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Performance analysis of Slotted CSMA/CA MAC protocol under different parameters for static IEEE 802.15.4 Wireless Sensor Networks

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Abstract- WSNs have emerged as an important area for research and development because of its application in monitoring and tracking. This paper, presents and discuss the performance of slotted CSMA/CA MAC protocol for static WSNs, with only minor add-ons to the protocol by tuning its parameter adequately. The performance of the slotted CSMA/CA MAC protocol is evaluated and analyzed for different network configurations to understand the impact of the protocol parameters such as super frame order, beacon order, back off exponent, frame size and CSMA/CA overheads on the network performance, namely in terms of throughput, average delay and energy consumed by the network. The proposed work is implemented on Qualnet 5.0.2 Network Simulator and the performance of CSMA/CA MAC protocol is evaluated for static WSNs.

Keywords- Wireless Sensor Network (WSN), Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), Back-off Exponent (BE), Medium access control (MAC) etc.

I. INTRODUCTION

Wireless sensor networks can provide low cost solution to verity of real-world problems. Recently there has been drastic improvement in WSN due to the growth in MEMS & NEMS and low power electronic technologies. WSN has the potentiality to connect the physical world with the virtual world by forming a network of sensor nodes [1]. WSNs are found suitable for many applications such as security, surveillance, environmental monitoring, precision agriculture, smart homes, automation, vehicular traffic management, habitat monitoring, creative industries, monitoring health of structures and disaster detection etc. Now node mobility in WSNs gives many other applications. IEEE 802.15.4 MAC protocol implements a simple CSMA-CA method to allow multiple devices to use the same frequency channel for their communication medium. There are two types of CSMA-CA: slotted and un-slotted. *Slotted CSMA-CA* is referred to as performing CSMA-CA while there is a super-frame structure in place. The *un-slotted CSMA-CA* algorithm is used when there is no super-frame structure. The motivation for evaluating the Slotted CSMA/CA is due to its flexibility for WSN applications as compared to the un-slotted CSMA/CA mode.

Related work: The performance of the slotted CSMA/CA mechanism in IEEE 802.15.4 was evaluated using discrete time Markov chain models [3]. Authors in [3] presented analytic models of the slotted CSMA/CA; these analytical models are interesting for capturing the behaviour of the protocol in terms of throughput and access delays. However, the impact of the *Beacon Order (BO)*, *Super-frame Order (SO)* and *Back-off Exponent (BE)* was not addressed. In [4], the authors have proposed a different Markov chain model of the slotted CSMA/CA mechanism and computed the throughput and energy consumption in saturation conditions.

The rest of the paper is organized as follows. Section II gives the overview of WSNs. Section III discussed slotted CSMA mechanism for MAC protocol in WSNs. Section IV present the performance parameters used for the analysis of slotted CSMA/CA. Section V present simulation and results with performance analysis of slotted CSMA/CA for different parameters. Finally section VI concludes the paper and gives some directions for future work.

II. Overview of 802.15.4 WSNs

The 802.15.4 WSNs consists of several components. The most basic is the device. A device can be a full-function device (FFD) or reduced-function device (RFD). A network shall include at least one FFD, operating as the PAN coordinator. IEEE 802.15.4 WSN can support Star Topology, Peer-to-peer Topology and Cluster-tree Topology [5]. The IEEE 802.15.4 WSNs defines Physical layer, which contains the radio frequency (RF) transceiver along with its low-level control mechanism, and a MAC sub layer that provides access to the physical channel for all types of transfer. Upper layers such as network and application are defined by Zigbee Alliances. The IEEE 802.15.4 MAC sub layer has two operational modes. They are: (a) Beacon-enabled mode: In this mode, beacons are periodically sent by the PAN or Coordinator to synchronize nodes that are associated with it. This mode uses super-frame which have contention access and contention free period which is divided into different guaranteed time slots (GTS). (b) Non beacon –enabled mode: In this mode PAN coordinator does not transmit beacons. It does not support GTS and uses un-slotted CSMA/CA MAC protocol. The IEEE802.15.4 allows the optional use of a super frame structure. The format of the super-frame is defined by the coordinator.

It is defined between two beacon frames and has an active period and an inactive period. Structure of super-frame is shown in figure 1.

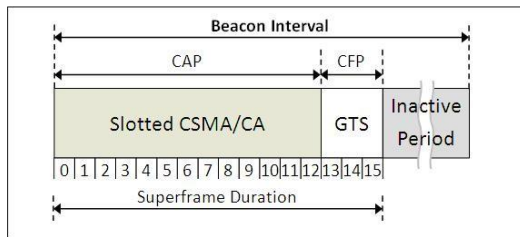


Figure1: Structure of super-frame

The structure of this super frame is described by the values of *macBeaconOrder* which defines beacon interval (BI) and *macSuperframeOrder* which defines super-frame duration (SD). BI and SO are given as:

$$BI = aBaseSuperframeDuration \times 2^{macBeaconOrder},$$

For $0 \leq macBeaconOrder \leq 14$

$$SD = aBaseSuperframeDuration \times 2^{macSuperframeOrder},$$

For $0 \leq macSuperframeOrder \leq macBeaconOrder \leq 14$

III. Overview of slotted CSMA/CA for 802.15.4 WSNs

The slotted CSMA/CA algorithm is based on a basic time Unit called Back-off Period (BP), which is equal to $aUnitBackOffPeriod = 80 \text{ bits} (0.32 \text{ ms})$. Each operation of slotted CSMA/CA (channel access, back-off count, CCA) can only occur at the boundary of a BP. Additionally, the BP boundaries must be aligned with the super-frame time slot boundaries. The slotted CSMA/CA back-off algorithm mainly depends on three variables:

1. The *Back-off Exponent (BE)* enables the computation of the back-off delay, which is the time before performing the CCAs. The back-off delay is a random variable between 0 and $(2^{BE} - 1)$.
2. The *Contention Window (CW)* represents the number of back-off periods during which the channel must be sensed idle before accessing to the channel. The standard set the default initialization value to $CW = 2$ (corresponding to two CCAs). In each back-off period, channel sensing is done during the 8 first symbols of the BP.
3. The *Number of Back-offs (NB)* represents the number of times the CSMA/CA algorithm was required to back-off while attempting to access the channel. This value is initialized to zero ($NB = 0$) before each new transmission attempt.

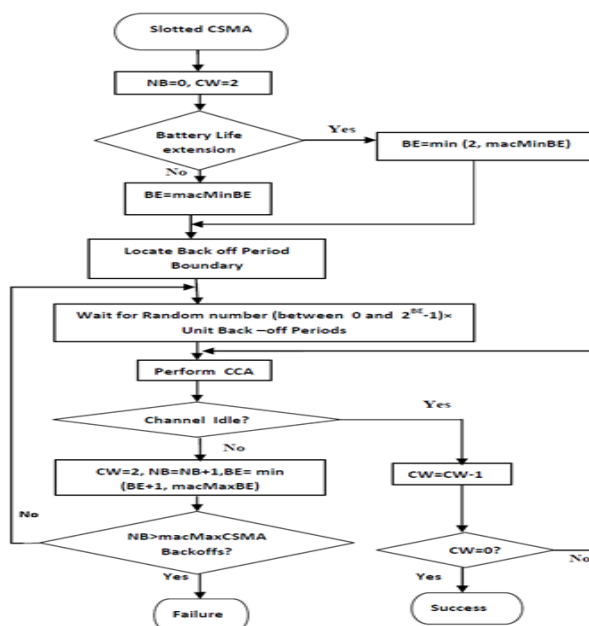


Figure2 Slotted CSMA/CA algorithm for 802.15.4

Figure2 provides the flowchart of the CSMA-CA algorithm. It can be summarised in five steps as follows.

Step 1 - Initialisation of NB, CW and BE: The number of back-offs and the contention window are initialised ($NB = 0$ and $CW = 2$).

Step 2 - random waiting delay for collision avoidance: The algorithm starts counting down a random number of BPs $[0, 2^{BE} - 1]$.

Step 3 - Clear Channel Assessment (CCA): When the timer expires, the algorithm then performs one CCA operation at the BP boundary.

Step 4 - busy channel: If the channel is assessed to be *busy*, CW is re-initialised to 2, NB and BE are incremented. . If the maximum number of back-offs is reached, the algorithm reports a failure to the higher layer, otherwise, it goes back to (Step 2).

Step 5 - idle channel: If the channel is assessed to be idle, CW is decremented. The CCA is repeated if $CW \neq 0$. If the channel is again sensed as idle ($CW = 0$), the node attempts to transmit.

IV. Performance Metrics

To understand the impact of different parameters on the behavior of slotted CSMA/CA MAC protocol for static WSNs following parameters have been analyzed for performance analysis of slotted CSMA/CA.

Throughput: It is defined as the total number of packets received at the sink node divided by the simulation time. It is generally measured in bits/Sec (bit/sec or bps). It is the fraction of traffic correctly received by the receiver normalized to the overall capacity of the network (250 kbps).

Average End-to-End delay: It indicates the length of time taken for a packet to travel from the source to destination. Delays due to route discovery, queuing, propagation and transfer time are included in the delay metric. It indicates the average data delay an application experiences during transmission of data.

Energy Consumption: This is the amount of energy consumed by MICAZ Mote devices during the periods of transmitting, receiving, idle and sleep. The unit of energy consumption used in the simulations is mWhr.

IV. Simulation and results

A. Model of test Scenario and simulation parameter

To study the impact of mobility in WSNs a cluster based sensor network with one sink node and 50 other nodes in 50m*50m area is considered as shown in figure 3. Here this test scenario considers five clusters with one PAN coordinators, four coordinators and remaining nodes are as normal devices. Simulation parameter for this model are shown in Table-I. Here MICAz energy model for MICAz motes have been used which gives the information about the energy consumed in different modes.

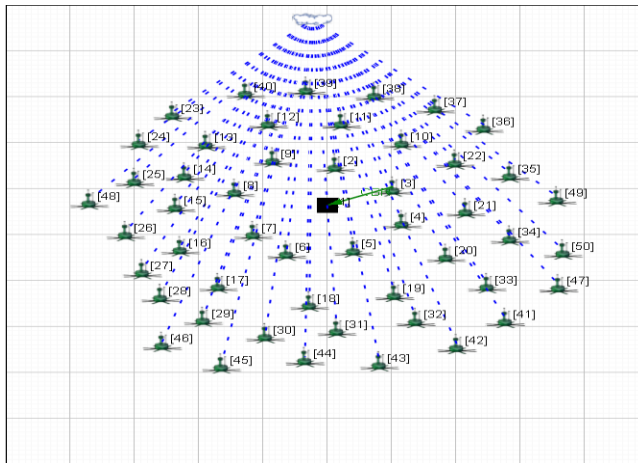


Figure 3 Model of Test Scenario

Parameter Name	Parameter Value
Simulation Tool	Qualnet 5.0.2
Simulation Time	120 Seconds
Channel frequency	2.4GHz
Radio type	802.15.4 Radio
Modulation Scheme	OQPSK
MAC Protocol	802.15.4
Routing Protocol	AODV
Traffic	CBR
aBaseSlotDuration	60 Symbols
aNumsuperframeslots	16
aUnitBackoffPeriod	20 Symbols
CW	2
MacMinBE	3
MaxCSMABackOff	5
CCA Detection time	8 Symbols
Beacon Order	3
Super frame order	3

Table -I. Simulation Parameters

Here the performance of CSMA/CA MAC protocol static WSNs is analysed. The PAN coordinator periodically generates beacon frames according to the BO and SO parameters. In order to focus on the performance analysis of the slotted CSMA/CA algorithm, we assume that the network is fully connected, i.e. all nodes hear each other (no hidden terminal problem). We assume that the generated data frames have a constant size and are equal in all nodes. The default value in our simulations is 300 bits for data payload and 104 bits for the MAC header size (according to the standard specifications [34]). The global offered load generated by all nodes application layers depends on the inter-arrival times. Basically, the performance of the slotted CSMA/CA mechanism will be evaluated as a function of the offered load in the network. The performance metrics analyzed in this paper for the analysis of slotted CSMA/CA mechanism are throughput, average End-to-End delay and energy consumed by the network. In our simulation we have used Qualnet 5.0.2 network simulator for modelling large wired and wireless networks. It enables users to: design new protocol models, optimize new and existing models, design large wired and wireless networks using pre-configured or user-designed models and analyze the performance of networks and perform what-if analysis to optimize them.

B. Performance analysis of slotted CSMA/CA for different parameters with simulation and results of each parameter

B.1. Impact of SO and BO

Setting BO and SO is one of the most important tasks of the PAN coordinator. In this thesis, we analyze the impact of BO and SO on the performance of slotted CSMA/CA. Figure 4, 5, 6 and 7 present the network throughput, the average delay, and energy consumed respectively, as a function of the offered load for different BO and SO values. Figure 4 observed that, as expected, low SO and BO values produce lower network throughput. This is basically due to two factors. First, the overhead of the beacon frame is more significant for lower SO values, since beacons are more frequent. Second, CCA deference is also more frequent in case of lower SO and BO values, leading to more collisions at the start of each super-frame. The increase in the super-frame order from SO and BO equal to 5 until 14 has little to no impact on the network throughput because the probability of deference is quite low, which reduces the amount of collisions due to simultaneous CCA deference in multiple nodes, and thus leads to higher network throughputs. Note that for high offered loads, the network throughput reaches a stable saturation throughput (around 62%).

Figure 5 shows average delay for different values of SO and BO Vs offered load. It shows that the average delays significantly increase with increase in SO and BO. Low SO and BO values result in lower average delays. This is mainly because backoff delays remain low due to frequent collisions after the CCA deference.

For higher values of SO and BO average delay increases because larger BO causes a longer inactive period, which may cause the buffered packets to experience a longer sleeping delay. Figure 6 shows energy consumed Vs different values of BO. Energy in three modes (transmit, receive and idle) is plotted against BO. As BO is decreased, energy consumption in transmit and receive mode is increases while in idle mode energy consumption is decreases with decrease in BO.

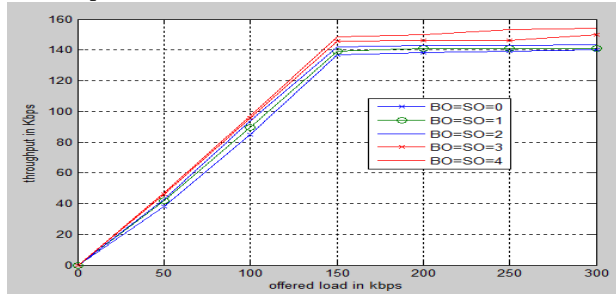


Figure 4 Throughput for different values of SO and BO Vs offered load

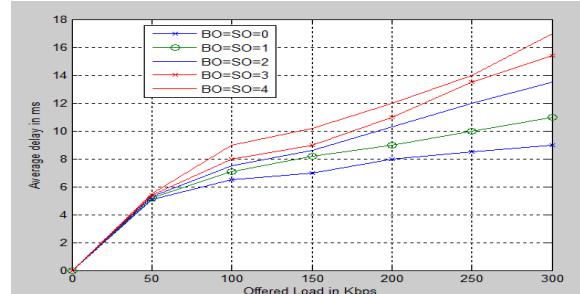


Figure 5 Delay for different values of SO and BO Vs offered load

This is due to fact that as with decrease in BO, duty cycle increases and reduces the idle period, due to which more time is devoted for transmission and reception while idle time is decreased, that is why energy consumed is more for lesser BO in active cases and it is less for lower BO in idle case. Figure 6 shows energy consumed Vs different values of SO, Energy in three modes (transmit, receive and idle) is plotted against SO. As SO is increased, energy consumption in transmit and receive mode is increasing while in idle mode energy consumption is decreasing with increase in SO. The fact can be defined as with increase in SO, duty cycle increases and reduces the idle period, due to which more time is devoted for transmission and reception while idle time is decreased, that is why, energy consumed is more for higher SO in active cases and it is less for higher SO in idle case.

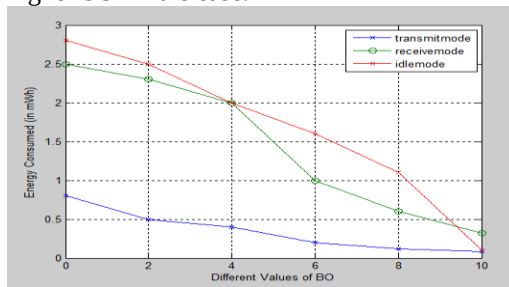


Figure 6 Energy consumed in mWhr Vs BO

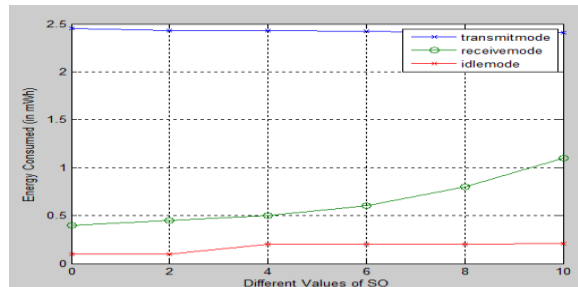


Figure 7 Energy consumed in mWhr Vs SO

B.2. Impact of Back-off Exponent (BE)

The Backoff Exponent (BE) is an important parameter in the backoff algorithm of slotted CSMA/CA. It enables the computation of the random backoff delay before trying to access the channel. The initial value, denoted as *macMinBE*, is set to 3 by default [6], but can be set differently by the MAC sub layer in the range [0, 5]. Setting *macMinBE* to 0 would disable collision avoidance during the first iteration of the algorithm. The purpose of this section is to study the impact of the initialization value *macMinBE* on network performance. We run the simulator for different values of *macMinBE* - from 0 to 5. For each configuration, we vary the inter-arrival times of the flows in each node to have different offered loads with a constant packet size. Each curve corresponding to a given *macMinBE* is obtained for seven different inter-arrival times. Figure 8 observed that the network throughput is independent from the initial value of the backoff exponent *macMinBE* for a "large-scale" WSN.

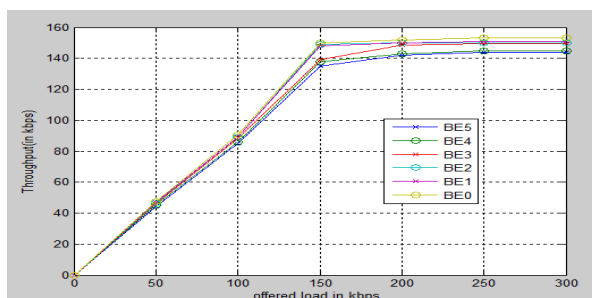


Figure 8 Throughput load for different values of BE Vs offered load

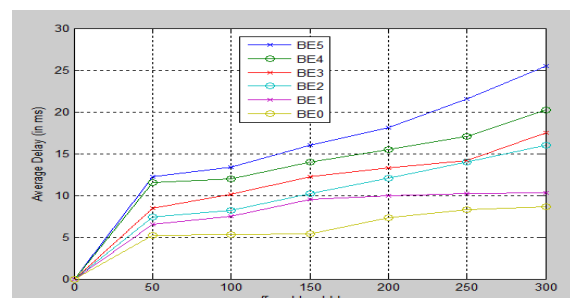


Figure 9 Average delay for different values of BE Vs offered load

This is because the lower limit of the back-off delay interval $[0, 2^{BE-1}]$ is not affected by the choice of *macMinBE*. However, the impact of *macMinBE* on the network throughput is quite important in small scale networks. In fact, increasing *macMinBE* will lead to relatively lower network throughput since the capacity of the network (250 kbps) is not entirely used for high *macMinBE*, but to significant higher success probability thanks to more efficient collision avoidance. Figure 9 observe that the average delay increases with *macMinBE* for a given offered load. Lower *macMinBE* values provide lower average delays with the same network throughputs. This is because the average back-off delays are higher for large $[0, 2^{BE-1}]$ intervals. Observe that for low offered loads, the variance of the average delays for different *macMinBE* is not significant (around 10 ms from *macMinBE* from 0 to 5). However, for high offered loads, the impact of *macMinBE* is significantly more visible. *MacMinBE* = 0 is the best configuration for an optimal network throughput/average delay trade off for small scale WSNs.

B. Impact of CSMA/CA overheads and frame size

The purpose of this section is to evaluate the impact of the slotted CSMA/CA overheads (backoff delay, contention window, i.e. CCA and CCA deference) on the saturation throughput. The *saturation throughput* is defined as the maximum traffic generated by a node using slotted CSMA/CA as a MAC protocol when it operates in the saturation mode. Thus, the maximum saturation throughput of one node is achieved when only this node sends its traffic to the network, i.e. no collision occurs, in saturation mode. Therefore, the simulations presented in this section consider one PAN coordinator that only sends beacon frames, one node that sends data frames and the network analyzer to sniff all generated traffic. Obviously, the maximum throughput cannot reach 100% even if no collision occurs. This is due to the impact of the back-off delay, forcing one node to wait even if the channel is idle, the impact of the contention window (two mandatory CCA operations), the impact of the CCA deference, when the remaining back-off periods in the super-frame are less than the number *n* required to transmit the entire frame and the beacon frame. We have evaluated the impact of data frame size on the performance of slotted CSMA/CA. We run the simulation for different data frame sizes of 300, 500, 700, 900 bits. For each configuration, we vary the inter-arrival times of the flows in each node to have different offered loads. From figure 4.9 it can be observed that the network throughput is better for longer data frames in high offered load conditions. This is because the slotted CSMA/CA overheads (backoff delay, CCA and CCA deference) have more impact on shorter frames and because probability of success is also higher for higher frame size.

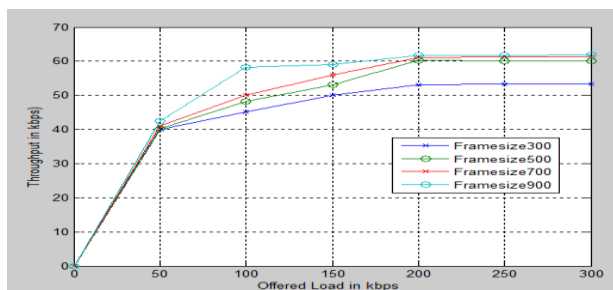


Figure 10 Throughput for different values of Frame Size

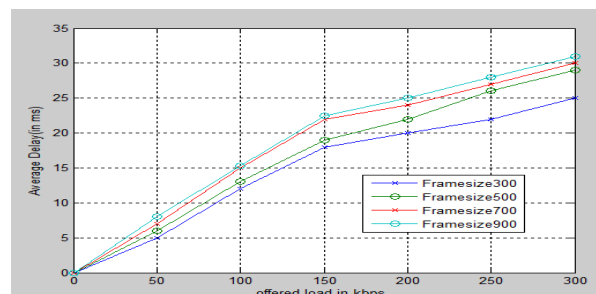


Figure 11 Average Delay for different values of Frame size

In Figure 4.10 it can be observed that the average delay experimented by long frames is a little bit higher. This is because longer frames have longer transmission times than shorter frames. However, the variation is not significant even for high offered load.

V. Conclusion and future work

In this chapter comprehensive performance evaluation and analysis of the slotted CSMA/CA medium access mechanism deployed by the IEEE 802.15.4 protocol in beacon-enabled mode is done. It has been shown that high super-frame orders provide better network throughput than low super-frame orders. On the other hand, low *SO* and *BO* values result in lower average delays in case of high offered loads. The impact of *macMinBE* on the network throughput is quite important in small scale networks. In fact, increasing *macMinBE* will lead to relatively lower network throughput but to significant higher success probability thanks to more efficient collision avoidance. *MacMinBE* = 0 is the best configuration for an optimal network throughput/average delay trade off. The impact of the slotted CSMA/CA overheads on the saturation throughput and the impact of data frame size on the performance of slotted CSMA/CA are evaluated.

In future this paper can be used as a guide to understand the slotted CSMA/CA MAC protocol for 802.15.4 WSNs, to design a new CSMA/CA MAC protocol for better throughput, average end-to-end delay and less energy consumption.

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