AN ANALYTICAL MODEL OF CONTENTION IN WIRELESS SENSOR NETWORKS USING TREE ROUTING

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Abstract - Presently, the focus of current research on Wireless Sensor Networks (WSNs) is predominantly on contention at the MAC layer, overlooking the traffic characteristics of upper-layer traffic, especially the interaction with the routing traffic. Hence, balancing network adaptation and data throughput is critical in WSN deployments. This paper introduces an analytical model to assess collision probabilities, applicable for evaluating the effectiveness of WSNs using tree routing protocols. It examines collision probabilities across various types of traffic load, including routing and data traffic, highlighting their interconnected influences. The model also employs practical parameters like routing information forwarding rate, acknowledgments, and data rate to enhance applicability. Validation through simulation demonstrates strong alignment between the analytical and simulated results, suggesting the model's efficacy in pre-deployment evaluations of WSN applications. This leads to the belief that the model can be a suitable candidate to evaluate the network performance before deploying WSN applications.

Key words - Wireless Sensor Networks; MAC; tree routing, contention.

1. Introduction

In a free space, a radio channel is shared by many nodes of a wireless network. However, this medium cannot be concurrently accessed by two or more nodes, as the transmission from one node may lead to conflicts or collisions at another node(s). Considering the energy perspective in WSNs, collisions negatively impact overall performance, reducing channel capacity due to corrupted packets and resulting in energy wastage as neighboring nodes engage in idle listening.

Two common strategies that address the challenge of facilitating efficient channel access for multiple nodes in WSNs are CSMA and TDMA. The TDMA approach solves channel access issues by implementing a schedule of timeslots, ensuring contention-free transmission for all network nodes. However, TDMA faces various drawbacks, such as challenges with timing synchronization and the assignment of effective time slots. To address these issues, several research works [1 - 3] have promoted global time synchronization, and a distributed TDMA approach is proposed [4] to alleviate these limitations, improving the practicality of TDMA for WSNs. On the other hand, the CSMA approach is commonly used in WSNs because of its simplicity. Nodes in contention employ a random backoff period, checking the channel activities and transmitting data if it is idle. If the radio channel is considered busy, the nodes repeat the process. The CSMA protocol at the MAC layer provides several benefits, such as simplicity, flexibility, and resilience, enabling nodes to join or leave the network effortlessly without additional procedures.

In WSNs, there are two main routing paradigms: tree routing (proactive) and reactive routing. Tree routing protocols [5 - 8] are more commonly used due to their various advantages, such as adaptability to node mobility and their suitability for many-to-one data collection applications. Under tree routing, WSNs generate two types of traffic patterns including routing traffic and data traffic.

Up to now, analyses of Medium Access Control (MAC) protocols have not explored the impact of collisions between traffic types (data and routing). Consequently, networks utilizing tree routing are often not optimally configured, potentially resulting in suboptimal performance for data transmission.

To bridge this gap, this paper introduces an analytical model for collision probability analysis in WSNs employing tree routing. The model incorporates considerations for acknowledgment transmissions and the routing flooding issue. Additionally, the individual and mutual probabilities of these two kinds of traffic are also investigated.

2. Background and related works

In the field of WSNs, various MAC protocols [9 - 15] have been studied and implemented. A stochastic model proposed in [16] assesses the performance of these MAC protocols. Additionally, the analysis of CSMA/CA protocol for ZigBee networks is investigated in [17], taking energy considerations into account. The evaluation of MAC protocols in unsaturated conditions [18, 19] explores the impact of sampling rates on collisions and throughput. Several evaluations of MAC protocols are carried out by simulations [20 - 22].

In [23] the analysis of interference in data collection service is proposed and validated. Moreover, in [14, 15] investigation on Radio Duty-Cycling protocols and improvements are studied and proposed to enhance the network performance using pipeline forwarding with validation from simulations and experiments.

However, these research efforts lack a comparison with the commonly used CSMA/CA protocol in real WSNs. Furthermore, the exploration of the trade-off between node adaptation and data traffic is notably absent. Therefore, this paper employs a cross-layer design to evaluate WSN traffic patterns, aiming to align with the traffic configuration of operational WSNs. The proposed model seeks to analyze the collision aspects of CSMA/CA protocols used in WSNs, considering the configuration of tree routing and periodic data transmission commonly employed in real-world WSNs.

3. Proposed analytical model of collision probabilities

3.1. Tree routing

In the configuration of most WSN applications, a network is formed with one or more root nodes (or sinks) and numerous sensor nodes. The role of the root node is to gather data packets from the sensor nodes. Currently, there are two common approaches to routing in WSNs: proactive and reactive. Reactive routing (e.g. TinyAODV) can reduce the routing overhead by only requesting the path to the root when it needs a path to send data packets to the root. In contrast, proactive routing (which tree routing belongs to) allows the root node to broadcast periodic beacons to signal routing information from the root to the network, establishing a collection tree. Tree routing updates the topology faster if any frequent changes happen inside the network (e.g. node may leave the network, node movement, or link broken due to weak received signal strength).

When receiving a beacon from a neighbor using tree routing (Figure 1a), each node will update its local database (e.g. neighbor management table) and then rebroadcast the new beacon with updated local information to other neighbors. Several parameters are exchanged between nodes such as RSSI, LQI, and ETX [5, 8].

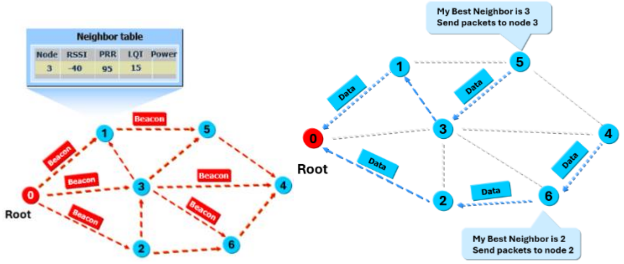

Figure 1. *a) Principle of establishment of routing tree*
b) Data collection using tree routing

Once the tree database is constructed, each sensing node transmits its packets to the root (Figure 1b) via its best neighbor node using multi-hop communication. The relationship between beacon and data rates impacts network performance. A higher beacon rate enables the network to adapt well to network topology changes; however, it may increase collisions and reduce the data packet reception rate. Investigating the influence of these factors can aid in optimizing network performance. Furthermore, in tree routing, the exchange of beacons occurs over time, regardless of whether nodes are transmitting their data packets or not.

In this paper, the proposed model focuses on WSNs using tree routing because this routing is the most popular routing approach used in practical applications (CTP [5], DSDV [6], RPL [8], Mint-Route [24], HYDRO [25]).

3.2. Assumptions

In this section, the collisions are now examined to discover the influence on the data and routing traffic to propose an analytical model for evaluation and comparison of the contention in WSNs. In this model, each node performs an initial backoff time before transmitting a packet. If the node detects the radio channel is busy using CCA, it immediately receives the packet (either a beacon or data packet) and suspends its backoff timer. Once the packet reception is complete, the node retains the suspended backoff timer to re-enter the channel access competition and send its packet. In addition, a fixed window of *CW* slots is used to randomly select the backoff period.

Theoretically, it is assumed that each contention slot *i* within the *CW* slots can exist in one of three states:

- The collision during this slot *i* is caused by the backoff mechanism or the hidden node problem.
- When slot *i* is not chosen, this slot is considered as idle.
- Data is successfully transmitted in this slot *i*.

Thus, if P_{c}, P_{i}, and P_{d} respectively represent the probabilities of slot *i* in each of the three states mentioned above, it is evident that:

$$P_i + P_c + P_d = 1 \tag{1}$$

When the radio channel is identified as busy, each node selects a backoff time within the range of [0, *CW*]. The *CW* represents the backoff window (or contention window) in CSMA, as illustrated in Figure 2.

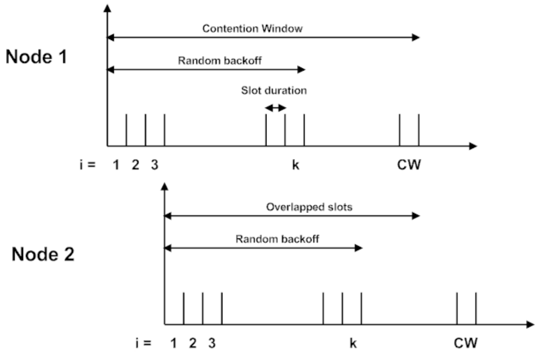

Figure 2. *Random backoff mechanism*

3.3. Effective contention window

During the competition phase for radio channel access, nodes can initiate backoff at different slots (as shown in Figure 2); thus, the number of overlapping contention slots between at least two nodes (which leads to collisions) may be less than CW. This count of overlapping slots (referred to as the random variable *X*) can vary anywhere within the range of [0, *CW*], following a uniform distribution over the observed time. The average of *X* represents the effective contention window among nodes when their starting backoff times differ. Gradually, the average of random variable *X* will approach the effective contention window CW_{eff}. Therefore, given the uniform distribution of *X* within the range [0, *CW*], the average number of overlapping contention slots (or effective contention window) among nodes can be approximated as follows:

$$CW_{eff} = E(x) = \sum_{i=0}^{CW} x_i \,.\, P(x = x_i) = \sum_{i=0}^{CW} x_i . \frac{1}{CW} \approx \frac{CW}{2} \qquad (2)$$

To simplify the model, it is assumed that other nodes compete for channel access within this effective collision window. Figure 3 shows the effective collision window estimation of overlapped slots with the contention window (*CW*) of 32 slots.

At this point, each node must occupy one slot within the effective contention window (having CW_{eff} contention slots). Since the effective contention window is fixed based on formula (2), and the probability of selecting a slot within it follows a uniform distribution, the probability of successfully choosing one slot among the CW_{eff} slots is determined as $1/CW_{eff}$. Furthermore, when each node has (N-1) neighboring nodes, P_i represents the probability that this slot is not occupied by any of the N nodes, as determined by the following formula:

$$P_i = (1 - \frac{1}{CW_{eff}})^N \qquad (3)$$

Similarly, the probability of successfully transmitting data (P_d) occurs when a node selects a contention slot while other nodes have different slots. Since data transmission can occur with N nodes, this probability is determined using the formula below:

$$P_d = \sum_{N} \frac{1}{CW_{eff}} .(1 - \frac{1}{CW_{eff}})^{N-1} = \frac{N}{CW_{eff}} .(1 - \frac{1}{CW_{eff}})^{N-1} \qquad (4)$$

From the equation system (1), (3), and (4), the probability of collision P_c can be obtained.

Furthermore, in the commonly used CSMA/CA MAC protocol [12, 13] which is usually used in practical design, the backoff is determined by a backoff exponent (BE) using the following: $CW = (2^{BE} - 1)$ [26].

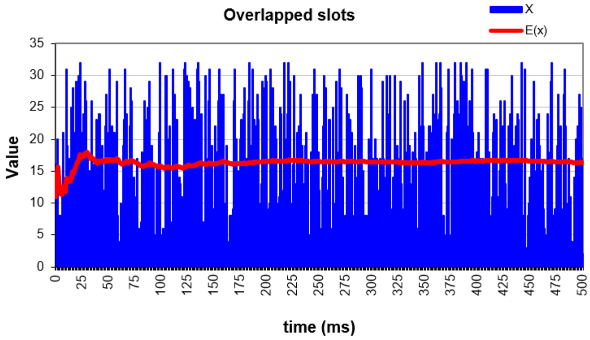

Figure 3. *Convergence of effective contention window*

3.4. Individual and mutual collision probabilities

It is important to note that collisions can occur with both data and routing traffic (beacons). Additionally, both beacons and data packets utilize the same frame in the MAC layer. Therefore, the total collision probability P_c is calculated as follows:

$$P_c^d + P_c^b + P_c^{d|b} + P_c^{b|d} = P_c \qquad (5)$$

where:

- P_c^d and P_c^b are the individual collision probabilities of only data and only beacon traffic respectively.
- $P_c^{d|b}$ is the mutual collision probability of data packets caused by beacons transmission and $P_c^{b|d}$ is the mutual collision probability of beacons caused by data packets transmission. However, beacon forwarding typically occurs at the start of each beacon interval, while data transmissions are distributed throughout the beacon period. As a result, the mutual collision probabilities can be ignored. Hence, (5) can be approximated to the following formula:

$$P_c^d + P_c^b = P_c \qquad (6)$$

In this approach, it is assumed that all nodes start to transmit data frames with the given data period that is set the same for all nodes. The model only considers all data packets coming from neighbor nodes including the data packets originating from neighbor nodes and the data packets forwarded by neighbor nodes. Moreover, the propagation delay can be neglected due to the high propagation velocity and the distance between the 2 nodes is tens of meters. Under these conditions, the distribution of arrival data packets at each node can be assumed to have a uniform distribution. However, in the analytical model, the collision probability (P_c) is not determined directly; this probability is calculated indirectly by determining the idle probability (P_i) of a slot and the probability of successful data transmission (P_d) and then using formula (1) to determine the collision probability (P_c).

3.5. Relation between data rate, acknowledgment rate and beacon rate

During a data period (inter-packet interval) of t_{ipi}, each node averagely transmits 1 data packet and 1 acknowledgment (ACK) packet. The collision of data packets is proportional to the rate $2/t_{ipi}$ (with $1/t_{ipi}$ for data packet and $1/t_{ipi}$ for ACK) as the ACK is also processed above the MAC layer. As a result, the ACK can be treated as a data packet in terms of collision. Since the beacon transmission does not require the ACK packet due to the broadcast mechanism, therefore beacon collision is only proportional to $1/t_{ibi}$ (where t_{ibi} is the inter-beacon interval). Retransmissions are not included in this model, as a retransmission can also be considered as a transmission of the data packet.

However, in practice, the collisions are due to the setting of the beacon period and data period. If any frame is collided at the MAC layer, then the sending node cannot receive the ACK frame. This activates the retransmission mechanism to resend the collided frame (still in the transmission buffer).

3.6. Beacon forwarding

Beacon transmission using broadcasting is typically synchronous. When one node transmits a new beacon, N neighboring nodes nearby forward this beacon after a short delay (accounting for propagation and processing time). This results in the number of beacon collisions being N times greater than those occurring when transmitting a single data packet (which is forwarded by only one neighboring node). Combining this with the considerations in section 3.5, if there are N contention nodes, the rate of collision probabilities can be expressed by the following ratio:

$$\frac{P_c^b}{P_c^d} = \frac{N\ .\ 1/t_{ibi}}{2/t_{ipi}}0 \tag{7}$$

Based on equations (6) and (7), the collision probabilities can be defined as follows:

$$\begin{cases} P_c^b = \dfrac{N.\dfrac{t_{ipi}}{2}}{t_{ibi} + N.\dfrac{t_{ipi}}{2}}.P_c \\ P_c^d = \dfrac{t_{ibi}}{t_{ibi} + N.\dfrac{t_{ipi}}{2}}.P_c \end{cases} \tag{8}$$

4. Simulation results and comparison

To examine the collisions discussed in the previous section, a modified version of the Cooja simulator [27] has been implemented to track the number of transmissions and collisions for each node. As a result, the collision probability can be calculated. A scenario is set up with N nodes (where N ranges from 3 to 21) in a 100m x 100m area, which typically represents the communication distance of sensor nodes.

Each node in this network can communicate with (N-1) other neighboring nodes. Consequently, the collision probability can range from low to high levels. The beacon period (t_{ibi}) and data period (t_{ipi}) are set to 8 seconds and 2 seconds, respectively, according to the routing protocol mentioned in [8]. In the simulation, when a sensor node has data to transmit, it initiates a random backoff. Following this, the node must perform a Clear Channel Assessment (CCA) to determine the state of the medium (idle or busy). For easier evaluation and comparison, in both analysis and simulation the maximum backoff time is set to the same value as follows:

$$CW.T_{slot} = T_{backoff}^{\max} + T_{CCA} = k_{\max}.T_{unitBackoffPeriod} + T_{CCA} \tag{9}$$

in which:

- CW: 32 slots in the contention window [16].
- $T_{unitBackoffPeriod}$: 16 µs, duration of a symbol [28].
- T_{slot}: 16µs, duration of one slot.
- $T_{backoff}^{\max}$: the maximum backoff time.
- T_{CCA}: 128µs, duration of CCA phase of which is 8 times of T_{slot} [28].
- k: a random integer with a uniform distribution. This value is selected for backoff time in the simulation and falls within the range [k_{min}, k_{max}]. This range is derived from the above equation and is utilized in the simulation.

For comparison with the proposed analytical model, with the given CW, data period, beacon period, and the network running time (which is equal to the simulation time) the collision probabilities P_i, P_d, and P_c are calculated from formulas (1), (3), (4) then using formula (8) to determine P_c^d and P_c^b.

In the simulation, there are 2 types of traffic: routing (beacons) and data packets. The routing protocol is always running to keep the topology updated over time. The routing and the data traffic levels can be configured as the parameter beacon period and data period respectively. Hence, two scenarios are simulated to determine collision probabilities as follows:

- If nodes do not send any data packets (by turning off the data transmission service inside each node), the collisions happen only due to beacons (routing). In this case, the collision probability caused by only beacon-beacon can be determined.
- If nodes are turned on with data packet transmission, inside the network there are several types of collision: beacon-beacon, data packet-data packet, and beacon-data packet. In this case, the mutual collision probabilities can be measured.

From measurement in the 2 above scenarios, the independent and mutual collision probabilities can be calculated and compared with the analytical model's results.

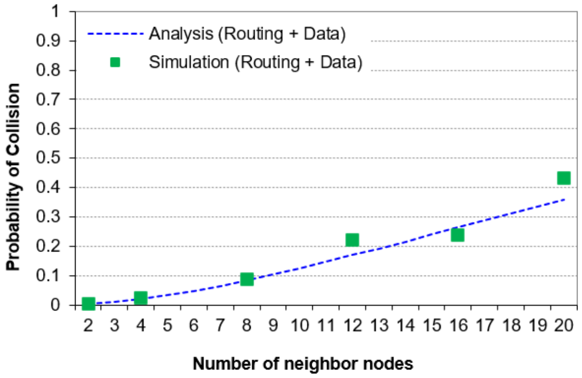

Figure 4. *Collision probability versus the number of neighboring nodes. The beacon and periods are set to 8 seconds and 2 seconds respectively*

In Figure 4, the simulation results and analysis of collision probability in relation to the number of neighboring nodes are presented. It is evident that if a node has more neighboring nodes, the collision probability increases due to higher collisions for transmitted beacons and data packets. However, when the number of neighboring nodes is less than 8, the collision probability remains rather low (below 0.065). This figure also illustrates that the analytical model aligns closely with the simulation results because it considers various practical factors such as synchronous beacon forwarding, overlapping slots, and acknowledgments. This finding supports a practical recommendation that the design of network size in multi-hop sensor networks can help reduce collisions.

To measure the collisions caused by beacons only, in this scenario, all nodes are configured to stop their data transmissions while only the routing protocol remains running. Subsequently, the collision probability of data packets can be calculated by subtracting the beacon collisions from the total collisions, as mutual collisions between beacons and data packets are neglected using (6). Figure 5 illustrates the individual collision probabilities for beacons and data packets, showing that the results from the simulation and analysis align closely. As the number of contention nodes increases, both the collision probabilities for beacons and data packets also rise. In scenarios with a high node density, the total collision probability for routing (beacons) and data packet transmission is approximately 0.31 and 0.12, respectively, when there are 20 neighboring nodes.

The figure also shows that the collision probability of beacons increases at a faster rate than that of data packets in both the simulation and analysis. This is attributed to the synchronous beacon forwarding of the tree routing protocol. In scenarios with more crowded contention nodes, the collision probability observed in the simulation is slightly higher than that in the analysis, due to mutual collisions and the number of retransmissions, which are not considered in the analysis. Another factor contributing to the discrepancy between the simulation and analysis results is the CCA, which is not included in the analysis because it is relatively small (only 16 μs) compared to the beacon and data periods (which span several seconds).

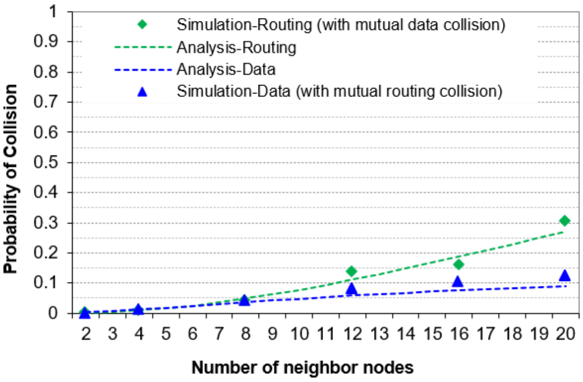

Figure 5. *Individual collision probabilities of beacons and data packets*

To assess the influence of data and beacon traffic on collision probability within the network, sensor nodes are set up with variable data periods and beacon periods to represent levels of data and routing traffic load. Figure 6 illustrates the simulation results, revealing that the overall average collision probability in the network reaches approximately 0.17 under high traffic conditions (with data and beacon periods set at 8 and 2 seconds, respectively). Conversely, when the traffic load is low (data or beacon period set at 60 seconds), the collision probability is significantly reduced.

Additionally, the findings depicted in this figure provide further evidence of a close alignment between simulation outcomes and analytical results. In real deployment of WSNs, the data period is typically configured to span several minutes, particularly in monitoring applications, resulting in a very low collision probability with this setup. The selection of the beacon period is influenced by the nodes' need to adapt to network changes either rapidly or gradually. In many widely employed routing protocols [5, 8] for IoT applications, the beacon period is typically set to 8 seconds if the adaptive beaconing mechanism [16] is not utilized, proving enough flexibility for most wireless sensing applications.

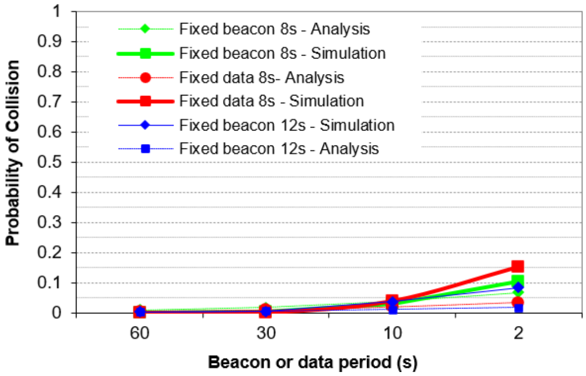

Figure 6. *Collision probability versus beacon and data period*

5. Conclusion and outlooks

The presented analytical model aims to provide a more accurate analysis of collision probabilities for beacons of routing information and data packets, considering several factors such as synchronous beacon forwarding, data rate, and ACK packet rate. The validation analysis indicates a close match between the proposed model and simulation results, specifically in terms of individual collision probabilities for data packets and beacons.

In future work, the exploration of mutual collision probabilities between beacons and data packets will be conducted, incorporating an adaptive beaconing forwarding mechanism.

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