with increase in the node numbers for the binary exponential CWs. However, in the networks of known traffic load and population, we can find a required CW that can achieve the best effective energy consumption and could be suitable for the WSNs.

6. Conclusion

In this paper, we propose a hybrid channel access mechanism for the WSN that combines the idea of CSMA-CA mechanism of IEEE 802.15.4 and backoff procedure of IEEE 802.11, if collision occurs among the nodes. An extended linear feedback model that explicitly analyzes our hybrid CSMA-CA as an underlying media access control is designed. Analytical models based on the extended linear feedback and Markov chain models are developed for the fixed and binary exponential contention windows to analyze and improve the energy efficiency of WSN. Theoretical and simulation results of our analysis show that energy consumption in WSN is increased with increase in size of the contention window and network population. It is observed that effective energy consumption in WSN is less by adopting an exponential contention window instead of a fixed one. Besides, the percentage of successful transmission probability is increased by adopting an exponential contention window. Hence, it is suggested to consider an exponential backoff mechanism in WSN, as power conservation and better percentage of successful probabilities can be achieved. If the sensors are deployed on a remote monitoring region, where recharge or replacement of batteries are not possible, adopting an exponential backoff mechanism could be useful. For the WSNs of known network population and traffic load, an optimal contention window can be derived from the use of fixed contention window to achieve the best effective energy consumption. Using this optimal contention window, one can have a reasonable successful probability for the packet transmission without extra wastage of the battery power.

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