Modeling IEEE 802.15.4 based Wireless Sensor Network with Packet Retry Limits

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ABSTRACT

In this paper, an analytical model for the beacon-enabled slotted CSMA-CA mechanism of IEEE 802.15.4 wireless sensor network is designed. The current mechanism of IEEE 802.15.4 CSMA-CA is extended to include the retransmission limit of the nodes with packet collision probability. A three-dimensional discrete time Markov chain model for the uplink traffic of wireless sensor network is designed to analyze the energy consumption and throughput of the nodes under unsaturated traffic conditions. The energy consumption and throughput are analyzed for different node numbers and data rates to estimate the possible number of nodes for the better performance in terms of throughput.

Categories and Subject Descriptors

C.2 [**Computer Systems Organization**]: Computer Communication Networks; G.0 [**Mathematics of Computing**]: General; I.6 [**Computing Methodologies**]: Simulation and Modeling

General Terms

Theory, Performance

Keywords

IEEE 802.15.4, Sensor Networks, Modeling, Throughput, Energy Consumption

1. INTRODUCTION

Wireless sensor network (WSN) is envisioned for a wide range of applications ranging from environmental surveillance, inventory tracking, health monitoring, home automation to networking in or around a human body. IEEE 802.15.4 [1] specifies the wireless MAC and PHY specifications for low-rate, low-power wireless personal area networks (WPANs) and is suitable for the wireless sensor networks. In a star topology of IEEE 802.15.4 network, communication is established between devices and a single central controller, called the personal area network (PAN) coordinator. A device typically has some associated application and is either the initiation point or the termination point for the network communications. The coordinator may be mains powered, while the devices will most likely be battery powered. The media access in star topology of IEEE 802.15.4 is contention based. However, using the optional superframe structure, time slots can be allocated by the PAN coordinator to the devices with time critical data.

The first simulation-based performance evaluations of the new medium access control protocol in IEEE 802.15.4, focusing on its beacon-enabled mode for small and low loaded star-topology network is evaluated in [2]. Their performance evaluation study reveals some of the key throughput-energy-delay tradeoffs inherent in the MAC protocol. In [3], authors have developed a simplified analytical procedure to calculate packet service time in a beacon-enabled 802.15.4 sensor cluster, which can be used to implement a simple admission control algorithm to be run at the cluster coordinator. Performance analysis in a beacon enabled IEEE 802.15.4 network is made in [4] under two duty cycle management distributed algorithms. The authors model and evaluate both policies using the theory of discrete time Markov chains and M/G/1/K queues with vacations. In [5], 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.

Performance of an IEEE 802.15.4 compliant network operating in the beacon enabled mode with both downlink and uplink traffic is analyzed in [6] through discrete time Markov chains and the theory of M/G/1 queues. In [7], authors have examined the reliability of the point to point communication with a real IEEE 802.15.4 hardware and run lengths distribution both in indoor and outdoor environments. In [8], the paper provides a simple, but nevertheless extremely accurate, analytical model to compute the IEEE 802.11 DCF throughput in the assumption of finite number of terminals and ideal channel conditions. The proposed analysis applies to both packet transmission schemes employed by DCF, namely the basic access and the RTS/CTS access mechanisms. The form of the analysis given in [9], is similar to that of [8] for IEEE 802.11 DCF, but the key difference in

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the main approximation assumption is that each device's carrier sensing probability, rather than its packet sending probability is assumed independent. In [10], authors analyze the performance limits of the slotted CSMA-CA mechanism of IEEE 802.15.4 in the beacon-enabled mode for broadcast transmissions in WSNs.

A new Markov chain model of the IEEE 802.15.4 is proposed in [11], and the throughput and energy consumption in saturation conditions are analyzed. The proposed model utilizes the probability of a device in the channel sensing states instead of the channel accessing states. A saturation throughput analysis of an IEEE 802.15.4 sensor network with a star topology is carried out in [12], under the assumption that each sensor has an infinite backlog of packets. However, we think that though IEEE 802.15.4 standard proposes the retransmission procedure, it does not consider the CSMA-CA mechanisms, if an acknowledgement is not received due to collision. It is observed that most of the works consider number of backoffs (NB) and contention window length (CW) or number of backoffs (NB) and backoff exponent (BE) in the performance evaluation. To the best of our knowledge, none of the work analyzes the effect of number of retry limit on the throughput or energy consumption analysis, though it has substantial effect on the performance. Besides, in the performance analysis of IEEE 802.15.4 MAC mechanisms, most work consider that each device always has a packet available for transmission, which is not realistic for the wireless sensor networks. Hence, we extend the current CSMA-CA mechanisms of the standard to include the number of retry (NRT) limits and develop a three-dimensional Morkov chain model to analyze its impact on throughput and energy consumption. The key difference of our model with the existing models is that we consider an unsaturated traffic condition of the network and develop the packet collision probability taking possibility of the collision in the channel.

The rest of the paper is organized as follows. Section 2 presents the system models of our work. Analytical models of IEEE 802.15.4 based wireless sensor network are designed in Section 3 and Section 4 presents the throughput and energy consumption analysis based on our models. Section 5 describes the performance evaluations and validation of our models. Concluding remarks are made in Section 6 of the paper.

2. SYSTEM MODEL

In our analytical models, a star topology of IEEE 802.15.4 based wireless sensor network with beacon-enabled slotted CSMA-CA and acknowledgements are considered. If a single transmission attempt is failed and the transmission is direct, the device repeats the data transmission or MAC command frame and waits for the acknowledgment up to a maximum duration of *aMaxFrameRetries*, which is the maximum number of retransmission times. If an acknowledgment is still not received after *aMaxFrameRetries* retransmissions, the MAC sublayer shall assume the transmission has failed and notifies the next higher layer of the failure. This situation eventually is referred to as a communication failure.

In the slotted CSMA-CA of IEEE 802.15.4, the MAC sublayer first initializes three variables i.e. the number of backoffs (NB), contention window (CW) and backoff exponent (BE) and then locates the boundary of the next backoff period, as shown in step 1 of Figure 1. 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*. 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. However, the value of BE shall not be more than *aMaxBE*, which means the maximum value of BE in the CSMA-CA algorithm and its value can be taken up to 5 as per the standard. It is to be noted that collision avoidance is disabled during the first iteration of the algorithm, if this value is set to 0. The MAC sublayer in a slotted CSMA-CA system shall also reset CW to 2. Then the MAC sublayer shall delay for a random number of complete backoff periods in the range 0 to $(2^{BE} - 1)$ units, as shown in step 2 of Figure 1 and then perform the first clear channel assessment (CCA), as shown in step 3 of Figure 1. Throughout the paper, the use of word standard is implied as the IEEE 802.15.4 standard.

In a slotted CSMA-CA system, the CCA shall start on a backoff period boundary. If the channel is assessed to be idle during the first CCA, the MAC sublayer in a slotted CSMA-CA system shall ensure that the contention window has expired before commencing transmission. To do this, the MAC sublayer shall first decrement CW by one, as shown in step 5 of Figure 1 and then determine whether it is equal to 0. If it is not equal to 0, the CSMA-CA algorithm shall return to perform the second CCA, as shown in step 3 of Figure 1. However, if it is equal to 0, the MAC sublayer assumes the channel access is a success and shall begin transmission of the frame on the boundary of the next backoff period. As per the standard, the packet transmission is considered as a success and the procedure is terminated immediately. Upon performing the first CCA, if a channel is assessed to be busy, the MAC sublayer shall increment the value of both NB and BE by one, ensuring that BE shall be no more than *aMaxBE*, as shown in step 4 of Figure 1. If the value of NB is less than or equal to the variable *macMaxCSMABackoffs*, the CSMA-CA algorithm shall return to step 2, as shown in Figure 1. Here, the variable *macMaxCSMABackoffs* represents the maximum number of times the CSMA-CA algorithm is required to backoff while attempting the current transmission and its value can be taken up to 3 as per the standard. If the value of NB is greater than *macMaxCSMABackoffs*, the CSMA-CA algorithm shall terminate with a *Channel Access Failure* status. As per the standard, the packet transmission is considered as a failure and the procedure is terminated.

2.1 Our Channel Access Mechanism

As per the IEEE 802.15.4 standard, if channel access is a success, a node starts transmitting packets and if the value of NB is greater than *macMaxCSMABackoffs*, channel access is considered as a failure. Besides, if a single transmission attempt is failed, the device repeats the process of transmitting data and waits for the acknowledgment up to a maximum of *aMaxFrameRetries*, which is the maximum number of retransmission times (NRT). If an acknowledgment is still not received after *aMaxFrameRetries* retransmissions, the MAC sublayer assumes the transmission has failed. It is to be noted that a sender may not receive the acknowledgement, if collision occurs during transmission or the packet is rejected due to some other reasons. Hence, in our model, since we consider a beacon-enabled slotted CSMA-CA, we care for receiving the acknowledgements after each successful transmissions. Accordingly, we extend the existing channel access mechanisms of the standard by taking number of retransmission times (NRT) that incorporates the channel re-accessing mechanism due to loss of an acknowledgement.

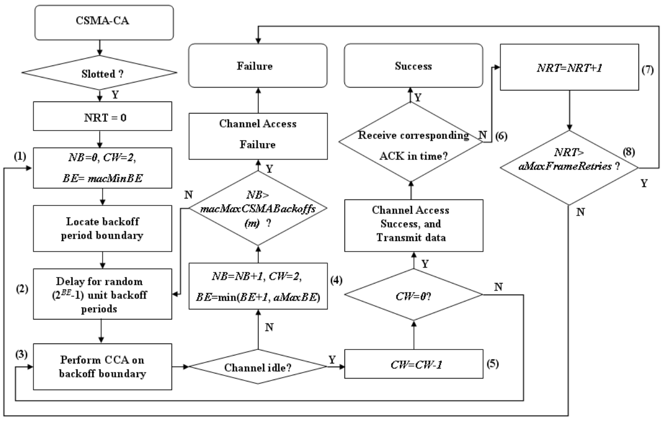

Figure 1: Flow chart of IEEE 802.15.4 channel access mechanisms with our extensions.

Our additional mechanisms totally comply with the standard. In our CSMA-CA mechanism, if the channel assess is a success, we do not consider it as a success unless the sender receives the acknowledgement due to collision. Moreover, if the channel assess is a success, the sender goes to step 6 of Figure 1 to check if the corresponding acknowledgement (ACK) is received on time. In our extension, if receiving ACK is true, transmitting packet is considered as a success. However, if receiving ACK is false, the value of NRT is incremented by 1, as shown in step 7 of Figure 1 and the sender compares its NRT value with the value of *aMaxFrameRetries*. As shown in step 8 of Figure 1, if the value of NRT is less than *aMaxFrameRetries*, it goes to step 1 of Figure 1 and follows the CSMA-CA mechanism to re-access the channel, otherwise the transmission procedure is considered as a failure. It is to be noted that the procedures given in steps 1 through 5 of Figure 1 are based on the standard and the procedures in steps 6 through 8 are our extensions, which do not violate any conditions of the standard.

3. ANALYTICAL MODELS

In this section, we propose a three dimensional discrete time Markov chain model to analyze the throughput and energy consumption of the nodes that includes the channel access mechanism of the standard as well as our extensions. In our model, N number of nodes are attached to a coordinator and form a star topology. It is assumed that all nodes of the network do not have packets at the same time to transmit i.e. all nodes of the network operates in *unsaturated* traffic conditions. For example, when some nodes are generating packets, some other nodes might be processing them whereas rest nodes are ready to transmit the packets. In order to satisfy the densely deployment property of the wireless sensor, value of BE is limited to 2, which may cause collisions frequently. Hence, the probability of packet collision and corruption are not negligible in our model.

3.1 Our Markov Chain Model

To analyze the performance of packet transmission probability of nodes under unsaturated traffic conditions, we design the discrete time three-dimensional Markov chain model, as depicted in Figure 2.

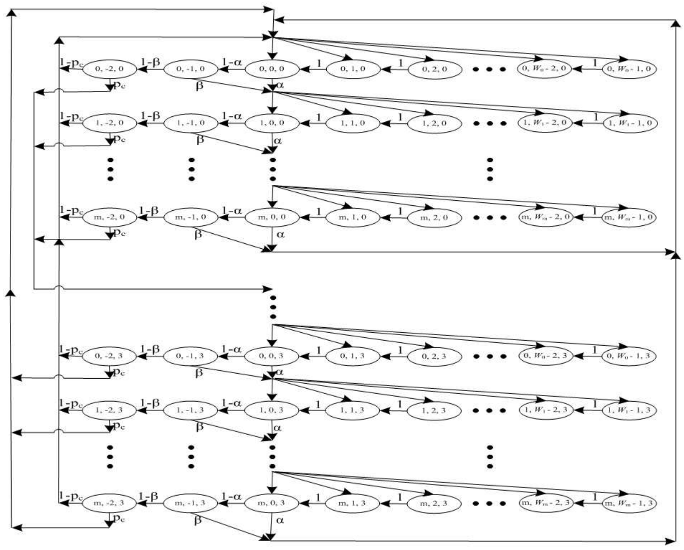

Figure 2: Our Markov chain model based on the transmission policy of IEEE 802.15.4

For a given node, the stochastic processes $s(t)$, $c(t)$ and $r(t)$ represent the backoff stage for NB, backoff counter for CW, and retransmission counter for NRT, respectively and are shown in Figure 2. We let

$$S_{j,x,k} = \lim_{t\to\infty} P\{s(t) = j, c(t) = x, r(t) = k\}$$

where, $j \in \{0, 1, ..., m\}, x \in \{-2, -1, ..., W_j - 1\}$, $k \in \{0, 1, ..., aMaxFrameRetries\}$, m represents the *macMaxCSMABackoffs* and $W_j = 2^{min(j+macMinBE,aMaxBE)}$. The time t corresponds to the beginning of the slot time and is directly related to the system time. After the backoff counter is decremented to zero, $S_{j,0,k}$ and $S_{j,-1,k}$ represent the states corresponding to the first CCA and the second CCA, respectively; and $S_{j,-2,k}$ represents the transmission state.

Let, α be the probability of assessing channel busy during the first CCA (CCA_1) and β be the probability of assessing channel busy during the second CCA (CCA_2), given that the channel was idle in CCA_1. A node goes to transmission state, if the channel is idle in both of the CCAs and attempts to transmit data. In our model, a node is considered to be in transmission state $S_{j,-2,k}$, only if it receives the acknowledgement successfully, which may happen due to absence of collision in the channel.

3.2 Packet Transmission Probability

It is to be noted that any node A senses the channel busy only if some other node B in the medium is in CCA_2 during node A's CCA_1 and starts a new transmission in slot CCA_2. This can only happen, if node B starts performing CCA_1 in slot 1 and the channel was idle at that time. Similarly, collision occurs in the medium, if both nodes A and B start their CCA_1 at the same time. Let, N be the number of nodes associated to the coordinator and p_c be the probability of a collision seen in the medium, when packets are transmitted on the medium after performing both CCAs. It is sufficient to note that the probability that a transmitted packet encounters collision is equal to the probability, when at least one of the $N-1$ competing neighbors are transmitting packets. Considering p_0 be the probability that a node is not in one of the state $S_{j,x,k}$, which reflects the unsaturated traffic conditions of the network, p_c can be given as follows:

$$p_c = 1 - [1 - (1 - p_0)\tau]^{N-1} \quad (1)$$

where, τ be the probability that a node is performing its first CCA. A discrete and integer time scale t and $t+1$ corresponds to the beginning of two consecutive slot times, and the backoff time counter of each station decrements at the beginning of each slot time. The stochastic process $s(t)$ represents the backoff stage and $s(t) = 0$ at time t. We assume that the probability to start sensing the channel is constant and independent of all other nodes. At the beginning of the first transmission, the stochastic process $r(t)$, representing the retransmission counter is set to 0 at time t and is incremented by 1 for each retransmission. With these assumptions, $s(t), c(t)$, and $r(t)$ form the three-dimensional Markov chain, as shown in Figure 2 and the corresponding transition probabilities can be formulated as follows:

$$P(j, x-1, k|j, x, k) = 1,$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 1 \le x \le W_j - 1; 0 \le k \le aMaxFrameRetries \end{cases} \quad (2)$$

$$P(j, -1, k|j, 0, k) = 1 - \alpha,$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le k \le aMaxFrameRetries \end{cases} \quad (3)$$

$$P(j+1, x, k|j, 0, k) = \frac{\alpha}{W_{j+1}},$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs - 1 \\ 0 \le x \le W_{j+1} - 1; 0 \le k \le aMaxFrameRetries \end{cases} \quad (4)$$

$$P(0, x, 0|macMaxCSMABackoff, 0, k) = \frac{\alpha}{W_0},$$
$$for \begin{cases} 0 \le x \le W_0 - 1 \\ 0 \le k \le aMaxFrameRetries \end{cases} \quad (5)$$

Equation 2 is the condition to decrease the backoff counter until it becomes 0 i.e. until it reaches the state $(0, 0, 0)$. At the state $(0, 0, 0)$, a node performs its first clear channel assessment (CCA_1) and the corresponding transition probabilities are given in equations 3 and 4. Equation 3 accounts for the fact that the node goes to the second channel assessment CCA_2 following the successful first channel assessment. Equation 4 accounts for the unsuccessful CCA_1. In particular, as considered in equation 4, when an unsuccessful CCA_1 occurs with probability α, the backoff stage increases and the new initial backoff value is randomly chosen in the range $(0, W_{j+1} - 1)$, for the given value of j, as defined in that equation. Equation 5, models the fact that once the backoff stage reaches at the value of *macMaxCSMABackoffs*, it is not increased in subsequent packet transmissions.

$$P(j, -2, k|j, -1, k) = 1 - \beta,$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le k \le aMaxFrameRetries \end{cases} \quad (6)$$

$$P(j+1, x, k|j, -1, k) = \frac{\beta}{W_{j+1}},$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs - 1 \\ 0 \le x \le W_{j+1} - 1; 0 \le k \le aMaxFrameRetries \end{cases} \quad (7)$$

$$P(0, x, 0|macMaxCSMABackoff, -1, k) = \frac{\beta}{W_0},$$
$$for \begin{cases} 0 \le x \le W_0 - 1 \\ 0 \le k \le aMaxFrameRetries \end{cases} \quad (8)$$

Equation 6 and 7 model the probability of successful and unsuccessful second clear channel assessment (CCA_2), respectively. Equation 6 models the fact that a node goes to the packet transmission state following a successful CCA_2. Equation 7 models the system after an unsuccessful CCA_2, in which a node goes to next backoff stage and stays within a randomly chosen backoff counter. Similarly, equation 8 gives the probability that there is failure in both sensing slots, i.e. in CCA_1 and CCA_2 and also fails up to the last backoff stages i.e. if the failure in both CCAs occurs and it continues till *macMaxCSMABackoff* becomes 0.

$$P(0, x, 0|j, -2, k) = \frac{1 - p_c}{W_0},$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le x \le W_0 - 1; 0 \le k \le aMaxFrameRetries \end{cases} \quad (9)$$

$$P(0, x, k+1|j, -2, k) = \frac{p_c}{W_0},$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le x \le W_0 - 1; \\ 0 \le k \le aMaxFrameRetries - 1 \end{cases} \quad (10)$$

$$P(0, x, 0|j, -2, aMaxFrameRetries) = \frac{p_c}{W_0},$$
$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le x \le W_0 - 1 \end{cases} \quad (11)$$

$$where, \quad W_j = 2^{min(j+macMinBE, aMaxBE)}, j \in \{0, 1, ..., m\}$$

It is to be noted that the packet transmission is considered to be a success in our assumption, if acknowledgement is received on time. Else, a node restarts the channel assessment until the value of the retransmission counter is greater than *aMaxFrameRetries*. Accordingly, equation 9 and 10 model the system for receiving the successful and unsuccessful acknowledgements, respectively. As given in equation 9, the transition probability for the successful packet transmission is presented, whereas the transition probability of unsuccessful transmission of packet due to collision in the medium is given in equation 10. Equation 11, models the system for the unsuccessful retransmission of packet, when a node crosses all of its limits such as the value of backoff counter (CW), backoff stages (NB) and retransmission counter (NRT). Note that the number of transmission attempts is limited and either ends with a success or failure.

Let, $M_i(s) = -1$ be the event that there is at least one transmission in the medium by another node in slot i and $M_i(c) = -1$ be the event that some node start sensing the medium during slot i. On the contrary, $M_i(s) \ge 0$ denotes the event that no station in the medium is transmitting in slot i and $M_i(c) \ge 0$ denotes the event that no station starts sensing during slot i, where slot i could be any time slot, e.g. slot CCA_1, slot CCA_2, slot 1 and so on. Then, the probability that a station is performing first CCA can be estimated as given in equation 12.

$$\tau = \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,0,k} \tag{12}$$

If $\lceil T_L \rceil$ and $\lceil T_{ACK} \rceil$ denotes time duration in the number of slots for transmitting an L-slot packet and receiving an acknowledgement, respectively, probability of first channel assessment is busy can be given as follows.

$$\alpha = \{(1-p_c)(\lceil T_L \rceil + \lceil T_{ACK} \rceil) + p_c \lceil T_L \rceil\}(1-\beta) \tag{13}$$
$$\times \{1 - [1-\tau(1-p_0)]^{N-1}\}(1-\alpha)$$

Lastly, we need an expression for β, which is the probability of sensing channel busy in the second channel assessment. The device will sense busy in slot CCA_2, if another device is going to transmit at the same slot, which has already started sensing the channel in slot 1 i.e. $(M_1(s) = -1$ and the channel was then idle i.e. $M_1(s) \geq 0)$. Hence,

$$\beta = P(M_{CCA_2}(s) = -1 \mid M_{CCA_1}(s) \geq 0)$$
$$= \left[\frac{\frac{\{1-[1-\tau(1-p_0)]^N\}(1-\alpha)(1-\beta)}{1-[1-\tau(1-p_0)]^N}}{\{1-[1-\tau(1-p_0)]^{N-1}\}(1-\alpha)(1-\beta) + \frac{\{1-[1-\tau(1-p_0)]^N\}(1-\alpha)(1-\beta)}{1-[1-\tau(1-p_0)]^N}} \right]$$
$$\times \{1 - [1-\tau(1-p_0)]^{N-1}\} \tag{14}$$

Besides the transition probabilities, the Markov chain steady state probabilities can be abbreviated, as follows:

$$D_1 = (1-\alpha)(1-\beta) \cdot p_c$$

$$D_2 = (1-\alpha)\beta + \alpha$$

The closed-form solution for the steady-state probabilities of the Markov chain can be given as follows:

$$S_{0,0,k} = \left[\frac{D_1(1-D_2^{m+1})}{1-D_2} \right]^k S_{0,0,0},$$
$$for \;\; 0 \leq k \leq aMaxFrameRetries \tag{15}$$

$$S_{j,0,k} = D_2^j S_{0,0,k}, for \begin{cases} 0 \leq j \leq macMaxCSMABackoffs \\ 0 \leq k \leq aMaxFrameRetries \end{cases} \tag{16}$$

$$S_{0,x,0} = \frac{W_0 - x}{W_0} \{ \sum_{j=0}^{macMaxCSMABackoffs} (S_{j,-2,aMaxFrameRetries} \cdot p_c)$$
$$+ \sum_{k=0}^{aMaxFrameRetries} \sum_{j=0}^{macMaxCSMABackoffs} [S_{j,-2,k} \cdot (1-p_c)]$$
$$+ \sum_{k=0}^{aMaxFrameRetries} S_{macMaxCSMABackoffs,0,k} \cdot \alpha$$
$$+ \sum_{k=0}^{aMaxFrameRetries} S_{macMaxCSMABackoffs,-1,k} \cdot \beta \},$$
$$for \;\; 0 \leq x \leq W_0 - 1 \tag{17}$$

$$S_{j,-1,k} = (1-\alpha) \cdot S_{j,0,k},$$
$$for \begin{cases} 0 \leq j \leq macMaxCSMABackoffs \\ 0 \leq k \leq aMaxFrameRetries \end{cases} \tag{18}$$

$$S_{j,-2,k} = (1-\alpha)(1-\beta) \cdot S_{j,0,k},$$
$$for \begin{cases} 0 \leq j \leq macMaxCSMABackoffs \\ 0 \leq k \leq aMaxFrameRetries \end{cases} \tag{19}$$

$$S_{j,x,k} = \frac{W_j - x}{W_j S_{j,0,k}},$$
$$for \begin{cases} 0 \leq j \leq macMaxCSMABackoffs \\ 0 \leq x \leq W_j - 1; 0 \leq k \leq aMaxFrameRetries \end{cases} \tag{20}$$

Since, sum of the probabilities must be 1, we get

$$1 = \sum_{j=0}^{macMaxCSMABackoffs} \sum_{x=0}^{W_j-1} \sum_{k=0}^{aMaxFrameRetries} S_{j,x,k}$$
$$+ \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,-2,k}$$
$$+ \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,-1,k} \tag{21}$$

4. THROUGHPUT AND ENERGY CONSUMPTION ANALYSIS

The throughput and energy consumption for each node of the network can be modeled as follows:

4.1 Throughput

Let, S be the system throughput and p_{tr} be the probability that there is at least one transmission in the considered slot time. Since, N number of nodes are associated to a coordinator, τ be the probability that the station is performing first CCA and p_0 be the unsaturated probability, the transmission probability is given as follows.

$$p_{tr} = (1-\alpha)(1-\beta)\{1 - [1-(1-p_0)\tau]^N\} \tag{22}$$

The probability p_s that a transmission occurring in the channel is successful is given by the probability that exactly one node transmits on the channel, given that at least one node transmits. Hence,

$$p_s = \frac{(1-\alpha)(1-\beta)N \times (1-p_0)\tau[1-(1-p_0)\tau]^{N-1}}{p_{tr}} \tag{23}$$

The unsaturated throughput S, defined as the fraction of time the channel is used to successfully transmit the payload bits in unit time can be estimated as follows.

$$S = \frac{p_s p_{tr} T_{pl}}{(1-p_{tr})\sigma + p_{tr} p_s T_s + p_{tr}(1-p_s) T_c} \tag{24}$$

where, T_{pl} be the payload length in number of slots, T_s be the duration of the slot time for a successful transmission, and T_c be the time spent during a collision. Here, σ is the duration of an empty slot time and the values T_{pl}, T_s, T_c, and σ must be expressed with the same unit. The number of occupied slots for the successful transmission, and collision are given in equations 25 and 26, respectively.

$$T_s = 2\lceil T_{CCA} \rceil + \lceil T_L \rceil + \lfloor \delta \rfloor + \lceil T_{ACK} \rceil \tag{25}$$

$$T_c = 2\lceil T_{CCA} \rceil + \lceil T_L \rceil + \lfloor \delta_{max} \rfloor \quad (26)$$

where, T_{CCA}, T_L, δ and T_{ACK} be the time durations (in number of slots) for performing a CCA, for transmitting L-slot packet, for waiting for an ACK and for receiving an ACK, respectively. Note that, in IEEE 802.15.4, a device waits for an ACK during *macAckWaitDuration* (equal to 2.7 slots in 2.4GHz channel). However, we assume that the waiting duration is two slots after the last transmission slot. In addition, we also assume that the backoff procedure starts at the first ACK waiting slot, as given in our Markov chain model.

4.2 Energy Consumption

Here, we have analyzed the normalized energy consumption, which is the average energy consumption to transmit one slot amount of payload. We consider the duration of each successful channel assessment (T_{CCA}) and the packet turnaround time. Taking P_s be the probability of transmission occurring in the channel is successful, and T_L be the time duration for transmitting an L-slot packet, total energy consumption per node can be analyzed as follows.

$$E = \frac{\tau\alpha T_{CCA} P_{RX} + \tau(1-\alpha)\beta \times 2T_{CCA} P_{RX}}{\tau(1-\alpha)(1-\beta)p_s T_{pl}} \quad (27)$$

$$+ \frac{\tau(1-\alpha)(1-\beta)[(1-p_s)E_c + p_s E_s]}{\tau(1-\alpha)(1-\beta)p_s T_{pl}}$$

where, P_{RX} be the energy consumption to receive and P_{TX} be the energy consumption to transmit a packet. T_{ta} be the turnaround time i.e time taken during each RX-to-TX or TX-to-RX, and P_{ta} be the turnaround power, which is taken as $\frac{P_{TX}+P_{RX}}{2}$. δ_{max} be the maximum time to wait for an acknowledgment frame to arrive following a transmitted data frame. The energy consumption for each successful transmission i.e. E_s and each collision i.e. E_c can be estimated as given in equation 28 and 29, respectively.

$$E_s = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} \quad (28)$$

$$+ T_{ta}P_{ta} + \delta_{max}P_{RX} \quad (29)$$

$$E_c = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} + T_{ta}P_{ta} \quad (30)$$

$$+ (\delta - T_{ta} + T_{ACK})P_{RX} \quad (31)$$

5. PERFORMANCE EVALUATION

In this section, we validate our model for the throughput analysis based on our analytical model and have analyzed the performance of throughput and energy consumption to estimate the possible number of nodes beyond which maximum unsaturated throughput cannot be possible. We have simulated our work using ns 2.29 and attempts are made in the simulation to emulate the real operations of each sensor as much as possible including the propagation time, packet delivery ratio, turnaround time and using the real parametric values, specified for the MICAz. In our simulations, we have considered a star topology with a radius of 3 meters, with one coordinator at the center and nodes are evenly distributed around it. We have used the IEEE 802.15.4 MAC/PHY specification and radio characteristics of IEEE 802.15.4 compliant product of CC2420. The transmission range of the transceiver is about 7 meters. The packet sizes assumed to be 10, 50 or 100 bytes, excluding the routing, MAC and PHY layer headers. The maximum PHY sublayer service data unit (PSDU) size that the node shall be able to receive is 127 bytes.

5.1 Model Validation

In order to validate our model for the throughput analysis, we consider the control frames, e.g. beacon frame, which are used to make network keep working. We use default parameter values defined for 2.4GHz frequency channels such as 3, 5, 4 and 3 for *macMinBE, aMaxBE, macMaxCSMABackoff* and *aMaxframeRetries*, respectively. We consider fixed number of 10 nodes attached to the coordinator and each time a node transmits fixed size of packets of 10, 25 or 50 bytes. Thus, to validate our model, we compare the simulation and analytical results for different data rate, as shown in Figure 3. It is found that the analytical results well match with the simulated one. However, as data rate increases, the control frames could be ignored, as a result of which the analytical and simulated results are extremely accurate at the higher data rate.

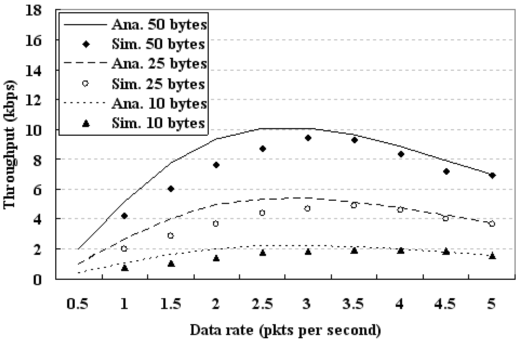

Figure 3: Validation of analytical and simulated results for the throughput

5.2 Throughput and Energy Analysis

In this section, we describe our simulation results of throughput and energy consumption for high data rates, taking packet delivery ratio into account.

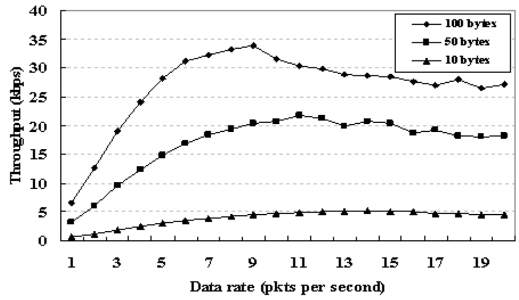

Figure 4: Throughput under high data rate

5.2.1 High Data Rate

As shown in Figure 4, we have considered 10 nodes in the star topology, attempting to transmit data to the coordinator. Each node competes with another to access the channel with packet sizes 100, 50 and 10 bytes. When the packet delivery ratio decreases rapidly, as shown in Figure 5, the

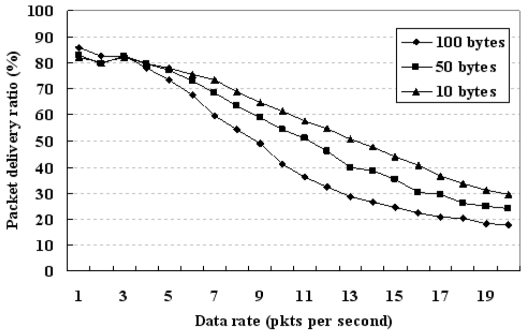

Figure 5: Packet delivery ratio under high data rate

corresponding throughput also decreases, as shown in Figure 4.

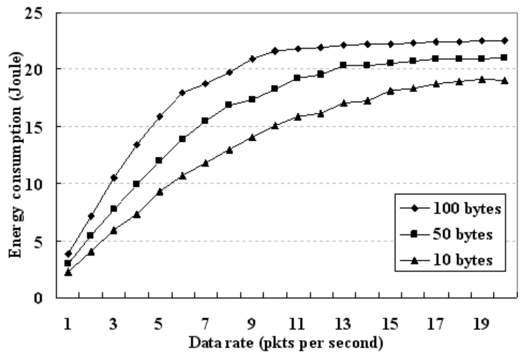

Figure 6: Energy consumption under high data rate

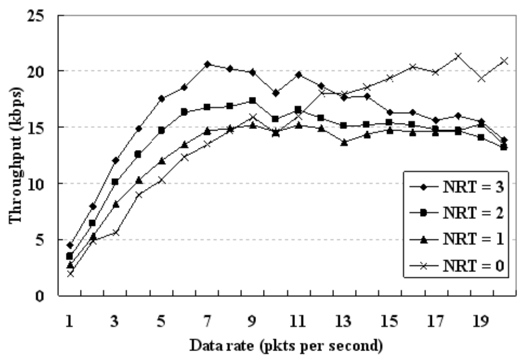

Figure 7: Throughput for different NRT

The energy consumption gradually approximates to a fixed value, as shown in Figure 6, as the capacity of this network is limited. In this experiment, nodes transmit the same number of packets per second for a fixed value of the x-axis. Consequently, the nodes with larger packet size could get a better throughput. The more energy consumed by packets with larger size is also due to this reason. When the data rate is low, the packet delivery ratios have no obvious differences between various packet sizes. However, the packets with larger size occupy the medium for a longer time. That is why the packet delivery ratios have obvious differences

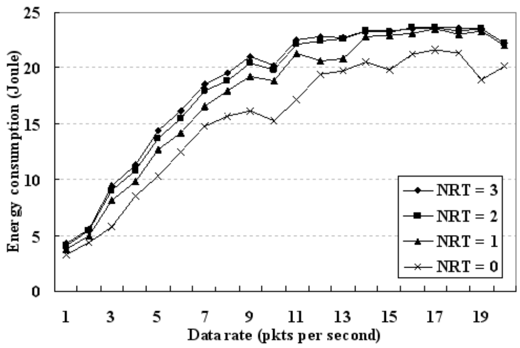

Figure 8: Energy consumption for different NRT

between various packet sizes as the data rate grows gradually. Using the parameters of our model, it is observed from Figure 4 that the throughput of the nodes give better performance for larger packet size and medium data rate. From Figure 6, it is inferred that the energy consumption is always higher either for the higher data rate or larger packet size, which is quite obvious.

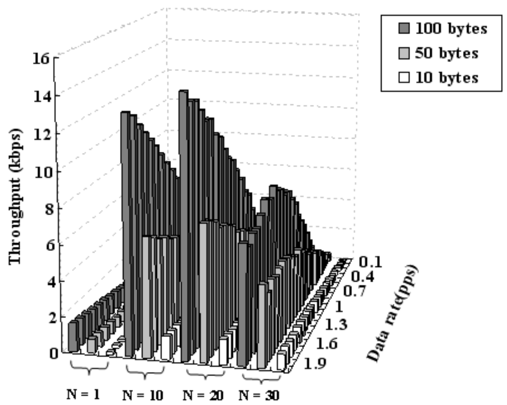

Figure 9: Throughput for different number of nodes

5.2.2 Effect of NRT Values

As number of retransmission is the new concept introduced in our model, we have analyzed its impact on the throughput and energy consumption, as shown in Figure 7 and 8, respectively. From Figure 7, it is observed that when data rate is less than 13 pps (packets per second), the throughput with NRT value equal to 3 is higher than others. Once the data rate exceeds 13 pps, the throughput with NRT equal 0 is higher than others. When data rate is lower (less than 13 pps) and collision occurs, the retransmissions of the collided packets actually increase the data rate. However, when data rate is higher (more than 13 pps) and collision occurs, the retransmission of the collided packets becomes a heavy burden on the network. The energy consumption for NRT equals to 0 is always less than that for the NRT equals to 1, 2, and 3, as shown in Figure 8. Energy consumption corresponding to the value of NRT=0 is comparatively less than other NRT values, as the packet is rejected, if acknowledgement is not received due to collision in the medium.

5.2.3 Effect of Node Numbers

When the data rate is low, the throughput generally increases along the data rate axis, as shown in Figure 9, whereas, the throughput increases until the number of nodes equal to 20. If the total data rate is too high, beyond the capacity of the network, many packets will be dropped due to collision. If there are too many nodes attempting to transmit, packets will be collided frequently. Hence, our simulation results suggests that the number of nodes associated to the coordinator, i.e. the value of N should not exceed 30.

6. CONCLUSION

In this paper, an extension to the existing CSMA-CA mechanism of IEEE 802.15.4 is proposed and a three-dimensional discrete time Markov chain model is developed to analyze the throughput and energy consumption of star topology of wireless sensor networks with packet retransmission limits. It is observed that the nodes having larger packet size could get a better throughput and the energy consumption of nodes increases with higher data rates. For higher value of the data rate (more than 13 pps), the retransmission limit reduces the throughput of the nodes, whereas the energy consumption is increased due to higher value of this parameter. From our analysis, it is concluded that the payload size should be made as large as possible in order to get better throughput.

7. REFERENCES

[1] IEEE 802.15.4, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)", Oct, 2003.

[2] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "Performance Evaluation of the IEEE 802.15.4 MAC for Low-Rate Low-Power Wireless Networks", in *Proceeding of IEEE Workshop on Energy-Efficient Wireless Communications and Networks (EWCN)*, 2004.

[3] J. Misic, S. Shafi, and V. B. Misic, "Admission control in 802.15.4 beacon enabled clusters", in *Proceeding of International Conference on Communications and Mobile Computing (IWCMC),* July, 2006.

[4] J. Misic and V. B. Misic, "Duty Cycle Management in Sensor Networks Based on 802.15.4 Beacon Enabled MAC", *Journal of Ad Hoc and Sensor Wireless Networks*, vol. 1, pp. 207-233, Mar, 2005.

[5] J. Misic, V. B. Misic, and S. Shafi, "Performance of IEEE 802.15.4 Beacon Enabled PAN with Uplink Transmission in Non-Saturation Mode - Access Delay for Finite Buffers", in *Proceeding of 1st IEEE International Conference on Broadband Networks*, pp. 416-425, Oct, 2004.

[6] S. Shafi, "Performance of a Beacon Enabled IEEE 802.15.4 Cluster with Downlink and Uplink Traffic", *IEEE Transactions on Parallel and Distributed Systems*, vol. 17, no. 4, pp. 361-376, Apr, 2006.

[7] M. Petrova, J. Riihijarvi, P. Mahonen, and S. Labella, "Performance Study of IEEE 802.15.4 Using Measurements and Simulations", in *Proceeding of IEEE Wireless Communications and Networking Conference (WCNC)*, vol. 1, pp. 487- 492, April, 2006.

[8] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function", *IEEE Journal on Selected Areas in Communications*, vol. 18, Mar, 2000.

[9] S. Pollin, M. Ergen, S. C. Ergen, B. Bougard, L. V. der Perre, F. Catthoor, I. Moerman, A. Bahai, and P. Varaiya, "Performance Analysis of Slotted IEEE 802.15.4 Medium Access Layer", http://www.soe.ucsc.edu/research /ccrg/DAWN/papers/ZigBee_MACvPV.pdf

[10] A. Koubâa, M. Alves, and E. Tovar, "A Comprehensive Simulation Study of Slotted CSMA/CA for IEEE 802.15.4 Wireless Sensor Networks", in *Proceeding of 6th IEEE International Workshop on Factory Communication Systems (WFCS)*, Jun, 2006.

[11] T. R. Park, T. H. Kim, J. Y. Choi, S. Choi, and W. H. Kwon, "Throughput and Energy Consumption Analysis of IEEE 802.15.4 Slotted CSMA-CA", *IEE Electronics Letters*, vol. 41, issue 18, Sep, 2005.

[12] C.K. Singh and A. Kumar, "Performance Evaluation of an IEEE 802.15.4 Sensor Network with a Star Topology" ece.iisc.ernet.in/ anurag/papers/anurag/singh-kumar05