Performance Analysis of Low Rate and Low Power IEEE 802.15.4 Standard for Personal Wireless Area Networks

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Summary

A new standard IEEE 802.15.4 was uniquely designed to suit personal wireless networks requirement consuming low power, provides low data rate and low cost. In this paper, an effort is made to analyze the performance of Low Rate and Low Power IEEE 802.15.4 in heterogeneous simulation environment. The simulation in NS2 is carried out for three types network topology with varying network density Both beacon and non beacon enabled experiments are carried out on different traffic type. It is already known fact that IEEE 802.15.4 outperforms than IEEE 802.11 in terms of routing overhead and also power consumption. In this paper, we also discuss the reasons that could degrade the overall network performance with varying node density. To cover all the scenarios, we have considered hierarchical topology and peer to peer beacon enabled network. Both beacon and non beacon enabled experiments are carried out on different traffic type.

Key words:

IEEE 802.15.4 , wireless networks.. Hierarchical topology and peer to peer beacon enabled network

1. Introduction

IEEE 802.15.4 is a new standard uniquely designed for low rate wireless personal area networks (LR-WPANs). It targets low data rate, low power consumption and low cost wireless networking, and offers device level wireless connectivity. The new IEEE 802.15.4 standard, compared with IEEE 802.11, is more efficient in terms of overhead and resource consumption. A host of new applications can benefit from the new standard, such as those using sensors that control lights or alarms, wall switches that can be moved at will, wireless computer peripherals, controllers for interactive toys, smart tags and badges, tire pressure monitors in cars, inventory tracking devices. 802.15.4 has been designed as a flexible protocol in which a set of parameters can be configured to meet different requirements. As such, we also try to find out how users can tailor the protocol to their needs and where the tradeoff is for some applications.

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IEEE 802.15.4 standard was designed for LR-WPANs. WPAN is an all-wireless deployment of sensor nodes, which include a sink, specifically known as PAN coordinator for short-range communication. The network architecture is such that a virtual backbone is formed, with the PAN coordinator serving as the core node while other devices function as child nodes that rely on their parent, in this case the PAN coordinator, during network establishment and communication. This basic topology can be extended to a multi-tiered hierarchical network by electing one or more child nodes as a coordinator or cluster-head to manage their own WPAN. Existing discussions on WSNs, and LR-WPANs in particular, assume immobile operation of wireless sensors.
This paper is organized as follows: Section 2 covers related work in this area. The description of IEEE 802.15.4 is covered in section 3. Different network scenarios are explained in the next section 4. In section 5, the simulation set up and experimental results are discussed. The last section 6 concludes this paper.

2. Related Work

This work is motivated by the tremendous potential of IEEE 802.15.4 in supporting simple, low-rate, and low-power applications for LR-WPANs. Before real time applications could be implemented, extensive performance evaluation on the standard is necessary to obtain an idea of what to expect, especially when critical issue like QoS is of concern. Therefore, several efforts on performance evaluations were conducted since the inception of IEEE 802.15.4. This paper is significantly different from other existing works because it covers simulation and different topological experiments focusing on small-scale networks with seven sensor nodes, thus providing simulated as well as actual performance measurements. While current evaluation studies on IEEE 802.15.4 focus on 1-hop J. Zheng and M.J. Lee [4] implemented the IEEE 802.15.4 network only, this paper describes the first experiment on multi-hop ad hoc networks. J. Zheng and M.J. Lee [4] implemented the IEEE 802.15.4 standard on ns2 simulator and subsequently produced the first performance evaluation on 802.15.4.

The literature comprehensively defines the 802.15.4 protocol as well as simulations on various aspects of the standard. This paper has a minor evaluation on the performance of hierarchical topology network and peer-to-peer networks. Other works [5,6] focused on simple 1-hop star network. G. Lu et. al. [6] implemented their own ns2 version of 802.15.4 and studied its performance in beacon-enabled mode while J.S. Lee [6] performed a realistic experiment using hardware devices. Finally, Timmons and Scanlon [7] presented an analytical analysis of the protocol in body are networking (BAN).

3. IEEE 802.15.4 overview

The 802.15.4 standard defines physical (PHY) and medium access control (MAC) layer protocols for supporting relatively simple sensor devices that consume minimal power and operate in an area of 10m or less. The point of service (POS) may be extended beyond 10m but this requires additional energy to operate. It also allows two types of topologies such as a simple one hop star or a self configuring peer-to-peer network to be established. In terms of wireless links, 802.15.4 operates in three license free industrial scientific medical (ISM) frequency bands, i.e. data rates of 250 kbps in the 2.4 GHz band, 40 kbps in the 915 MHz band, and 20 kbps in the 868 MHz band. The first band has 16 channels while the second has 10. The latter was allocated one channel. Though only one channel is used at a time, the additional channels allow the flexibility of switching to another in case the existing becomes not conducive. There are two categories of devices in 802.15.4. One of them is called full-function device (FFD) while the other is reduced-function device (RFD). RFD is crude device supporting simple application such as a switch or sensor. It is usually controlled by FFD device. RFDs can be used to communicate among themselves and with FFDs. The former is desired in this paper because it can take on the role of a router that enables peer-to-peer communication. In terms of addressing, the protocol assumes the use of either 16bit short or extended 64-bit IEEE addresses. The latter is available in all devices by default and is commonly known as physical (MAC) address while the previous is allocated by the PAN coordinator which the device is associated with. In the following section we shall describe briefly the IEEE 802.15.4 standard particularly the MAC and PHY layer.

A. PHY Layer

The PHY layer provides an interface between the MAC sub layer and the physical radio channel. It provides two services, accessed through two service access points (SAPs). These are the PHY data service and the PHY management service. The PHY protocol performs energy detection (ED) scan and clear channel assessment (CCA) on the channel to detect any ongoing activities and relay the results to the MAC layer. A channel is considered busy if the activity levels detected exceed certain threshold value. Another important assessment is link quality. Upper layers protocols(MACandnetwork) depend on this information before deciding on using a particular channel because external interferences such as noise and electromagnetic signal could affect the network performance. If a particular channel is not feasible, there are 26 other channels available under 802.15.4 to be selected. As part of 802.15.4 effort in preserving energy, the radio transceiver can be turned off if inactive (not receiving or transmitting).

B. MAC Layer

This layer provides an interface between upper layers and the PHY layer. It handles channel access, link management, frame validation, security, and nodes synchronization. In our approach, we adopt beaconless mode which implies unslotted CSMA/CA mechanism. For this mode, the PAN coordinator is responsible of handling only device association/disassociation and (short) address allocation in case the 64-bit IEEE addressing is not used. The CSMA/CA protocol is an important mechanism for channel access but does not include the RTS/CTS handshake, considering low data rate adopted in 802.15.4. This mechanism evaluates the channel and allows data packets to be transmitted if the condition is suitable (free of activities). Otherwise the algorithm shall back off for certain periods before assessing the channel again. Without the RTS/CTS handshake, it would appear to encourage packet collisions due to hidden nodes [8]. Nodes are considered hidden if they are out of signal range of each other.

4. Network Scenarios

We define three so-called “network growing” scenarios, in which the network is enhanced by incrementally adding new nodes, and by incremental introduction of new sensor network applications. Starting from a simple scenario and moving towards more challenging ones we want to examine how IEEE 802.15.4 networks (WPAN) can self organize to support sensor application coexistence and inter-working. The scenarios under consideration are described and illustrated below.

IEEE 802.15.4 has been designed as a flexible protocol in which a set of parameters can be configured to meet different requirements. The topology of this network is hierarchical.

In a hierarchical topology, a device only communicates with its coordinator. This is used to evaluate the association efficiency under different number of beaconing coordinators and different beacon orders. The same network topology, transmission range, frequency band, data rate and peer to peer application sessions are used. Except PAN coordinator (node 0) and the leaf nodes depicted in grey, which are pure devices, all the other nodes serve as both coordinator (to its children) and device (to its parent). A device can only reach the adjacent devices to it. All other devices are hidden. This is used to study the device orphaning behaviour, how often orphaning happen and what percentage of orphaning, in terms of number of orphaned devices or number of orphaning, can be recovered.

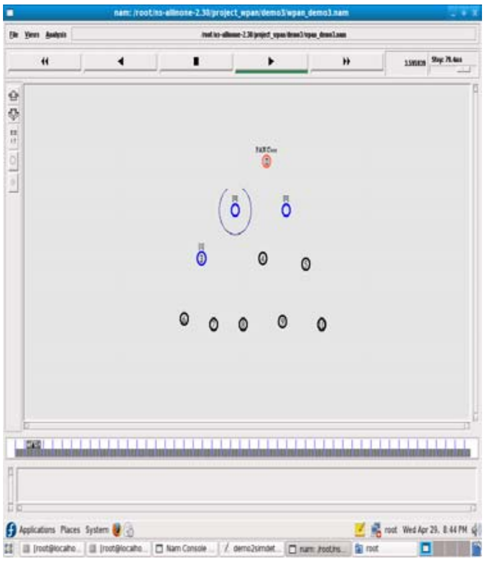

Figure 1. Hierarchical topology with PAN Coordinator (red node)

ZigBee employs either of two modes, beacon or non-beacon to enable the to-and-fro data traffic. Beacon mode is used when the coordinator runs on batteries and thus offers maximum power savings, whereas the non-beacon mode finds favor when the coordinator is mains-powered.

Second topology is known as peer to peer peer-to-peer topology with beacon enabled mode. This is also target the collision behavior of 802.15.4., which consists of one central coordinator and up to one hundred one devices as shown in the Figure 2. In this topology, a device only communicates with its coordinator. This is used to evaluate the association efficiency under different number of beaconing coordinators and different beacon orders. The same network topology, transmission range, frequency band, data rate and peer to peer application sessions are used. Except PAN coordinator (node 0) and the leaf nodes depicted in grey, which are pure devices, all the other nodes serve as both coordinator (to its children) and device (to its parent). A device can only reach the coordinator and two devices adjacent to it. All other devices are hidden.

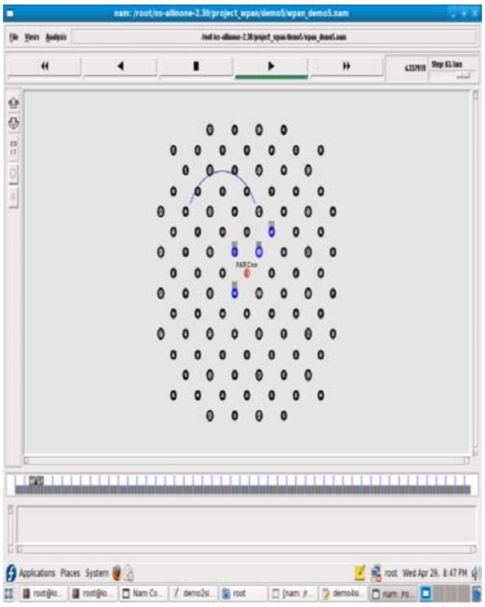

Figure 2. Peer-to-peer beacon enabled Network (101 nodes)
(Association of nodes in the initial stage)

In the beacon mode, a device watches out for the coordinator's beacon that gets transmitted at periodically, locks on and looks for messages addressed to it. If message transmission is complete, the coordinator dictates a schedule for the next beacon so that the device ‘goes to sleep'; in fact, the coordinator itself switches to sleep mode. While using the beacon mode, all the devices in a mesh network know when to communicate with each other. In this mode, necessarily, the timing circuits have to be quite accurate, or wake up sooner to be sure not to miss the beacon. This in turn means an increase in power consumption by the coordinator's receiver, entailing an optimal increase in costs.

The non-beacon mode will be included in a system where devices are ‘asleep' nearly always, as in smoke detectors and burglar alarms. The devices wake up and confirm their continued presence in the network at random intervals. On detection of activity, the sensors ‘spring to attention', as it were, and transmit to the ever-waiting coordinator's receiver (since it is mains-powered). However, there is the remotest of chances that a sensor finds the channel busy, in which case the receiver unfortunately would ‘miss a call'. Thus third topology is peer-to-peer topology with beacon enabled mode.

5. Simulation Results and Analysis

5.1 Performance Metrics

We define the following metrics for studying the performance of 802.15.4.

Packet delivery ratio: The ratio of packet successfully sent to packets received in MAC Sub-layer.

PDR: *Number of packets received / Number of packets sent X 100*

Hop Delay: The transaction time o f passing a packet to a one-hop neighbor, including time of all necessary processing, back off as well as transmission, and averaged over all successful end-to-end transmissions within a simulation run.

Hop Delay: *End Time – Start Time / Total number of received packets*

Routing Overhead: The total number of control packets transmitted during communication.

Successful association rate: The ratio of devices successfully associated with a coordinator to the total devices trying to associate with a coordinator. In our simulation, a device will retry in one second if it fails to associate with a coordinator in the previous attempt. The association is considered successful if a device is able to associate with a coordinator during a simulation run, even if multiple association attempts have been made.

Association efficiency: The average number of attempts per successful association

5.2 Experimental Setup

Scenario - 1

In this set of experiments for measuring the performance behaviour of IEEE 802.15.4 such as packet delivery ratio, delay and successful association, we have considered hierarchical topology with beacon enabled mode. The following specifications are used for the experiment.

Node density: 11 (Including center PAN coordinator)
Simulation Area: 50 x 50 m^2
Traffic Type: CBR/FTP/Poisson
Traffic flow: 0 to all other devices
Transmission Range: 10 meters
Routing Protocol: AODV
Duration: 900 seconds
Data rate: 250 kbps
Beacon order: 0 to 10.

The table 1.1 shows the captured simulation data from the hierarchical topology wpan. The number of packets dropped very negligible in case of Poisson distribution. This is due to uniform generation of packets with respect to adaptability of network. But the application traffic FTP generates huge routing overhead with also high PDR (93%). The Hop Delay of CBR and Poisson is almost nearer and FTP has recorded still low delay. This is because of flow of traffic in Poisson uses probability distribution function.

Table 1.1 Simulation data for hierarchical topology

Traffic Type	No of Packets sent	No of Packets received	No of Packets forwarded	No of Packets Dropped	PDR (Packet Delivery Ratio)	Hop Delay	Routing Overhead	Association Efficiency (%)
CBR	1844	5731	0	22	32.17	0.0174	7600	100%
FTP	32636	30535	0	417	93.56	0.0032	63591	100%
Poisson	1814	5700	0	6	31.82	0.0175	7523	100%

No significant difference has been observed in the packet delivery ratio among the three data transmission methods. Nevertheless, the hop delay varies, which will definitely affect the packet delivery ratio in upper layers. The hop delay indirect data transmission is much shorter than those in indirect and GTS data transmissions.

Scenario - 2

In this set of experiments for measuring the performance behaviour of IEEE 802.15.4 such as packet delivery ratio, delay and successful association, we have considered peer to peer topology with beacon enabled mode. The following specifications are used for the experiment.

Node density: 101 (Including center PAN coordinator)
Simulation Area: 80 x 80 m^2
Traffic Type: CBR/FTP/Poisson
Traffic flow: 0 to all other devices
Routing Protocol: AODV
Transmission Range: 9 meters
Duration: 900 seconds
Beacon Order: In sequence (0 to 99)
Data Rate: 250 kbps

The table 1.2 shows the captured simulation data from the peer to peer with beacon enabled mode in WPAN. The number of packets dropped very high in case of FTP. This is due to beacons where device watches out for the coordinator's beacon that gets transmitted at periodically, locks on and looks for messages addressed to it. Due to this a huge amount of control packets are generated and gets collided resulting in dropping of packets. But the application traffic FTP generates huge routing overhead with also high PDR (91%) and CBR and Poisson maintains almost same.

Table 1.2 Simulation data for Peer to peer with beacon enabled mode

Traffic Type	No of Packets sent	No of Packets received	No of Packets forwarded	No of Packets Dropped	PDR (Packet Delivery Ratio)	Hop Delay	Routing Overhead	Association Efficiency
CBR	7467	9895	0	5707	75.46	0.0101	23071	100%
FTP	18650	20338	0	9579	91.70	0.0049	48569	99%
Poisson	7469	9875	0	5725	75.63	0.0101	23071	100%

But there is slight drop in the PDR for FTP (75%) and Poisson (75%). The Hop Delay of CBR and Poisson are almost same and FTP has recorded low delay. This is because of flow of traffic in Poisson uses probability distribution function for generating packets and transmission.

No significant difference has been observed in the packet delivery ratio among the two data transmission methods (CBR and Poisson). There is drop in PDR and routing overhead remains almost same. Nevertheless, the hop delay varies, which will definitely affect the packet delivery ratio in upper layers. The hop delay indirect data transmission is much shorter than those in indirect and GTS data transmissions.

6. Conclusion

ZigBee is one of the global standards of communication protocol formulated by the relevant task force under the IEEE 802.15 working group. The fourth in the series, WPAN Low Rate/ZigBee is the newest and provides specifications for devices that have low data rates, consume very low power and are thus characterized by long battery life. It brings to light a host of new applications as well as changes many other existing applications. It is the first standard to allow simple sensors and actuators to share a single standardized wireless platform.

To evaluate the general performance of this new standard, we develop an NS2 simulator, which covers all the 802.15.4 MAC and network layer primitives, and carry out two sets of experiments, that is, experiments of:

(1) Hierarchical topology with PAN Coordinator

(2) Peer-to-peer beacon enabled Network (101 Nodes including one PAN Coordinator)

Detailed experimental results are presented, and analyses and discussions are given.

No significant difference has been observed in the packet delivery ratio among the three data transmission methods. Nevertheless, the hop delay varies, which will definitely affect the packet delivery ratio in upper layers. The hop delay indirect data transmission is much shorter than those in indirect and GTS data transmissions.

The obtained simulation data from the peer to peer with beacon enabled mode in WPAN. The number of packets dropped very high in all the three cases. This is due to beacons where device watches out for the coordinator's beacon that gets transmitted at periodically, locks on and looks for messages addressed to it. Due to this a huge amount of control packets are generated and gets collided resulting in dropping of packets. Association and tree formation in 802.15.4 proceed smoothly in both beacon enabled mode and non beacon enabled mode, which implies 802.15.4 possesses a good self-configuration feature and is able to shape up efficiently without human intervention. The orphaning and coordinator relocation (recovery from orphaning) mechanism provides for a device a chance of self-healing from disruptions.

In the beacon mode, a device watches out for the coordinator's beacon that gets transmitted at periodically, locks on and looks for messages addressed to it. If message transmission is complete, the coordinator dictates a schedule for the next beacon so that the device 'goes to sleep'; in fact, the coordinator itself switches to sleep mode. The non-beacon mode will be included in a system where devices are 'asleep' nearly always, as in smoke detectors and burglar alarms. The devices wake up and confirm their continued presence in the network at random intervals. On detection of activity, the sensors 'spring to attention', as it were, and transmit to the ever-waiting coordinator's receiver (since it is mains-powered).

For the lack of RTS/CTS, 802.15.4 is expected to suffer from hidden terminal problems. Our experiment results match this expectation. But for low data rates up to one packet per second, the performance degradation is minor. The default CSMA-CA back-off period in 802.15.4 is too short, which leads to frequent repeated collisions. Superframes with low beacon orders can also lower the slotted CSMA-CA back-off efficiency and lead to high collision probability at the beginnings of superframes. Our simulation study shows that 802.15.4 is an energy-efficient standard favouring low data rate and low power consumption applications.

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