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Simulative Performance Evaluation of 802.15.4 with Different Modulations for Wireless Sensor Networks

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Abstract: This paper presents the simulative performance analysis of different modulations schemes for Signal/Noise (SNR), packets marked noise and Packet Loss Ratio (PLR) using IEEE 802.15.4 based OPNET simulative model for Wireless Sensor Networks (WSNs). It is proved that Minimum Shift Keying (MSK) is desirable in IEEE 802.15.4 WSN if SNR is to be maximized. Also it is proved that if packets marked noises are to be minimized then Binary Phase Shift Keying (BPSK) at the PAN (Personal Area Network) Coordinator & GTS (Guaranteed Time Slot) End Device and MSK at the Non GTS End Device should be preferred. Furthermore it is proved that if PLR is to be reduced to minimum then MSK at the PAN Coordinator and BPSK at the End devices should be preferred. Overall there is trade-off for the use of modulation schemes in 802.15.4 WSNs.

Key words: Signal/noise ratio, packets marked noise, packet loss ratio, QAM_64, MSK.

1. Introduction

Wireless networks are nowadays largely used in areas crowded of radio disturbances, due to electrical and electronic appliances and devices, wireless communication systems and other networks sharing the same frequency bands. As a consequence, destructive interferences frequently arise, and effects loss of performance and poor reliability consequently occur. Typical interference effects are loss of data packets, transmission delays, jitter, loss of synchronization, noise and so on.

IEEE 802.15.4 low rate – wireless personal area network standard is of particular interest to Wireless Sensor Network (WSN) research community because it is the first wireless communication standard built around devices with severe constraints on power consumption rates. Thus it is widely anticipated that IEEE 802.15.4 will play a major role in WSN applications. The standard may support variety of network topologies. An interesting one is star configuration, where a PAN Coordinator cyclically queries a set of End Devices (sensor nodes), one by one, and the End Devices reply transmitting a short data unit (frame) containing the information acquired by the sensor. The transmission between the PAN Coordinator and the End Device is performed inside the 2.4 GHz ISM band, at 250 kbps and exploiting one of the 16 available channels. For each sensor node of the network, the PAN Coordinator dedicates a time interval, called polling window, of the fixed time length. The PAN Coordinator starts waiting a backoff period, and then senses the air according to the CSMA/CA protocol. If the channel band is free, it transmits frame to whole of the network containing the information like the destination node address, time stamps etc.. The sensor node queried, after a pre-fixed short delay replies with an acknowledgement (ACK) and then waits for the second back-off period. At the end of the wait, it senses the air and if free it transmits the Maximum Size Data Unit (MSDU). In case of
correct reception, PAN Coordinator issues the ACK and at the end of the polling window it passes to the subsequent sensor node (End Device). If the sensor node does not receive the ACK from the PAN Coordinator, it waits for another backoff period and then retires to transmit. At the expiration of polling window if the ACK has not been received yet, the data packet from that sensor is considered lost.

Early work on 802.15.4 has been reported by the various researchers [1-27]. Some have investigated various performance issues like: delay, throughput evaluation of GTS mechanism [1]. Some have worked on adaptive modulation suitable for wireless sensor networks with SER and throughput constraints [3]. Some researchers have carried out the research on reducing the packet losses in networks of commodity IEEE 802.15.4 sensor motes [5]. Few others have worked on packet loss analysis of IEEE 802.15.4 MAC without acknowledgements [8]. Some researchers have also investigated the impact of queuing discipline on packet delivery latency in ad hoc networks [11]. Some researchers have analyzed and modeled error process in IEEE 802.15.4 [12]. Few others have analyzed packet error rate of Zigbee under the interference of RFID [15]. Some researchers have compared frequency in both medium and high SNR cases [18]. Researchers have also estimated SNR using a priori information [19]. Some have also estimated SNR for OFDM systems [21]. Some have used SNR to sense spectrum in radio networks [22]. Some researchers have used SNR to combat multipath fading [25]. But none of the researchers have so far compared the modulation schemes in 802.15.4 for signal / noise ratio, packets marked noise and packet loss ratio for different WPAN devices. This paper proposes the comparison of different modulation schemes (MSK, BPSK, QAM_64) to determine the suitability of the scheme according to the device type (FFD/RFD).

Rest of the paper is organized as follows: Section 2 constitutes the system description which contains the different scenarios and parametric tables of the model. Section 3 describes the results and discussions derived from the simulations carried out on 802.15.4 for different modulation schemes. Finally section 4 concludes the paper.

2. System Description

The simulation model implements physical and medium access layers defined in IEEE 802.15.4 standard. The OPNET® Modeler 14.5 is used for developing 802.15.4 wireless sensor network.

Fig. 1 shows three different Scenarios: BPSK, MSK and QAM_64. BPSK Scenario as shown in Fig. 1(a) contains one PAN Coordinator, one analyzer and thirty two end devices out of which sixteen are Guaranteed Time Slots (GTS) enabled and rest are non GTS devices. PAN Coordinator is a fully functional device which manages whole functioning of the network. Analyzer is a routing device which routes the data between PAN coordinator and the End Devices. End Devices are the fixed stations that communicate with the PAN Coordinator in Peer to Peer mode, support GTS and non GTS traffic respectively. Similar Scenarios have been created for MSK and QAM_64 as shown in Fig. 1 (b & c).

Fig. 2 shows the node models for three types of WPAN devices used for modeling 802.15.4 scenarios. PAN Coordinator, GTS and Non GTS end device have the same node model as shown in Fig. 2 (a) while the node model for analyzer is depicted in Fig. 2 (b).

As it has been observed from the Fig. 2 (a), a node model for PAN Coordinator, GTS and Non GTS end device have the same node model as shown in Fig. 2 (a) while the node model for analyzer is depicted in Fig. 2 (b).

As it has been observed from the Fig. 2 (a), a node model for PAN Coordinator, GTS and Non GTS end device has three layers: physical, MAC and application layers. Physical layer consists of a transmitter and a receiver compliant to the IEEE 802.15.4 specification, operating at 2.4 GHz frequency band and data rate equal to 250 kbps. MAC layer implements slotted CSMA/CA and GTS mechanisms. The GTS data traffic coming from the application layer is stored in a buffer with a specified capacity and dispatched to the network when the corresponding GTS is active. The non time-critical data frames are stored in an unbounded buffer and based on slotted CSMA/CA algorithm are transmitted to the network.
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Fig. 1  Network Scenarios (a) BPSK (b) MSK (c) Quadrature (QAM_64).

Fig. 2  Node Model (a) PAN Coordinator, GTS and Non GTS end device (b) Analyzer.

during the active Contention Access Period (CAP). This layer is also responsible for the generation of beacon frames and synchronizing the network when a given node acts as a PAN Coordinator. Finally is the topmost application layer which is responsible for generation and reception of traffic consists of two data traffic generators (i.e., Traffic Source and GTS Traffic Source) and one traffic sink. The traffic source generates acknowledged and unacknowledged data frames transmitted during CAP. GTS traffic source can produce acknowledged and unacknowledged time-critical data frames using GTS mechanism. The
traffic sink module receives frames forwarded from lower layers. Fig. 2 (b) shows the node model for the analyzer which consists of sink and a radio receiver.

Corresponding process models for PAN Coordinator, GTS end device, Non GTS end device and analyzer that deals with each and every operation on the data are depicted in Fig. 3.

Fig. 3 (a) shows the process model for the PAN Coordinator, GTS and Non GTS end device. It consists of the various states: Init whose function is to initialize MAC and GTS scheduling; Wait_beacon which is responsible for synchronizing the traffic of the node with rest of the WPAN in order to minimize the collisions; Idle which is responsible for introducing delays in order to make the maximum use of the resources; gts_slot which is responsible for generation, reception and management of GTS traffic; Backoff_timer used for sensing the medium and transfer of data, CCA - for interrupt processing. Similarly Fig. 3 (b) shows the process model for analyzer which consists of init and idle states. Basically the process model explains how the data is sent from the generating node to the PAN Coordinator, taking into consideration the availability of PAN Coordinator as it has to communicate with the other similar nodes.

Here three different Scenarios have been created with
three different modulation formats: BPSK, MSK and QAM_64. Following parameters have been set for these scenarios as shown in Table 1 like: destination MAC address (Acknowledged Traffic Source) of the PAN coordinator is broadcast while for GTS enabled end device and Non GTS end device the value is common i.e. PAN coordinator. Similarly the value of Superframe order in WPAN Settings is 6 (common for PAN coordinator, GTS end device and Non GTS end device).

### 3. Results and Discussions

Simulation has been carried out with three different

<table>
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<tr>
<th>Table 1</th>
<th>Parametric values for PAN Coordinator, GTS and Non GTS End Device in BPSK, MSK and QAM_64 Scenarios.</th>
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<td>Parameter \ Scenario</td>
<td>PAN Coordinator</td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK, MSK, QAM_64</td>
</tr>
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<td>Acknowledged traffic source</td>
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<td>Destination MAC address</td>
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<td>MSDU size (bits)</td>
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scenarios of IEEE 802.15.4 WPAN for Wireless Sensor Network (WSN) having QAM_64, MSK and BPSK modulation formats respectively: Quadrature (QAM_64), MSK and BPSK. In this section, results for radio receiver signal / noise ratio, packets marked noise and packet loss ratio have been presented and discussed for different types of devices in wireless sensor networks like: Fully Functional Devices (FFD’s)– those devices that control the network and manage the routing tables, Reduced Functional Devices (RFD’s) – those devices which can communicate to the FFD but not to the other RFD’s.

3.1 Radio Receiver Signal / Noise Ratio

3.1.1 Fully Functional Device–PAN Coordinator

Fig. 4 shows signal/noise ratio at the PAN Coordinator is 5262.9, 5071.1 and 4865.3 dB for MSK, BPSK and QAM_64 respectively. It is observed that signal/noise ratio is maximum in case of MSK because delays in MSK reduces the phase shift and results in amplifier-friendly signals; also the interference from the adjacent signals is less because of the lower side lobes which improves its signal/noise ratio [24, 26]. Also it has been observed that signal/noise ratio is minimum in case of QAM_64 for the reason that in QAM_64 decision points are comparatively closer to each other, so more susceptible the channel is to noise as the decision boundaries get smaller to accommodate more decision points which gives rise to more noise as a result of which signal/noise ratio decreases [17, 20, 27]. From the above results it is concluded that if signal/noise ratio is to be considered at the PAN Coordinator then MSK should be preferred.

3.1.2 Reduced Functional Device – GTS End Device

Fig. 5 represents that the packets marked noise at the GTS end Device are: 1.1364, 0.9958 and 0.8748 for QAM_64, MSK and BPSK respectively. It is observed that packets marked noise are minimum in case of BPSK because transmitter and receiver are synchronized and it is able to modulate only 1 bit/sec [26, 27]. It has also been observed that packets marked noise are maximum in case of QAM_64 because it has large number of decision points which are very close to each other, so making the channel more susceptible to noise as the decision boundaries get smaller to accommodate more decision points, it becomes harder to distinguish which boundary the decision point was intended to lie in, all

3.1.3 Reduced Functional Device – Non GTS End Device

Fig. 6 shows that the signal / noise ratio at the Non GTS End Device is: 3880.1, 3781.5 and 3732.1 dB for MSK, BPSK and QAM_64 respectively. It is observed that signal / noise ratio is maximum in case of MSK [24, 26]. Also it has been observed that signal / noise ratio is minimum in case of QAM_64 [17, 20, 27]. From the results obtained in the Figs. 4-6, it is concluded that Minimum Shift Keying (MSK) is comparatively more suitable as compared to the other modulation schemes in all type of devices in 802.15.4 wireless sensor networks if signal / noise ratio of radio receiver is to be considered.

3.2 Radio Receiver Packets Marked Noise

3.2.1 Fully Functional Device – PAN Coordinator

Fig. 7 represents that the packets marked noise at the radio receiver of the PAN Coordinator are: 1.1364, 0.9958 and 0.8748 for QAM_64, MSK and BPSK respectively. It is observed that packets marked noise are minimum in case of BPSK because transmitter and receiver are synchronized and it is able to modulate only 1 bit/sec [26, 27]. It has also been observed that packets marked noise are maximum in case of QAM_64 because it has large number of decision points which are very close to each other, so making the channel more susceptible to noise as the decision boundaries get smaller to accommodate more decision points, it becomes harder to distinguish which boundary the decision point was intended to lie in, all
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Fig. 5 Radio receiver signal / Noise ratio at the GTS end device.

Fig. 6 Radio receiver signal / Noise ratio at the non GTS end device.

Fig. 7 Radio receiver packets marked noise at the PAN coordinator.

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3.2.2 Reduced Functional Device–GTS End Device

Fig. 8 reveals that the packets marked noise at the radio receiver of GTS End Device are: 1.2004, 1.0652 and 1.0268 for QAM_64, MSK and BPSK respectively.

It is observed that packets marked noise are minimum in case of BPSK [26, 27]. It has also been observed that packets marked noise are maximum in case of QAM_64 [20, 27].

3.2.3 Reduced Functional Device–Non GTS End Device

Fig. 9 shows that the packets marked noise at the radio receiver of Non GTS End Device are: 1.1728, 1.0815 and 1.0073 for QAM_64, BPSK and MSK respectively. It is observed that packets marked noise are minimum in case of MSK because delays in MSK reduces the phase shift and results in amplifier friendly signals also MSK suffers less from the adjacent signal interference [24, 26]. It has also been observed that packets marked noise are maximum in case if QAM_64 [20, 27].

From the results obtained in the Figs. 7, 8, and 9, it is concluded that if packets marked noise at the radio receiver of the PAN coordinator and GTS End Device are to be minimized then BPSK should be preferred. On the other hand if packets marked noise at the radio receiver of the Non GTS End Device are to be reduced to minimum then MSK is comparatively most suitable.

3.3 Radio Receiver Packet Loss Ratio

3.3.1 Fully Functional Device – PAN Coordinator

Fig.10 indicates that the packet loss ratio at the radio receiver of PAN Coordinator is: 19.3543, 1.3791 and 0.7472 for QAM_64, BPSK and MSK respectively. It is observed that MSK suffers least from the adjacent signal interferences as it has much smoother phase...
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Fig. 9 Radio receiver packets marked noise at the non GTS end device.

Fig. 10 Radio receiver packet loss ratio at the PAN coordinator.

Fig. 11 Radio receiver packet loss ratio at the GTS end device.

Fig. 12 Radio receiver packet loss ratio at the non GTS end device.

3.3.2 Reduced Functional Device – GTS End Device

Fig. 11 shows that the packet loss ratio at the radio receiver of GTS End Device is: 17.9024, 1.9287 and 1.4175 for QAM_64, MSK and BPSK respectively. It is observed that packet loss ratio is minimum in case of QAM_64 because states in QAM_64 are very close to each other, therefore are more prone to errors due to noise and distortion [20, 27].

3.3.3 Reduced Functional Device – Non GTS End Device

Fig. 12 represents that the packet loss ratio at the radio receiver of Non GTS End Device is: 15.2762, 0.6365 and 0.4605 for QAM_64, MSK and BPSK respectively. It is observed that packet loss ratio is minimum in case of BPSK [26, 27]. It has also been observed that packet loss ratio is maximum in case of QAM_64 [20, 27].

From the above results obtained in the Figs. 10, 11, and 12, it is concluded that if packet loss ratio at the radio receiver of different types of devices in 802.15.4 wireless sensor network is to be taken into consideration then MSK should be preferred at the PAN Coordinator (FFD) and BPSK at the GTS and Non GTS End Device (RFD). Also it is concluded that QAM_64 is unsuitable for any type of device in IEEE 802.15.4 for WSN if the Packet Loss Ratio (PLR) at the radio receiver is to be taken into consideration.

4. Conclusions

Simulative performance study of LR-WPAN (Low Rate - Wireless Personal Area Network) 802.15.4 for WSN based on simulation model implemented in OPNET® Modeler 14.5 is conducted. Three different modulation scenarios: BPSK, MSK and QAM_64 are
analyzed. Results reveal that signal / noise ratio at the PAN Coordinator, GTS and Non GTS End Device is: [5262.9, 5071.1, 4865.3], [3772.8, 3587.7, 3545.3] and [3880.1, 3781.5, 3732.1] dB for MSK, BPSK and QAM_64 respectively. Further results reveal that packets marked noise at the PAN Coordinator, GTS and Non GTS End Device are: [1.1364, 0.9958, 0.8748], [1.2004, 1.0652, 1.0268] and [1.1728, 1.0073, 1.0815] for QAM_64, MSK and BPSK respectively. Further more it is revealed that packet loss ratio at the PAN Coordinator, GTS and Non GTS End Device is: [19.3543, 0.7472, 1.3791], [17.9024, 1.9287, 1.4175] and [15.2762, 0.6365, 0.4605] for QAM_64, MSK and BPSK respectively. It is concluded that if SNR is to be maximized at the PAN Coordinator as well as End Devices then MSK should be preferred. Also it is concluded that if SNR is to be considered in IEEE 802.15.4 WSN then QAM_64 is unsuitable. Further it is concluded that if packets marked noise at the radio receiver of PAN Coordinator and GTS End Device are to be minimized then BPSK should be preferred but if packets marked noise at the radio receiver of Non GTS End Device are to be reduced to minimum then MSK is more suitable. Furthermore it is concluded that if PLR at the radio receiver of any type of End Device is to be reduced to minimum then BPSK should be preferred. Overall it is concluded that there is trade-off for the use of modulation formats for different types of devices in 802.15.4 wireless sensor networks.

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