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Design and analysis of collision free MAC for wireless sensor networks with or without data retransmission

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ABSTRACT

In this paper, a new communication mechanism for IEEE 802.15.4 based Wireless Sensor Networks (WSNs) is designed to reduce the collisions and to prevent simultaneous data transmission by the nodes. Analytical models are designed for the uplink traffic in beacon-enabled slotted CSMA/CA with acknowledgements. In order to avoid the collisions and thereby the number of retransmissions, a new medium access control (MAC) protocol is designed. Beside, the current mechanism of IEEE 802.15.4 CSMA/CA is extended to develop the analytical models by including retransmission limits of the nodes with packet collision probability. Taking uplink traffic of the sensors, a Markov chain model is developed to analyze the energy consumption and throughput of the nodes and to study the impact of various network parameters such as the data rate, packet size and node numbers. The proposed models show that the throughput of the system is reduced and energy consumption is increased due to data retransmissions irrespective of the data rates.

1. Introduction

The development of new technologies has prompted to consider the wireless sensors as the alternatives to reduce costs and improve reliability in wireless communication. Earlier twisted shielded pair or multidrop ethernet buses were used in Wireless Sensor Networks (WSNs) for various applications. However, now true web-based networks are used in WSNs implementation on the factory floor. For many industrial applications such as in oil and gas industry, food and beverage products, chemical products and green energy production, IEEE 802.15.4 (2006) medium access control (MAC) protocol enabled wireless sensors are used. In WSN, communication is established between the sensors (devices) and a personal area network (PAN) coordinator. A sensor runs with some applications to collect data and can act as an initiation or termination point in the network for the purpose of communications. The PAN coordinator is the primary controller of the network and is used to initiate, terminate or route communication around the network, which is quite suitable for the WSNs. The coordinator may be mains powered, while the devices will most likely be battery powered.

IEEE 802.15.4 based WSNs can be operated either as a star or peer-to-peer (P2P) topology based on the application requirements. In the star topology, communication is established between the devices and the PAN coordinator, which acts as a single central controller of the network. Peer-to-Peer is a connection just between a pair of devices, which are one-hop away. Though, peer-to-peer topology has a PAN coordinator, it differs from the star topology in that any device can communicate with any other device as long as they are in the communication range of one another and can talk directly without help of a coordinator. However, source and destination nodes in a star topology are two-hops away from each other and a sender has to transmit data to the receiver with help of a PAN coordinator. The media access in star topology of IEEE 802.15.4 is contention based and connectivity to higher performance networks is provided through a PAN coordinator.

According to the standard, there are two channel access mechanisms. The beacon-enabled channel access mechanism uses a slotted carrier sense multiple access method with collision avoidance (CSMA/CA). In this mechanism, the beacon frame is transmitted in the first slot of each superframe whose format is defined by the coordinator. The purpose of transmitting such beacons is to synchronize with the sensors those are attached to the coordinator. Upon receiving the beacon, sensors can identify the network and can know the structure of the superframe. However, if beacons are not available, a simpler unslotted CSMA/CA can be used. The superframe is divided into contention access period (CAP) and contention free period (CFP),

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which is optional. If any sensor (device) has data to transmit to the coordinator, first it has to compete with other sensors using a slotted CSMA/CA mechanism during the contention access period (CAP).

In order to give better supports to the industrial markets, IEEE 802.15.4 MAC (IEEE Standard for Local and metropolitan area networks-Part, 2011) is amended by IEEE 802.15.4e (IEEE Standard for Local and metropolitan area networks-Part, 2012) standard that enhances and adds more functionality to the former one. Since, applications like factory automation, control of conveyor belts in cargo requires low latency wireless devices, IEEE 802.15.4e standard proposes to consider a low latency deterministic network (LLDN) device and coordinator that operates in a star topology. Though, the latest standard proposes different MAC behavior modes based on various industrial applications, the basic channel access mechanism as proposed in IEEE 802.15.4 remains unchanged. The standard suggests three possible superframe structures similar to the superframe structure proposed in IEEE 802.15.4 (2006), and a deterministic synchronous multi-channel extension (DSME) multi superframe structure having an enhanced beacon with an information element is proposed in IEEE Standard for Local and metropolitan area networks-Part (2011). Though the standard proposes superframe structure with low latency beacons, it clearly specifies the optional use of any superframe structure. The data transfer model of IEEE 802.15.4e (IEEE Standard for Local and metropolitan area networks-Part, 2012) is similar to the previous standards. A device first listens to the network beacon if it wants to transfer data to a PAN coordinator. It synchronizes to the superframe structure if the beacon is found and then transmits data frame to the PAN coordinator in its assigned time slots.

Rest of the paper is organized as follows. Section 2 presents the related work on performance analysis. Problem analysis and motivation of our work are presented in Section 3. System models of our work are described in Section 4. Analytical models based on IEEE 802.15.4 standard are developed in Sections 5 and 6 presents the performance analysis of throughput and energy consumption based on our models. Section 7 describes the performance evaluations and validation of our models. Concluding remarks are made in Section 8.

2. Related works

Performance of an IEEE 802.15.4 compliant network operating in the beacon enabled mode with both downlink and uplink traffic is analyzed in Misic et al. (2006) through discrete time Markov chains. In Pollin et al. (2008), authors design the performance models for the slotted CSMA/CA under saturated and unsaturated periodic traffic conditions in which each device's carrier sensing probability is assumed to be independent. Authors have analyzed the network performance in Chen et al. (2014) considering the effect of senor node density, data transmission rate and communication duration. Though they have studied the performance of the network, no analysis is done in terms of packet retransmission due to collision. Authors in Faridi et al. (2010) design Markov chain model for the behavior of a node in IEEE 802.15.4 based wireless PAN in ACK mode. Though, they consider saturated traffic conditions of the nodes, the retransmission model is similar to Sahoo and Sheu (2008). A delay sensitive slotted contention based MAC protocol (Doudou et al., 2014) for the wireless sensor networks is proposed, in which several MAC protocols those affect the transmission delay are analyzed. However, no performance analysis model is presented in the work.

Authors in Ye et al. (2004) propose the Sensor-MAC (S-MAC) protocol that can locally manage the synchronization and periodic sleep listen schedules based on these synchronization. However, they do not analyze theoretically the performance of the protocol to study the energy consumption and throughput. An energy efficient TDMA-based algorithm is proposed in Rajendran et al. (2003) to increase the utilization of classical TDMA. However, authors neither consider the effect of collision on the energy consumption nor design any model to analyze the throughput and energy consumption. The CSMA/p^* protocol is proposed in Tay et al. (2004), which can achieve low latency in many traffic conditions. However, idle listening is caused due to listening to all slots before sending data and therefore energy consumption is higher. Authors in Rasheed et al. (2014) evaluate the energy consumption of slotted CSMA/CA algorithm of IEEE 802.15.4 MAC in idle and backoff periods. However, they have not studied how collision affects the energy consumption. Besides, their study is only based on the simulation results without any theoretical modeling. Authors in Mehta et al. (2009) develop an a analytical model to study the performance of Guaranteed Time Slots (GTS) traffic in IEEE 802.15.4 networks for emergency situations. However, they have not analyzed the energy consumption and throughput due to collision and data retransmission in the Contention Access Period (CAP).

Authors in Alvi et al. (2012) analyze the performance of the nodes in a wireless PAN during CAP taking slotted CSMA/CA algorithm in to account. Though reliability and transmission failure probability are analyzed in the work, throughput is not analyzed due to retransmission of packets in an unsaturated traffic condition. Authors in Park et al. (2013) propose a Markov chain model to minimize the power consumption of the nodes in IEEE 802.15.4 based network with retransmissions and acknowledgments. However, no analysis is given to achieve the reliability of data transmission. Though the end-to-end delay analysis of a cluster-tree based topology in WSN is studied in Liu et al. (2014), performance analysis under unsaturated traffic condition with or without collision is not analyzed. The analysis given in Wijetunge et al. (2011) is based on the work in Sahoo and Sheu (2010), though a Markov chain model is proposed to study the performance of IEEE 802.15.4 MAC protocol. A collision avoidance MAC Zhao et al. (2016) for WSNs is proposed to achieve the collision free access of the network in which each transmitter has to adjust its next transmission time. Authors simply design algorithms to reduce the number of collisions without going for any analysis to study the energy consumption and throughput. Authors in Lee and Lee (2016) develop an energy-efficient MAC protocol based on the receiver-initiated asynchronous duty cycling and analyze it using Markov chain with a finite number of states those represent the queue length at the wake-up of nodes. However, the effect of retransmission, backoff mechanism and contention window are not modeled to analyze the energy consumption and throughput.

In Weng et al. (2011), authors present an information quality based sampling frequency of sensor nodes and the packet loss rate during data transmission. Though authors consider IEEE 802.15.4 based WSN to address the quality of information sensing and forwarding of periodic sampled data to the sink, no theoretical model is designed to study the performance of the proposed work. An energy consumption analysis of the unslotted CSMA/CA MAC is designed in El Korbi and Saidane (2016) based on the discrete Markov chain model. Though, authors model the transition probabilities for the backoff and retransmission mechanisms, no theoretical analysis is made considering the unsaturated traffic with or without collision in the medium. Authors in Farooq and Kunz (2016) study the impact of IEEE 802.15.4 MAC on event detection ratio, available bandwidth estimator and flow admission control by enabling and disabling the acknowledgements. They have used Cooja simulator to study the impact of the MAC layer ACKs on the performance of IEEE 802.15.4. However, the work is mainly simulation based without any theoretical modeling and without considering the transmission due to collision. Performance of heterogeneous unsaturated networks for the one-hop, star-topology based IEEE 802.15.4 networks with slotted CSMA/CA is analyzed in Lv and Zhu (2012). Performance analysis of IEEE 802.15.4 based MAC is analyzed in Mouftah et al. (2013) using different traffic and network conditions without considering retransmission and unsaturated traffic condition.

Taking a distributed approach based on the received packets, performance analysis of IEEE 802.15.4 periodic bidirectional communication is analyzed in Sandor et al. (2015). Jitter and packet loss rate of the peer-to-peer communication are considered as the performance indicators. However, the MAC protocol of IEEE 802.15.4 is not analyzed for the packet with retry limits due to collision. Performance analysis of the multi-hop unslotted IEEE 802.15.4 networks is studied in Di Marco et al. (2012) without analyzing throughput and energy consumption issues. Though mathematical model for the energy consumption analysis of IEEE 802.15.4 networks is designed in Martalo and Buratti (2013), collision of data, retransmission due to collision and acknowledgement are not considered. The authors in Bradai et al. (2014) have overviewed different MAC protocols including IEEE 802.15.4 to find the appropriate MAC for the wireless body area networks (WBAN). Though authors suggest suitable MAC protocol for the WBAN, no performance metric such as throughput, latency and energy consumption for the suggested MAC is studied. Though a Markov chain model is designed (Wijetunge et al., 2012) for the IEEE 802.15.4 networks under unsaturated traffic conditions, the analysis is based on for unslotted CSMA/CA MAC in non-beacon enabled protocol. Performance evaluation of IEEE 802.15.4 MAC with sleep mode is studied in Xiao et al. (2011). Though authors design an embedded discrete-time Markov queuing model, retransmission limit and acknowledgement are not considered in their model.

2.1. Contributions

In this paper, a new CSMA/CA mechanism is proposed to avoid the collision due to hidden terminals and to reduce the number of clear channel assessments. In order to reduce the number of clear channel assessments, a new communication model is designed. Besides, we have designed mathematical models to analyze the performance of the WSN taking data retransmission in absence of the acknowledgement due to collision in the medium. A three dimensional Markov chain model is designed to analyze the energy consumption and throughput of the WSN under unsaturated traffic condition. The main contributions of our work as compared to some related literature are summarized in Table 1.

3. Problem analysis

Let us consider an IEEE 802.15.4 enabled single channel star topology based WSNs in which a coordinator is attached to several wireless sensors. According to CSMA/CA mechanism of IEEE 802.15.4, each node has to compete with others for accessing the channel before transmitting data to the coordinator. Here, we analyze the carrier sensing mechanisms in IEEE 802.15.4 and the related difficulties as follows.

3.1. Existing IEEE 802.15.4 MAC mechanism

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 Fig. 1. The value of backoff exponent (BE) could be either initialized to the value of *macMinBE* or 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* cannot 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 resets *CW* to 2 and goes for backoff delay for a random number of backoff periods in the range of 0 through $(2^{BE} - 1)$ units, as shown in step 2 of Fig. 1. Then a node performs its first clear channel assessment (CCA), as shown in step 3 of Fig. 1. In a slotted CSMA/CA system, the CCA starts 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 ensures that the contention window has expired before commencing the transmission. To do this, the MAC sublayer first decrements the value of *CW* by one, as shown in step 5 of Fig. 1 and then determines whether it is equal to 0. If it is not equal to 0, the CSMA/CA algorithm returns to perform the second CCA, as shown in step 3 of Fig. 1. However, if it is equal to 0, the MAC sublayer assumes the channel access is a success and starts transmitting the frame on the boundary of the next backoff period. As per the standard, herewith the packet transmission is considered as a success and the procedure is terminated.

Upon performing the first CCA, the MAC sublayer increments the value of both *NB* and *BE* by one if the channel is assessed to be busy, ensuring that *BE* shall be no more than *aMaxBE*, as shown in step 4 of Fig. 1. If the value of *NB* is less than or equal to the variable *macMaxCSMABackoffs*, the CSMA/CA algorithm returns to step 2, as shown in Fig. 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 terminates with a *Channel Access Failure* status and notifies the next higher layer of the failure. As per the standard, herewith the packet transmission is considered as a failure and the procedure is terminated.

3.2. Problems

In the existing IEEE 802.15.4 MAC, a node assumes the medium is busy, if the measured received signal strength indication (RSSI) is higher than a prefixed threshold during clear channel assessment (*CCA*) procedure of a node. Before transmitting any data, a node has to go for the clear channel assessment twice. If a node's first clear channel assessment (CCA_1) is successful, whereas second clear channel assessment (CCA_2) is failed, it could be possible that either another node in the system is transmitting data to the coordinator or the coordinator is exchanging acknowledgement with the sender. For

Table 1
Comparison and contributions.

Features	S-MAC [Ye et al. 2004]	TRAMA [Rajendran et al. 2003]	CSMA/ p^*Tay et al., 2004	RefRasheed et al., 2014	RefMehta et al., 2009	Our Protocol
Analytical models	No	No	No	No	No	Yes
Retransmission	No	No	No	No	No	Yes
ACK Consideration	No	No	No	No	No	Yes
Collision mitigation	No	No	No	No	No	Yes
Two CCAs	Yes	Yes	Yes	Yes	Yes	No
No. of backoffs (NB)	No	No	No	No	No	Yes
Contention Window length (CW)	No	No	No	No	No	Yes
Channel usage duration	No	No	No	No	No	Yes

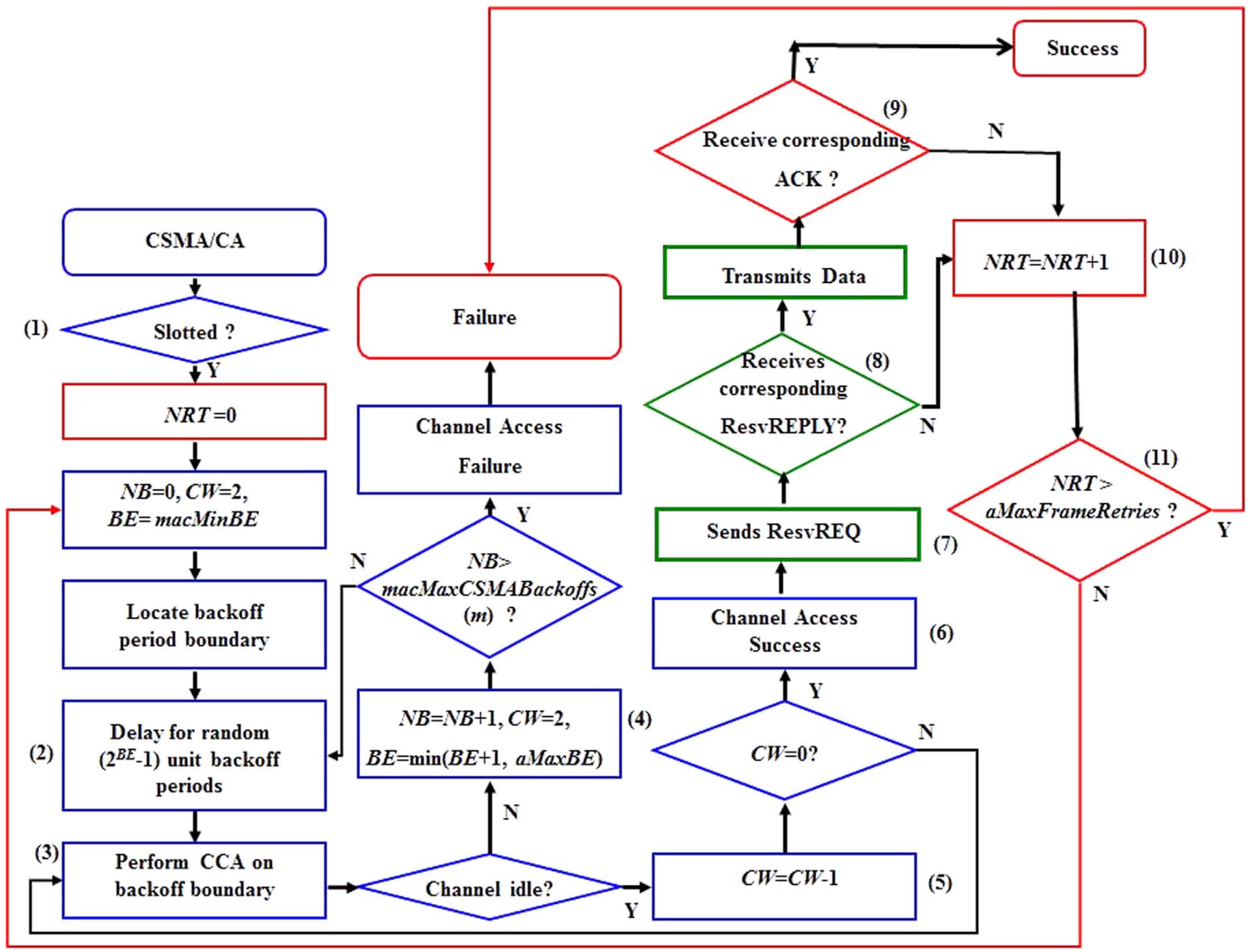

Fig. 1. Proposed IEEE 802.15.4 CSMA/CA mechanism to avoid unnecessary CCAs, but with retry limits.

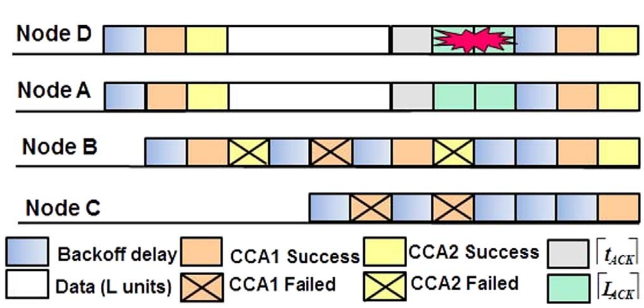

Fig. 2. Channel access mechanism by multiple nodes in IEEE 802.15.4.

example, as shown in Fig. 2, node *B* does not assess the channel busy during its first CCA as node *A* is performing its second CCA. However, node *B* senses the channel busy during its second CCA (CCA_2) as node *A* starts transmitting data to the coordinator, which is considered as a failure of CCA_2 of node *B*.

In another case, if node *B* performs its CCA_1 during the idle slot t_{ACK} of node *A*, it finds its CCA_1 is successful. But, it will sense the channel busy in its CCA_2 as the coordinator sends the acknowledgement (ACK) in slots L_{ACK}, as shown in Fig. 2. In order to consider the effect of this idle slot, integer number of slots that fit into this time is taken and therefore duration of the idle slot is taken to be $\lceil t_{ACK} \rceil$=1 slot. Since, the acknowledgement for IEEE 802.15.4 is 11Bytes long, which is slightly more than a slot, duration of $\lceil L_{ACK} \rceil$ is taken to be 2 slots. After backoff delay of node *B* and *C*, they perform their CCA_1 when node *A* is transmitting data to the coordinator and therefore their CCA_1 is failed as shown in Fig. 2. As per the standard, a node goes for the backoff delay if its CCA_1 or CCA_2 is failed and then continues to sense the channel until the value of *BE* and *NB* crosses the maximum prescribed value proposed in the standard, i.e. maximum value of BE (aMaxBE)=5 and maximum value of NB (macMAXCSMABackoffs)=4.

From the analysis, it is observed that a node has to perform either CCA_1 or CCA_2 maximum up to 5 times, if either of the channel assessments is failed. After failure of any CCA, a node has to switch to the backoff delay and returns to re-perform the CCA. We think that a node should avoid to perform its second CCA (CCA_2), if it senses the channel busy in its first CCA as either data or *ACK* transmission is going on by other nodes in the channel.

In another scenario, in case of hidden terminals, two nodes may assess the channel at the same time and can transmit data if both of their CCAs are successful. However, they cannot get the ACK as both of their data is collided. For example, as shown in Fig. 2, though CCA_1 and CCA_2 of both nodes *A* and *D* are successful, their data is collided and both nodes are unable to receive the ACK. In this case, both nodes have to go for the random backoff and repeat the CCA mechanism from the start. We think that the collision due to hidden terminals should be avoided as repetition of CCAs and retransmission of data due to collision must affect the performance of the network in terms of energy and throughput. Hence, we propose a new medium access control (MAC) mechanism for IEEE 802.15.4 enabled WSNs and analyze the performance of the network with or without collision taking retransmission limits of a node into account.

3.3. Goals

Based on our motivations, we design a new MAC mechanism within scope of the standard, which can reduce multiple clear channel assessments to improve the network throughput and minimize the power consumption. The proposed method can be implemented within the Contention Access Period (CAP) of the superframe of a node without any additional overhead on the existing superframe structure. In order to reduce the collisions, we develop a novel communication mechanism that can prevent nodes to transmit their data simultaneously. In this case, all hidden terminals get information about other competing nodes in advance and no retransmission of data is required as the network will be free from collisions.

It could be possible that a node may not receive the ACK even if no collision is there in the medium. Failure of receiving ACK may be due to interference, noise and other factors of the network. As per IEEE 802.15.4 standard, if a node is failed to receive the ACK, it can repeat the transmission procedure up to a maximum number of retry limits *(NRT)* and the packet is rejected, if the value of *NRT* exceeds the limit. Since, repetition of such transmission combined with the channel assessment procedure affects the performance of the network, we develop a three-dimensional Markov chain model.

4. System model

In our system model, each node is distributed around a central coordinator and is within its communication range. In a typical Wireless Sensor Network, since sensed data generally flow from the ordinary sensors to the coordinators, we concentrate only on the uplink data transfer method in a beacon-enabled slotted CSMA/CA taking accounts of the acknowledgements, where a device periodically listens to the network beacon. It is assumed that each node generates the data packet of uniform length of L units and tries to send to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an acknowledgment frame.

4.1. Proposed collision free MAC without retransmission

In this subsection, we propose a new MAC mechanism for the beacon enabled slotted CSMA/CA of IEEE 802.15.4 standard to reduce the number of clear channel assessments and to avoid the collision in the system due to hidden terminals. As per the standard, a node synchronizes to the superframe structure of the coordinator as soon as it receives the beacon. Within the contention access period (CAP) of the superframe, each node may compete to get the channel by performing CCA_1 and CCA_2 before sending any data. As shown in Fig. 3, we propose that a node should broadcast a reservation request (*ResvREQ*) packet indicating its channel usage duration of L units of data slots as soon as its channel access is successful. It is to be noted that a node has to go for a short random backoff period after its channel access is successful and before broadcasting the *ResvREQ* packet. Then, the coordinator broadcasts a reservation reply (*ResvREPLY*) packet indicating the channel occupancy of $L + 3$ slots so that other nodes who are still trying to assess the channel or their channel access is already successful, stop sending the data packet in order to avoid any collision and the subsequent retransmissions. Since, $\lceil t_{ACK} \rceil$ =1 slot and $\lceil L_{ACK} \rceil$=2 slots, $L + 3$ slots are used to reserve the channel. This new handshaking procedure can be done in certain mini control slots following CCA_2 of a node as shown in Fig. 3.

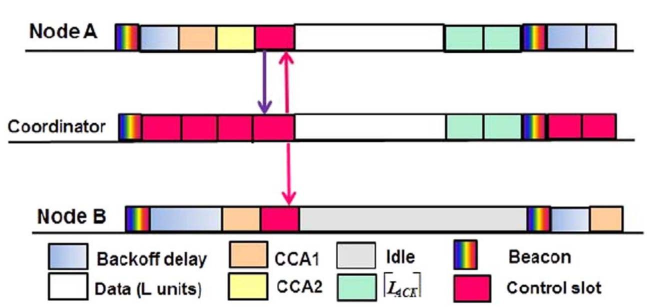

Fig. 3. Proposed communication model to avoid unnecessary carrier sensing.

Upon receiving the *ResvREPLY* packet, a sender has to transmit its data to the coordinator whose receipt is confirmed by getting the *ACK*. As shown in step 6 of Fig. 1, if both CCAs of a node are successful, it sends the *ResvREQ* packet to the coordinator as given in step 7 of Fig. 1. If the node receives the corresponding *ResvREPLY* packet from the coordinator, it transmits data as shown in step 8 of Fig. 1. However, if it does not receive *ResvREPLY* packet, it assumes collision in the channel and goes for the data retransmission as given in the following subsection. It is to be noted that the proposed communication mechanism can be executed within the CAP, which lies within the beacon period of a superframe. We suggest that a node should sense the channel busy during the exchange of *ResvREQ* and *ResvREPLY* packet and duration of each such packet can be considered to be one mini slot. If a node senses the channel busy during its CCA_1, it should listen to the channel immediately in the next mini slot instead of going for the backoff delay.

By doing so, the node can receive the *ResvREPLY* message broadcast by the coordinator and therefore can get information about the channel busy duration. However, if no *ResvREPLY* message is received in that slot (immediate slot after the slot used for its CCA_1), it must conclude that its CCA_1 is performed during the idle slot t_{ACK} of another node. Hence, listening to the channel will be useless as *ACK* will be exchanged by the coordinator and therefore a node should go for the random backoff as usual. Similarly, if a node senses the channel busy in its CCA_2, it is proposed that the node should listen to the channel immediately in the next slot instead of going for the backoff delay and performs CCA_1 subsequently. However, if that node does not receive the *ResvREPLY* message in this slot, it infers that its CCA_1 has performed during the idle slot t_{ACK} of another node and its CCA_2 has failed as exchange of *ACK* is going on. Hence, a node may go for the backoff delay and starts performing the CCA_1 as per the standard.

4.2. Proposed MAC mechanism with retransmission

As described in the previous subsection, it is shown that there will be no collision in the medium as no two nodes can transmit data at the same time. However, it is assumed that a sender may fail to receive the acknowledgment due to interference or noise in the medium and can go for the retransmission. In this case, we suggest that a node can go for the retransmission procedure as described in the standard. As per the standard, if a single transmission attempt is failed for not receiving the acknowledgment, the device shall repeat the process of transmitting the data and waits for the acknowledgment up to a maximum of *aMaxFrameRetries* times (according to the standard, value of *aMaxFrameRetries* can be considered up to 3), which is the maximum number of retransmission times *(NRT)*. If an acknowledgment is still not received after *aMaxFrameRetries* retransmissions, MAC sublayer assumes the transmission is failed and the situation is eventually referred to as a communications failure.

If retransmission mechanism is considered, the existing channel access mechanisms of the standard should be extended by considering the number of retransmission times (NRT) that incorporates the channel re-accessing mechanism due to loss of an acknowledgement. In a slotted CSMA/CA of IEEE 802.15.4, though the CSMA/CA algorithm may terminate with a channel access success status, we do not consider the data transmission is a success, unless the sender receives the acknowledgement. Accordingly, in our retransmission based channel access mechanism, a sender goes to step 9 of Fig. 1 to check if the corresponding acknowledgement (ACK) is received on time or not. If receiving ACK is true, packet transmission is considered as a success, otherwise value of *NRT* is incremented by 1, as shown in step 10 of Fig. 1 and the sender compares its *NRT* value with the value of *aMaxFrameRetries*. As shown in step 11 of Fig. 1, if value of *NRT* is less than *aMaxFrameRetries*, it goes to step 1 of Fig. 1 and follows the CSMA/CA mechanism to re-access the channel, otherwise the whole data transmission procedure is considered as a failure.

5. Analytical models

In our analytical models, it is assumed that *N* number of nodes are attached to a coordinator and transmission from any node to the coordinator is allowed, i.e we analyze the performance of the uplink traffic only.

5.1. Proposed Markov chain model

To analyze performance of the packet transmission probability of IEEE 802.15.4 based wireless sensor network, we propose a discrete time three-dimensional Markov chain model, as depicted in Fig. 4. For a given node, we define the stochastic process $s(t)$ that represents the backoff stage for the first random variable *NB*. The stochastic process $c(t)$ represents the backoff counter for the second random variable *CW*. The stochastic process $r(t)$ represents the retransmission counter for a given value of *NRT*, which can be varied between 0 through 3. The processes $s(t)$, $c(t)$, and $r(t)$, which define the state of a device at the backoff unit boundaries, are shown in Fig. 4. Let

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

where, $j \in \{0, 1, \ldots, m\}$, $x \in \{-2, -1, \ldots, W_j - 1\}$, $k \in \{0, 1, \ldots, aMaxFrameRetries\}$, 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. It is to be noted that till dates in all of the works it is assumed that the node enters to the transmission state after CCA_1 and CCA_2 are successful. However, in our model, a node is considered to be in transmission state $S_{j,-2,k}$, only if it receives the

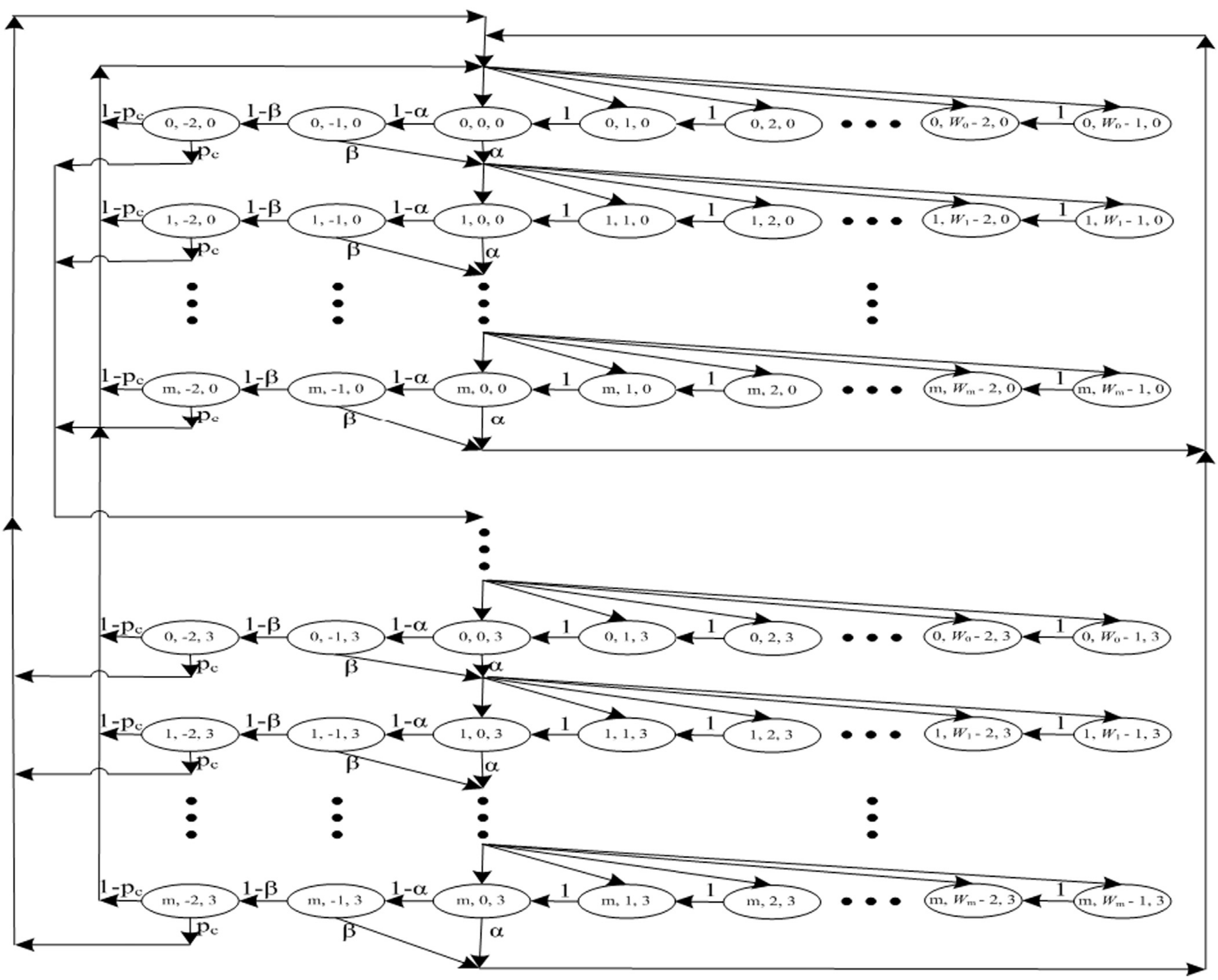

Fig. 4. Our Markov chain model based on retransmission policy of IEEE 802.15.4.

acknowledgement successfully, which may happen due to absence of collision in the channel. In our model, if channel is idle during both CCAs, but collision occurs during the transmission attempts, a node increases the value of its *NRT* and again goes to the channel assess procedure.

5.2. Channel assess probability

As mentioned earlier, $c(t)$ is the stochastic process representing the backoff counter for a given station. 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 Fig. 4 and the corresponding transition probabilities can be formulated as follows:

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

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

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

$$P(0, x, 0|macMaxCSMABackoff, 0, k) = \frac{\alpha}{W_0}, for \begin{cases} 0 \le x \le W_0 - 1 \\ 0 \le k \le aMaxFrameRetries \end{cases} \quad (4)$$

Eq. (1) is the condition to decrease the backoff counter 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 Eqs. (2) and (3). Eq. (2) accounts for the fact that the node goes to the second channel assessment CCA_2 following the successful first channel assessment. Eq. (3) accounts for the unsuccessful CCA_1. In particular, as considered in Eq. (3), 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. Eq. (4), models the fact that once the backoff stage reaches at the value of *macMaxCSMABackoffs*, it is not increased in subsequent packet transmissions. $P(j, -2, k|j, -1, k) = 1-\beta$,

$$for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le k \le aMaxFrameRetries \end{cases} \quad (5)$$

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

$$P(0, x, 0|macMaxCSMABackoff, -1, k) = \frac{\beta}{W_0}, for \begin{cases} 0 \le x \le W_0 - 1 \\ 0 \le k \le aMaxFrameRetries \end{cases} \quad (7)$$

Eqs. (5) and (6) model the probability of successful and unsuccessful second clear channel assessment (CCA_2), respectively. Eq. (5) models the fact that a node goes to the packet transmission state following a successful CCA_2. Eq. (6) 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, Eq. (7) 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.

5.3. Packet retransmission probability

If acknowledgement of a transmission is not received on time, there is packet retransmission as described in Section 4.2 of Section 4. In this case, a node restarts the channel assessment until the value of the retransmission counter is greater than *aMaxFrameRetries*. Accordingly, Eqs. (8) and (9) model the system for receiving the successful and unsuccessful acknowledgements, respectively. As given in Eq. (8), 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 Eq. (9). Eq. (10), 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). However, Eq. (8) through 10 are replaced by the collision probability $p_c = 0$, if the MAC mechanism without retransmission is considered as described in Section 4.1 of Section 4.

$$P(0, x, 0|j, -2, k) = \frac{1-p_c}{W_0}, for \begin{cases} 0 \le j \le macMaxCSMABackoffs \\ 0 \le x \le W_0 - 1; 0 \le k \le aMaxFrameRetries \end{cases} \quad (8)$$

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

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

$$W_j = 2^{min(j+macMinBE, aMaxBE)}, j \in \{0, 1, \ldots, m\} \quad (10)$$

5.4. Conditional channel access probability

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 Eq. (11).

$$\tau = \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,0,k} \quad (11)$$

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.

$$\alpha = \{(1-p_c)(\lceil T_L \rceil + \lceil T_{ACK} \rceil) + p_c \lceil T_L \rceil\}(1-\beta) \times \{1 - [1-\tau(1-p_0)]^{N-1}\}(1-\alpha) \quad (12)$$

Where p_0 is 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. 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, $\beta = P(M_{CCA_2}(s) = -1 | M_{CCA_1}(s) \geq 0)$

$$= \left[\frac{\frac{\{1-[1-\tau(1-p_0)]^N\}(1-\alpha)(1-\beta)}{1-[1-\tau(1-p_0)]^N}}{\{1-[1-\tau(1-p_0)]^{N-1}\}(1-\alpha)(1-\beta) + \frac{\{1-[1-\tau(1-p_0)]^N\}(1-\alpha)(1-\beta)}{1-[1-\tau(1-p_0)]^N}} \right] \times \{1-[1-\tau(1-p_0)]^{N-1}\} \quad (13)$$

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

$$D_1 = (1-\alpha)(1-\beta)\cdot p_c \quad (14)$$

$$D_2 = (1-\alpha)\beta + \alpha \quad (15)$$

However, if our proposed protocol of MAC mechanism without retransmission is considered, Eqs. (12) and (14) will be replaced by $p_c = 0$ as no collision in the medium is taken into account.

5.5. Steady state probability

It is to be noted that the network parameters $j \in \{0, 1, \ldots, m\}$, $x \in \{-2, -1, \ldots, W_j - 1\}$, $k \in \{0, 1, \ldots, aMaxFrameRetries\}$, affect performance of the network, where m represents the *macMaxCSMABackoffs* and $W_j = 2^{min(j+macMinBE, aMaxBE)}$. Hence, the closed-form solution for the steady-state probabilities based on our Markov chain model are given as follows: $S_{0,0,k} = \left[\frac{D_1(1-D_2^{m+1})}{1-D_2}\right]^k S_{0,0,0}$, $for 0 \leq k \leq aMaxFrameRetries$ (16)

$$S_{j,0,k} = D_2^j S_{0,0,k}, \; for \begin{cases} 0 \leq j \leq \; macMaxCSMABackoffs \\ 0 \leq k \leq \; aMaxFrameRetries \end{cases} \quad (17)$$

$$S_{0,x,0} = \frac{W_0 - x}{W_0} \left\{ \sum_{j=0}^{macMaxCSMABackoffs} (S_{j,-2,aMaxFrameRetries} \cdot p_c) + \sum_{k=0}^{aMaxFrameRetries} \sum_{j=0}^{macMaxCSMABackoffs} [S_{j,-2,k} \cdot (1-p_c)] + \sum_{k=0}^{aMaxFrameRetries} S_{macMaxCSMABackoffs,0,k} \cdot \alpha + \sum_{k=0}^{aMaxFrameRetries} S_{macMaxCSMABackoffs,-1,k} \cdot \beta \right\}, \; for \; 0 \leq x \leq W_0 - 1 \quad (18)$$

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

$$S_{j,-2,k} = (1-\alpha)(1-\beta)\cdot S_{j,0,k}, \; for \begin{cases} 0 \leq j \leq \; macMaxCSMABackoffs \\ 0 \leq k \leq \; aMaxFrameRetries \end{cases} \quad (20)$$

$$S_{j,x,k} = \frac{W_j - x}{W_j S_{j,0,k}}, \; for \begin{cases} 0 \leq j \leq \; macMaxCSMABackoffs \\ 0 \leq x \leq \; W_j - 1; \; 0 \leq k \leq \; aMaxFrameRetries \end{cases} \quad (21)$$

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

$$1 = \sum_{j=0}^{macMaxCSMABackoffs} \sum_{x=0}^{W_j-1} \sum_{k=0}^{aMaxFrameRetries} S_{j,x,k} + \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,-2,k} + \sum_{j=0}^{macMaxCSMABackoffs} \sum_{k=0}^{aMaxFrameRetries} S_{j,-1,k} \quad (22)$$

However, by considering our proposed MAC mechanism without retransmission, Eq. (18) can be replaced with $p_c = 0$.

6. Performance analysis

In this section we use our analytical models to study the throughput and energy consumption issues of sensors under unsaturated traffic condition by taking a fixed delay of 100 slots before going into the first delay stage and after sending the previous packet.

6.1. Throughput analysis

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.

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

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,

$$p_s = \frac{(1-\alpha)(1-\beta)N \times (1-p_0)\tau[1-(1-p_0)\tau]^{N-1}}{p_{tr}} \quad (24)$$

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.

$$S = \frac{p_s p_{tr} T_{pl}}{(1-p_{tr})\sigma + p_{tr} p_s T_s + p_{tr}(1-p_s) T_c} \quad (25)$$

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 Eqs. (26) and (27), respectively.

$$T_s = 2\lceil T_{CCA} \rceil + \lceil T_L \rceil + \lfloor \delta \rfloor + \lceil T_{ACK} \rceil \quad (26)$$

$$T_c = 2\lceil T_{CCA} \rceil + \lceil T_L \rceil + \lfloor \delta_{max} \rfloor \quad (27)$$

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 2.4 GHz 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.

6.2. Energy consumption analysis

In this section, we have analyzed the normalized energy consumption, which is the average energy consumption to transmit one slot amount of payload. For each successful transmission or reception of a packet, we consider the duration of each successful channel assessment (T_{CCA}) and the packet turnaround time. Considering 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.

$$E = \frac{\tau\alpha T_{CCA} P_{RX} + \tau(1-\alpha)\beta \times 2T_{CCA} P_{RX}}{\tau(1-\alpha)(1-\beta)p_s T_{pl}} + \frac{\tau(1-\alpha)(1-\beta)[(1-p_s)E_c + p_s E_s]}{\tau(1-\alpha)(1-\beta)p_s T_{pl}} \tag{28}$$

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 Eqs. (29) and (30), respectively.

$$E_s = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} + T_{ta}P_{ta} + \delta_{max}P_{RX} \tag{29}$$

$$E_c = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} + T_{ta}P_{ta} + (\delta - T_{ta} + T_{ACK})P_{RX} \tag{30}$$

7. Performance evaluation

In this section, we validate our models by comparing the analytical results with the simulation one. Our simulation is performed using NS-2, in which all nodes form a star topology with a radius of 3 m with one coordinator at the center and other nodes are evenly distributed around it. The transmission range of the transceiver is taken to be 7 m. The packet size is 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 considered to be 127 bytes.

7.1. Model validation

In order to validate our model, we consider the beacon frames as the control frames to keep the network working. We use the default parameter values such as 3, 5, 4 and 3 for *macMinBE, aMaxBE, macMaxCSMABackoff* and *aMaxframeRetries*, respectively as defined in 2.4 GHz frequency channels. Fixed number of nodes are attached to the coordinator and a node transmits fixed size of packets of 10, 50 or 100 bytes each time. Thus, to validate our model, we have compared the simulation and analytical results for different data rates, as shown in Figs. 5, 6 and 7. As shown in Fig. 5, the throughput is evaluated for different data rates and it is found that the analytical result quite matches with the simulated one. As shown in Fig. 6, validation of analytical and simulation results for energy consumption is presented. It is observed that the energy consumption gradually reaches to a saturated value with increase in the data rates as capacity of the network is limited. The packet delivery ratio that is defined as the percentage of the ratio of the number received packets to the number of the sent packets is validated as shown in Fig. 7. The packet delivery ratio is validated for the analytical with our simulation results for different data rates taking different size of the data packets. As shown in the figure, our analytical results very well match with the simulation.

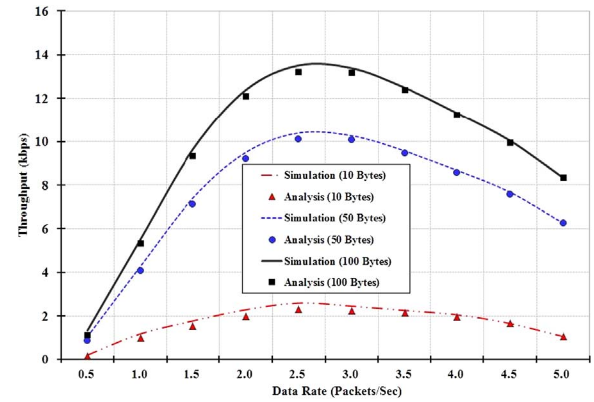

Fig. 5. Validation of throughput for different data rates.

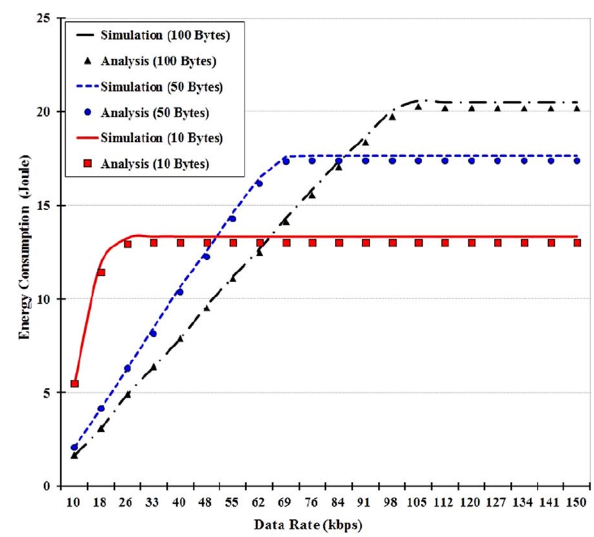

Fig. 6. Validation of energy consumption for different data rates.

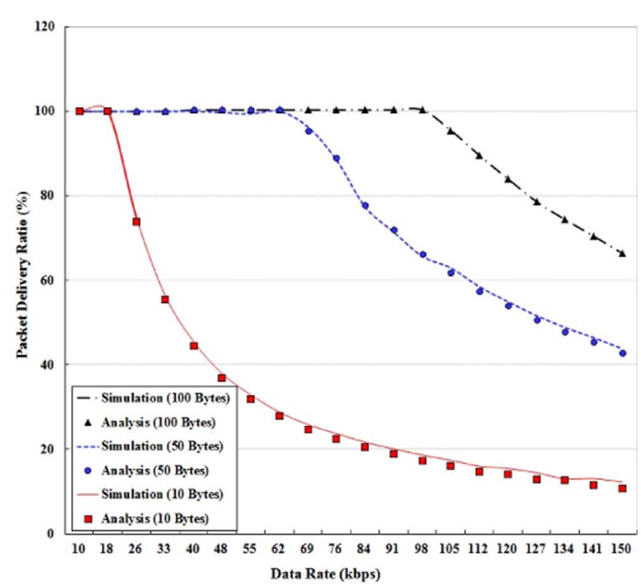

Fig. 7. Validation of packet delivery ratio for different data rates.

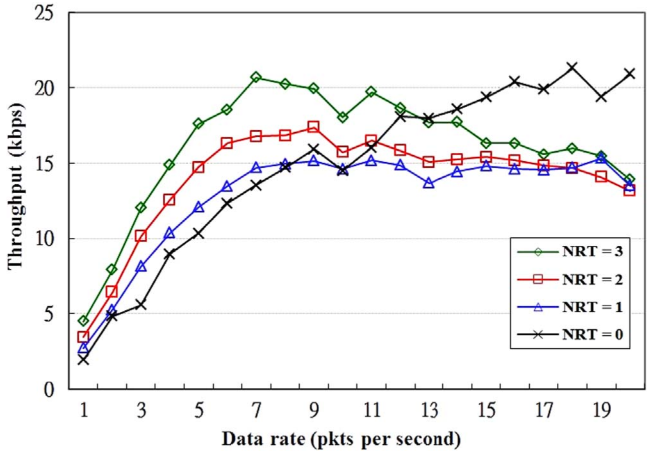

Fig. 8. Throughput for different values of NRT.

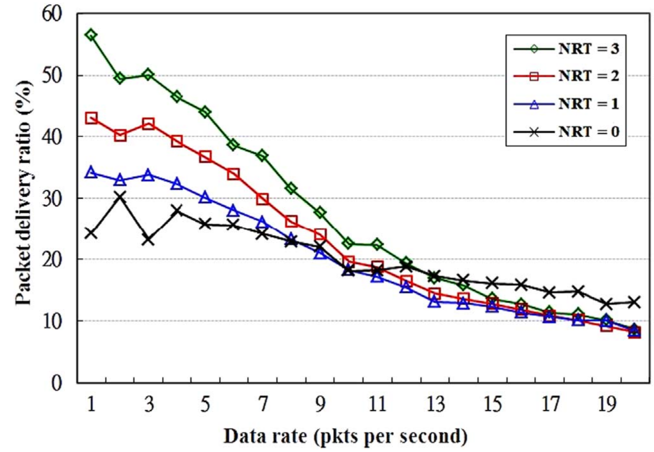

Fig. 10. Packet delivery ratio for different values of NRT.

7.2. Evaluation of our protocol

In this section, we evaluate our protocol under unsaturated traffic conditions and the results with event based simulation. The unsaturated case reflects a scenario with periodic monitoring intervals, where all nodes do not generate packets at the same time and thereby do not have packets to transmit. This reflects the unsaturated traffic condition, as assumed in our model. In order to simulate our protocol in an environment with or without collision, we use different values for the number of retransmissions (NRT). If there is no collision in the system, a node does not need to retransmit the packet as the packet transmission is assumed to be successful. Accordingly, the value of NRT=0 in our simulation, if there is no collision in the system. However, the value of NRT is taken to be 1, 2 or 3 in case of collision in the network. A node has to retransmit a packet due to collision and a node has to retransmit the packet twice or thrice that corresponds to the value of NRT=2 or 3, if the retransmission is failed again due to repetition of collision. It is to be noted that the maximum value of NRT=3 according to IEEE 802.15.4 MAC mechanism, which is considered in our simulation.

As the number of retransmissions is the new concept introduced in our models, we have evaluated the throughput, energy consumption and packet delivery ratio for different values of NRT as shown in Figs. 8, 9 and 10, respectively for different data rates (packets/sec). From Fig. 8, it is observed that the throughput with NRT value equal to 3 is higher than others when the data rate is less than 13 pps (packets per second). 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 Fig. 9. 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. In Fig. 10, we can see that the packet delivery ratio decreases dramatically for NRT equal to 1, 2 or 3. The dropped packets will not be retransmitted while NRT is equal to 0. For this reason, when the data rate is lower (less than 13 pps), the packet delivery ratio is lower for NRT equal to 0. The retransmission makes the data rate increasing.

7.3. Comparison of our protocol

In order to compare the performance of our protocol with similar protocols, we have simulated our protocol, S-MAC (Ye et al., 2004), TRAMA (Rajendran et al., 2003) and CSMA/p^*(Tay et al., 2004) in terms of throughput, average energy consumption and packet delivery ratio for different number of nodes and data rates as shown in Fig. 11 through Fig. 16. We have compared our protocol with S-MAC (Ye et al., 2004) as it is a well known medium access control protocol for the sensor networks. Since, TRAMA (Rajendran et al., 2003) is an energy efficient collision free MAC protocol for the WSN and our protocol analyzes the energy consumption with or without collision in the medium, we have compared our protocol with it. We have considered

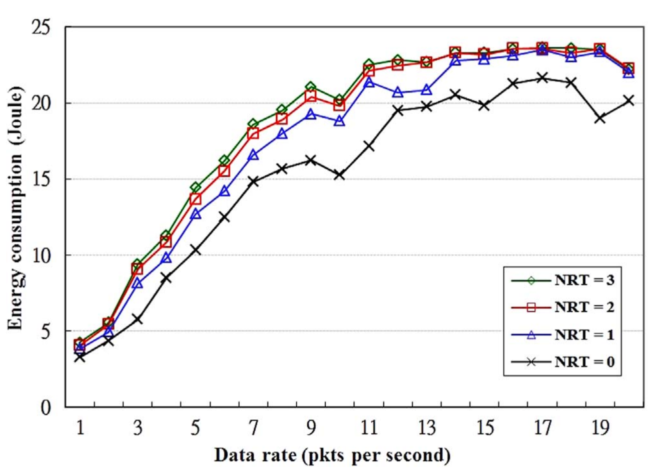

Fig. 9. Energy consumption for different values of NRT.

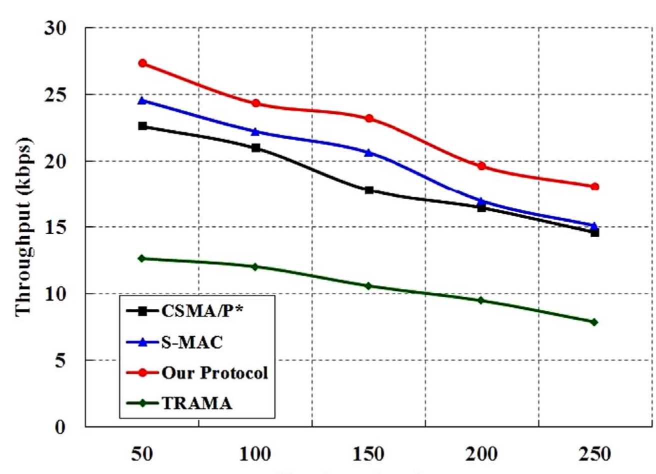

Fig. 11. Comparison of throughput for different number of nodes.

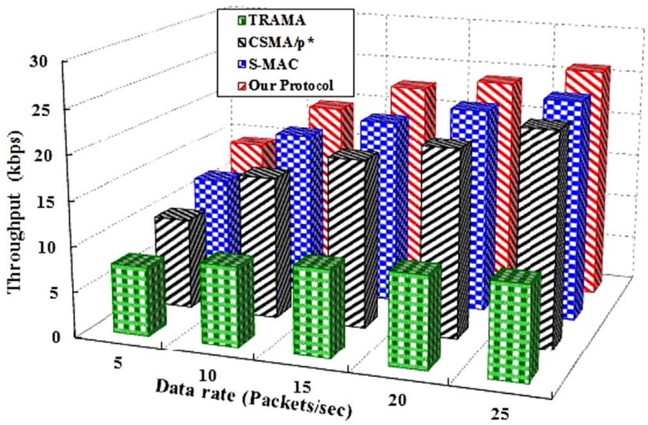

Fig. 12. Comparison of throughput for different data rates.

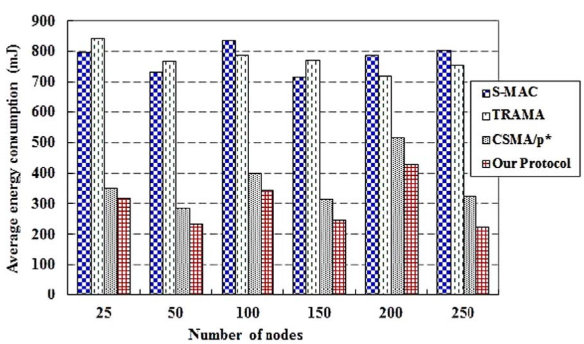

Fig. 13. Comparison of energy consumption for different number of nodes.

CSMA/p^*(Tay et al., 2004) to compare with our protocol as they propose to reduce the collision and thereby to improve the energy consumption and throughput.

The throughput for different number of nodes is simulated as shown in Fig. 11. It is observed that our protocol outperforms over other protocols though it decreases with increase in the number of nodes. Since, our CSMA/CA protocol can avoid the collisions, its performance is better as compared to others. As shown in Fig. 12, throughput of all protocol is increased with increase in the data rates. The throughput of S-MAC is better than other protocols as the time synchronization overhead is prevented with sleep schedule announcements, which enables the smooth transmission of data. However, our protocol gives better performance over others as it can reduce the number of collisions due to our proposed backoff mechanism. The average energy consumption of our protocol for different number of nodes is compared with others as shown in Fig. 13. Though energy

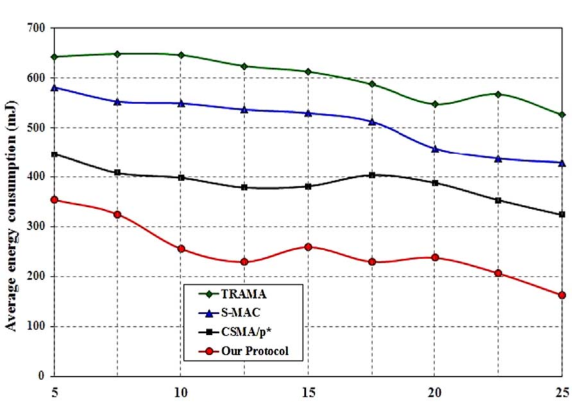

Fig. 14. Comparison of energy consumption for different data rates.

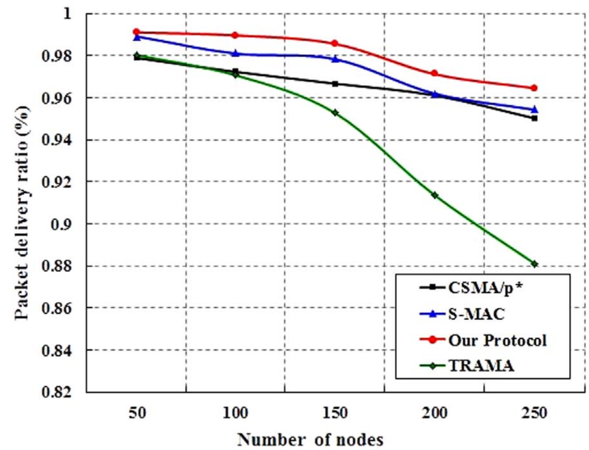

Fig. 15. Comparison of packet delivery ratio for different number of nodes.

consumption of our protocol is lowest as compared to others due to minimum number over hearings, TRAMA performs the worst as compared to S-MAC and CSMA/p^* as it is not energy efficient.

Average energy consumption for different data rates is simulated as shown in Fig. 14. Average energy consumption of CSMA/p^* is better then S-MAC and TRAMA as it can achieve very low latency for different data rates. But, our protocol shows the best performance as idle listening caused by listening to all slots before sending data is minimized. Moreover, numbers of CCAs in our protocol are less than all other protocols, which is another reason for the minimum energy consumption. As shown in Fig. 15, packet delivery ratio in TRAMA drastically decreases with increase in the number of nodes, which is due to the long waiting time because of the longer duty cycle. However, our protocol can outperforms over all other protocols as there is less numbers or no collision along with shortest duty cycle is considered. The packet delivery ratio in CSMA/p^* and S-MAC is almost same as depicted in Fig. 16, since both of them maintain similar form of collision avoidance mechanism. However, packet delivery ratio of our protocol is better than the rest protocols though it remains almost same even if the data rate is increased. It could be due to few collisions in the system that reduces the packet delivery ratio in spite of increase in data rates.

8. Conclusion

In this paper, a beacon-enabled slotted CSMA/CA with acknowl-

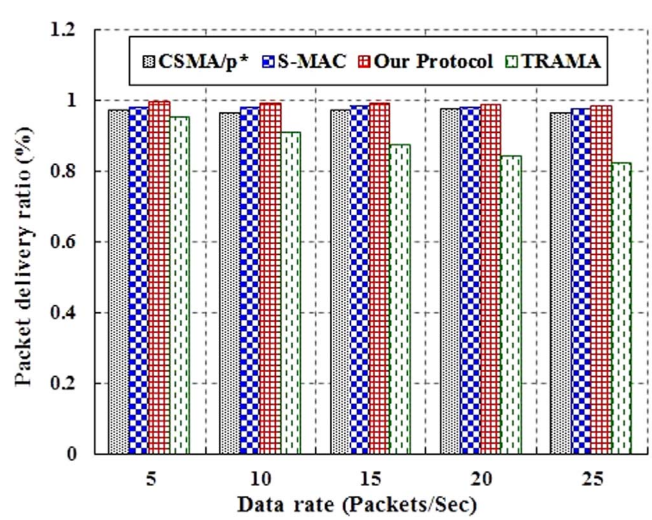

Fig. 16. Comparison of packet delivery ratio for different data rates.

edgement of IEEE 802.15.4 based Wireless Sensor Network is considered and analytical models are developed to study the throughput and energy consumption of the network under unsaturated traffic condition. In order to reduce the number of clear channel assessments, a new communication model is proposed. An extension to the existing CSMA/CA mechanism with number of retransmission limits is proposed and a three-dimensional Markov chain model is developed. Simulation results show that the standard is suitable for the low data rate transmission rather than higher data rates. It is observed that we should make the payload size as large as possible in order to get better throughput. Since throughput of the network is reduced for several retransmissions with higher data rates, it is concluded that retransmission of collided packets could be considered for the network of lower data rate such as wireless sensor networks.

Acknowledgements

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