Performance Evaluation of Beaconed IEEE 802.15.4 under NS2

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Abstract- **A low-rate wireless personal area network, or LR WPAN, is a network designed for low-cost very-low-power short range wireless communications. IEEE 802.15.4 standard is designed for low power and low data rate applications with high reliability. Protocol performance is examined by changing different Medium Access Control (MAC) parameters. A wireless sensor network (WSN) composed of nodes, which transmit data to a sink through direct links, is considered. Upon reception of a query from the sink, the nodes transmit their packets by using the carrier-sense multiple access with collision-avoidance algorithm defined by IEEE 802.15.4. In this paper, we propose an extended model of the Beacon enabled IEEE 802.15.4 in the aim to analyze and evaluate network performances. Series of extensive simulations were performed to analyze the impact of the different data rates on the network performance based on commonly known metrics. In particular, we examine data delay, packet delivery performance and the throughput for different duty cycle rates.**

Index Terms —IEEE 802.15.4, low-rate wireless personal area networks (LR-WPAN), Medium Access Control (MAC), wireless sensor network (WSN), Carrier-sense multiple access with collision-avoidance (CSMA-CA).

I. INTRODUCTION

Main aim of IEEE 802.15.4 standard is to provide a low cost, low power and reliable protocol for wireless monitoring of patient's health. This standard defines physical layer and MAC sub layer. Three distinct frequencies bands are supported in this standard. However, 2.4 GHz band is more important. This frequency range is same as IEEE 802.11b/g and Bluetooth. IEEE 802.15.4 network supports two types of topologies, star topology and peer to peer topology. Standard supports two modes of operation, beacon enabled (slotted) and non-beacon enabled (unslotted). IEEE 802.15.4 [1],[2],[3] is a short-range wireless technology intended to provide applications with relaxed throughput and latency requirements in wireless personal area networks (PANs). The key features of 802.15.4 are low complexity, low cost, low power consumption, and low data rate transmissions.

The IEEE 802.15.4 Working Group [5] focuses on the standardization of the bottom two layers of the International Standards Organization/Open Systems Interconnection (ISO/OSI) protocol stack. In particular, the standard only defines the physical and medium access control (MAC) aspects. The other layers are normally specified by industrial consortia such as the ZigBee Alliance [6].

II. TOPOLOGIES

The topologies defined in the original 802.15.4-2003 standard are maintained in all the other versions of the standard.

The standard defines two types of devices a Full-Function device (FFD) and a Reduced-Function device (RFD) [1], [3], [4], [9].

The FFD is capable of all network functionalities and can operate in three different modes: it can operate as a PAN coordinator, a coordinator or it can serve simply as a device. An RFD device is low on resources and memory capacity and is capable only of very simple applications such as a node which senses light or temperature.

The PAN can operate in star or peer-to-peer topologies. The PAN can adopt any of the two topologies depending on the type of application.

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The PAN can adopt any of the two topologies depending on the type of application. In the star topology communication can only take place between the devices and the PAN coordinator. The PAN coordinator is responsible to inaugurate or terminate communications in the network and is often mains powered. Only an FFD can be a PAN coordinator. In order to establish the network, an FFD is activated and becomes a PAN coordinator and a unique PAN identifier is chosen which is not in use by any other star network in range. Both FFD and RFD are now allowed to join the network. The star topology finds applications in home automation, games, interactive toys and in personal health care.

In the peer-to-peer topology all FFD devices in the network can communicate with each other while the RFD devices can only communicate with the PAN coordinator. In this topology, more complex networks such as mesh networks can be organized however the 802.15.4 does not cover such networks. Peer-to-peer networks can be used in dense sensor networks.

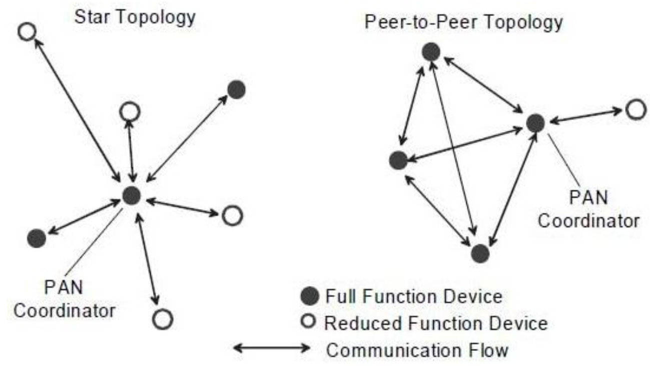

Fig.1. IEEE 802.15.4 Network Topologies [10].

III. IEEE 802.15.4 MEDIUM-ACCESS CONTROL PROTOCOL

Medium Access Control (MAC) protocols play an important role in overall performance of a network. In broad, they are defined in two categories contention-based and schedule-based MAC protocols. In contention-based protocols like Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), each node content to access the medium. If node finds medium busy, it reschedules transmission until medium is free. In schedule-based protocols like Time Division Multiple Access (TDMA), each node transmits data in its pre-allocated time slot. According to the IEEE 802.15.4 MAC protocol in beacon enbled mode [1], the access to the channel is managed through a superframe, starting with the beacon packet transmitted by the PAN coordinator. The superframe is subdivided into the following three parts: 1) an inactive part; 2) a contention access period (CAP), during which nodes use a slotted CSMA/CA; and 3) a contention-free period (CFP), containing a number of GTSs that can be allocated by the PAN coordinator to specific nodes. The PAN coordinator may allocate up to seven GTSs, but a sufficient portion of the CAP must remain for contention based access. The minimum CAP duration is equal to 440 Ts, where Ts is the symbol time.

The IEEE 802.15.4 standard allows the optional use of a superframe structure. The superframe is bounded by network beacons sent by the coordinator and is divided into 16 equally sized slots. All transactions shall be completed by the time of the next network beacon. The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes. The format of the superframe is defined by the coordinator. The superframe can have an active and an inactive portion, as shown in Fig. 2. The active portion of each superframe is composed of three parts: a beacon, a contention access period (CAP) and a contention-free period (CFP). The beacon shall be transmitted, without the use of carrier sense multiple access with collision avoidance (CSMA-CA), at the start of slot 0, and the CAP shall commence immediately after the beacon. Any device wishing to communicate during the CAP between two beacons shall compete with other devices using a slotted CSMA-CA mechanism.

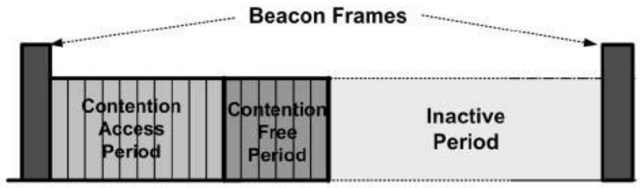

Fig. 2. SuperFrame of CSMA/CA[10].

The CFP, if present, follows immediately after the CAP and extends to the end of the active portion of the superframe. No transmissions within the CFP shall use a CSMA-CA mechanism to access the channel.

IV. CSMA/CA

CSMA/CA is a modification of Carrier Sense Multiple Access (CSMA). Collision avoidance is used to enhance performance of CSMA by not allowing node to send data if other nodes are transmitting. In normal CSMA nodes sense the medium if they find it free, then they transmits the packet without noticing that another node is already sending packet, this results in collision. CSMA/CA results in reduction of collision probability.

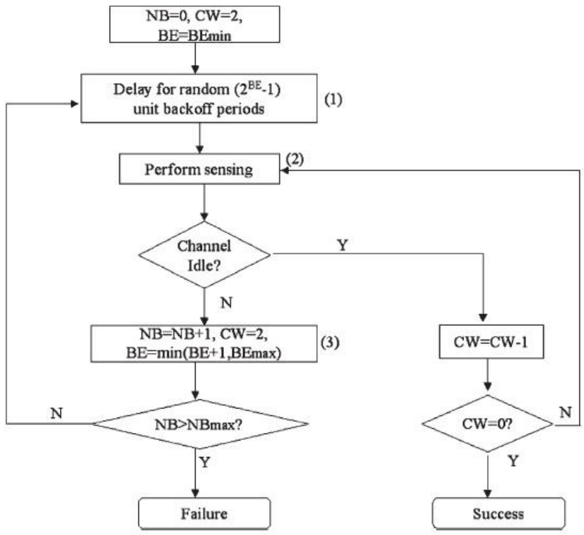

Fig. 3. Flow Chart of CSMA/CA Operation[11].

It works with principle of node sensing medium, if it finds medium to be free, then it sends packet to receiver. If medium is busy then node goes to backoff time slot for a random period of time and wait for medium to get free. With improved CSMA/CA, Request To Send (RTS)/Clear To Send (CTS) exchange technique, node sends RTS to receiver after sensing the medium and finding it free. After sending RTS, node waits for CTS message from receiver. After message is received, it starts transmission of data, if node does not receive CTS message then it goes to backoff time and wait for medium to get free. CSMA/CA is a layer 2 access method, used in 802.11 Wireless Local Area Network (WLAN) and other wireless communication. One of the problems with wireless data communication is that it is not possible to listen while sending, therefore collision detection is not possible.

CSMA/CA is largely based on the modulation technique of transmitting between nodes. CSMA/CA is combined with Direct Sequence Spread Spectrum (DSSS) which helps in improvement of throughput. When network load becomes very heavy then Frequency Hopping Spread Spectrum (FHSS) is used in congestion with CSMA/CA for higher throughput, however, when using FHSS and DSSS with CSMA/CA in real time applications then throughput remains considerably same for both. Fig. 4 shows the timing diagram of CSMA/CA.

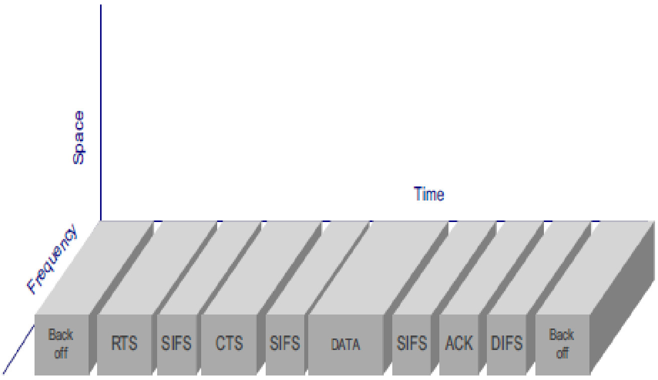

Fig. 4. Timing Diagram of CSMA/CA[11].

$$D = Tbo + Tdata + Tta + Tack + Tifs \quad (1)$$

Data transmission time $Tdata$, Backoff slots time Tbo, Acknowledgement time $Tack$ are given by equation 2, 3, and 4 respectively[2].

$$Tdata = \frac{Lphy + Lmac\,hdr + payload + Lmacftr}{Rdata} \quad (2)$$

$$Tbo = boslots * Tboslots \quad (3)$$

$$Tack = \frac{Lphy + Lmac\,hdr + Lmacftr}{Rdata} \quad (4)$$

The following notations are used:

$T_{bo} = Back\ Off\ Period$
$T_{data} = Transmission\ Time\ of\ Data$
$T_{ta} = Turn\ Around\ Time$
$T_{ack} = Acknowledgement\ Transmission\ Time$
$T_{ifs} = Inter\ Frame\ Space$
$T_{phy} = Length\ of\ Physical\ header$
$L_{machdr} = Number\ of\ MAC\ header$
$Payload = Number\ of\ data\ byte\ in\ packet$
$L_{macftr} = Size\ of\ MAC\ footer$
$bo_{slots} = Number\ of\ back\ off\ slots$
$T_{boslots} = Time\ for\ a\ back\ off\ slot$
$R_{data} = Data\ Rate$

In CSMA/CA mechanism, packet may loss due to collision. Collision occurs when two or more nodes transmits the data at the same time. If ACK time is not taken in to account then there will be no retransmission of packet and it will be considered that each packet has been delivered successfully. The probability of end device successfully transmitting a packet is modelled as follows [8].

$$Pbackoffperiod = \frac{1}{2^{BE}} \quad (5)$$

$$Ptss = \frac{1}{D}\left(1 - \frac{1}{D}\right)^{BE-2} \quad (6)$$

$$= (1 - p)^{BE-2}$$

Where, D is the number of end devices that are connected to router or coordinator. BE is the backoff exponent in our case it is 3. $Ptss$ is the probability of transmission success at a slot. 1 D is the probability of end device successfully allocated a wireless channel.
General formula for $Ptimedelayevent$ is given by equation 8.
Probability of time delay caused by CSMA/CA backoff exponent is estimated as in [7]. Maximum number of backoff is 4. Value of BE=3 has been used in following estimation and we estimate by applying summation from 3 to 5. $Ptde$ is the probability of time delay event.

$$Ptde = \sum_{n=0}^{2^{BE-1}} n \frac{1}{2BE} p1 - p^{BE-2} \quad (7)$$

$$Ptde = \sum_{n=0}^{7} n \frac{1}{2BE} p + \sum_{n=8}^{15} n \frac{1}{2BE} p + \sum_{n=16}^{31} n \frac{1}{2BE} p \quad (8)$$

Expectation of the time delay is obtained as from [7]. PE_A and PE_B are taken from equations 7 and 8 respectively.

$$E[TimeDelay] = P(EA/EB)$$

$$= \frac{\sum_{n=0}^{7} n \frac{1}{2BE} p + \sum_{n=8}^{15} n \frac{1}{2BE} p + \sum_{n=16}^{31} n \frac{1}{2BE} p}{\sum_{n=0}^{2^{BE-1}} n \frac{1}{2BE} p1 - p^{BE-2}} \quad (9)$$

V. EXPERIMENTAL SETUP

The NS2 version 2.30 was used for carrying out some simulation experiments, with patches for the IEEE 802.15.4 LR-WPAN code implemented by J.Zheng [15]. The implementation covered the essential functionalities except security and the contention free period which consisted of slot reservations for Qos application. In the current experiments, we adopted the same PHY layer and radio parameters. Some extensions to the Mac layer were introduced to accommodate to the proposed simulation settings. We considered the 868 MHz frequency band. A Beacon enabled star topology network is studied. It is assumed that the Beacon interval is composed of active and inactive parts. The simulation scenarios were run in static environment where 15 FFD nodes were distributed around a circle of 10 meter radius, with the PAN coordinator at the center Figure 5. We used the Constant Bit Rate CBR traffic for all simulation sessions [12][15][16].

Parameter	Value
Traffic Type	CBR
Number of Nodes	15
Number of Flows	8
Number of Coordinators	1
Node Movement	None
Node Position	Manual (Along a circle of radius POS)
Traffic Direction	Node -> Coordinator
Packet Size	70Bytes

Table 1. Parameters for Simulation

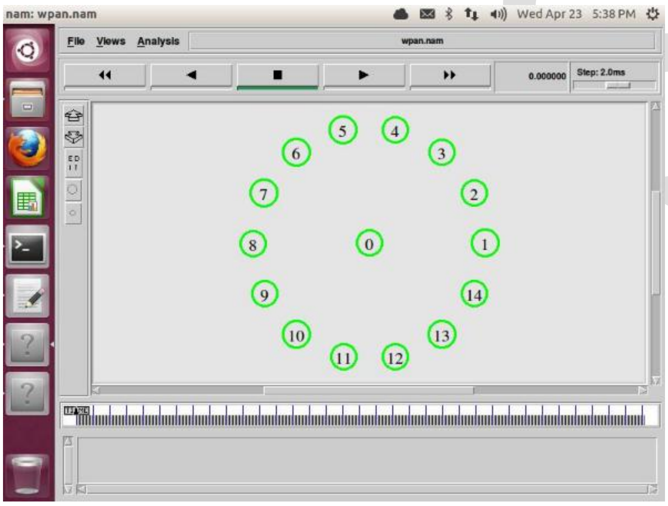

Fig 5. Network Topology.

VI. RESULTS

An extensive series of simulations was carried out using the IEEE 802.15.4 Beacon-enabled. The network performance was analyzed by varying the time interval between the packets. After analyzing the trace file, we extract the following metrics which are used to study the performance of the proposed model of the IEEE 802.15.4. All metrics are defined with respect to MAC sublayer and PHY layer in order to isolate their effects from those of upper layers.

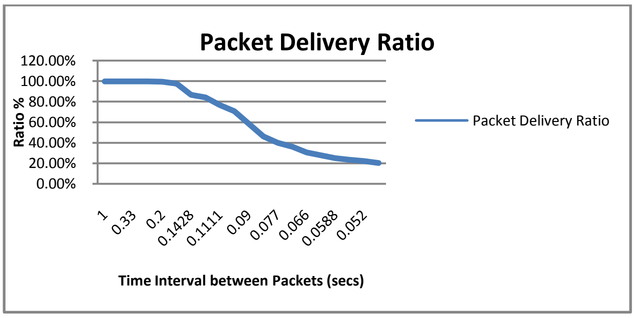

Fig.6 Data Packet Delivery Ratio

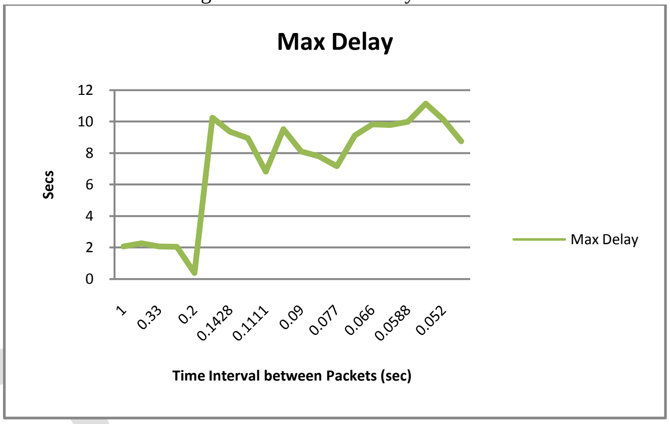

Fig 7. Maximum Delay results

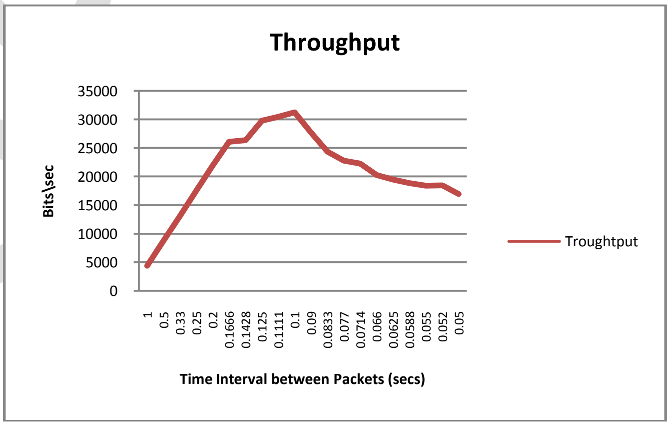

Fig 8. Throughput results.

VII. CONCLUSIONS

In this paper, focus on the modification of the IEEE 802.15.4 module into the NS2 simulator and its performance evaluation. Additional settings (BO=SO=3) is included to investigate their effects on the network performances. Hence, we analyze the achieved throughput for different duty cycle. We observed that lower data rate order gives a worse throughput because of the higher packet drop probability. The IEEE 802.15.4/Zigbee using the Beacon mode achieves high Packet Delivery Ratio active transmitting and standby period can be adjusted(SO and BO). The packet delivery ratio show that the drop probability increase with the increase in the data rate for IEEE 802.15.4 for Wireless Sensor Networks having 15 nodes with 1 coordinator.

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