Topology Based Performance Analysis of IEEE 802.15.4 for Wireless Sensor Networks

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ABSTRACT
Wireless Local Area Networking standard (Wi-Fi) and the WPAN standard (Bluetooth and Zigbee) products utilize the same unlicensed 2.4 GHz ISM band. Co-existence between such wireless technologies within the same frequency spectrum is crucial to ensure that each wireless technology maintains and provides its desired performance requirements. Wireless Personal Area Networks are formed using tiny sensor devices which have several resource constraints. 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 IEEE 802.15.4 in heterogeneous simulation environment. The simulation in NS2 is carried out for three types network topology with varying network density. To cover all the scenarios, we have considered scatternet, piconet and peer to peer topologies. 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 as well as association efficiency.
KEYWORDS
802.15.4, WPAN, WSN, LR-WPAN, NS2

1. Introduction

IEEE 802.15.4 is an established set of specifications for wireless personal area networking (WPAN), i.e., digital radio connections between computers and related devices. This kind of network eliminates use of physical data buses like USB and Ethernet cables. The devices could include telephones, hand-held digital assistants, sensors and controls located within a few meters of each other. IEEE 802.15.4 is one of the global standards of communication protocol. 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.
Wireless sensor networks (WSN) are complex distributed systems of nodes with sensing, data processing and storage capability, wireless-communication interfaces and, in general, limited power. They are used for the surveillance and control applications in a diverse range of micro and macro environments, such as wild life habitats, urban environments, technical and biological systems and structures [1][2]. One of the central research topics in wireless sensor networking is the design of protocols optimized for the constraints of sensor nodes and for requirements of data dissemination in the network. Disseminations requirements are very specific data from source nodes, potentially highly correlated, may be generated and periodically, on a query, or on a particular event routed, either directly, towards the observer nodes (sinks), or towards aggregation nodes for further processing. Sensing areas may be queried by many observer nodes connected at arbitrary nodes; each query may specify required fidelity, timeliness and reliability. In the past many specific solutions optimized for particular sensing tasks have been proposed and analyzed, which brought better understanding of necessary functionality of the general energy efficient communication stack for wireless sensor networks [3].
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.

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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 802.15.4protocol as well as simulations on various aspects of the standard. This paper has a minor evaluation on the performance of 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 irregular. The sensor nodes are placed randomly on the phenomenon. This is also known as “ScatterNets” which is used to extend the coverage and number of devices is varied.

Second topology is known as one-hop star or Piconet, which consists of one coordinator and up to seven devices. In a piconet, 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.

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 favour when the coordinator is mains-powered.

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 neighbour, 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

The general simulation parameters are depicted on Appendix -1.

Scenario-1

We have identified three set of experiments for measuring the performance of behavior of IEEE 802.15.4 such as packet delivery ratio, delay and control packet overhead. In addition to this, we have also measured the performance of LR-WPANs (Low Rate- WPAN) includes association, orphaning and different transmission modes. In this non –beacon enabled mode is considered and run in multi-hop environment. LR-WPANs use both pure CSMA-CA and slotted CSMA-CA. The following specifications are used for the experiment. Refer Appendix-2 for simulation setup.

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 irregular. The sensor nodes are placed randomly on the phenomenon. This is also known as “ScatterNets” which is used to extend the coverage and number of devices is varied. The simulation starts from with 10 nodes adding 10 nodes up to 50 nodes with 9 meter transmission range which covers the neighbors along diagonal directions. 802.15.4 operates at an over air data rate of 250 kbps in non-beacon enabled mode.

5.3 Result Analysis

In this experiment the nodes are placed in random places and hence it is known as” scatternet. Initially simulation starts with 10 nodes and incrementally node density is incremented by 10 nodes up to 50 nodes. Each of the iteration will consist of three set traffic flows identified or marked in different colours and no random motion. These combinations of the nodes are chosen randomly and user can make the selection of any source and destination. In figure 6 the performance of wpan is analyzed by changing the node density. In the beginning the CBR performs well as the number of nodes is minimum. During increase in the nodes at 50 the PDR drops drastically to 35 %. In all other cases an average of 80% PDR is resulted. This is because of peer to peer application traffic will have impact of delivery ratio drop sharply from 86% to 35%.

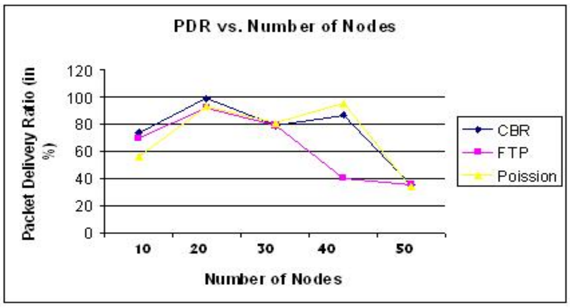

Figure 1.1 Packet Delivery vs. Number of Nodes

In general, 802.15.4 maintains a high packet delivery ratio for application traffic up to 40 (86%), but the value decreases quickly as node density increases. The main advantage of 802.15.4 is not using RTS/CTS as in case of 802.11 standard. In case of FTP performs average as the number of nodes is minimum. During the increase in the nodes gradually the PDR also increases up to 96 % and start dropping slowly towards 35% when node density is 50. In all other cases an average of 70% PDR is resulted. This is because of peer to peer application traffic will have impact of delivery ratio drop sharply from 69% to 96%.

In case of Poisson traffic performs less when compared to CBR and FTP as the number of nodes is minimum initially. During increase in the nodes gradually the PDR also increases up to 95 % and start dropping slowly towards 34% when node density is 50. In all other cases an average of 85% PDR is resulted. This is because of peer to peer application traffic will have impact of delivery ratio drop sharply from 55% to 96% and collisions are ignorable to such traffic loads. The RTS/CTS mechanism also affects the network latency (Hop Delay). We measure the average hop delay for different traffic in comparison, and the results are depicted in Fig. 1.2. The initial FTP results show that 802.15.4 higher delay than CBR and Poisson. Nevertheless, this comparison is unfair to 802.15.4, since it operates at a data rate of 250 kbps while 802.11 operates at 2 Mbps in most of the simulation experiments.

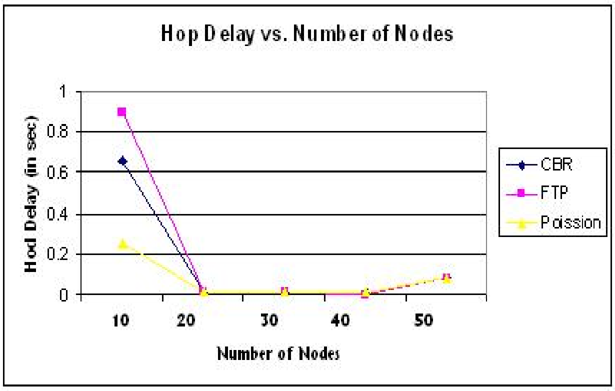

Figure 1.2. Hop Delay vs. Number of Nodes

Taking this into account, we normalize the hop delay according to the media data rate, which gives us a different view that the hop delay of 802.11 is around 3.3 times of that of 802.15.4. The hop delay for sink-type application traffic is 22% (for Poisson) to 66% (for CBR) higher than that for peer-to-peer application traffic FTP is 80%. The increment of delay is expected, since all the traffic flows now need to converge on the sink node.

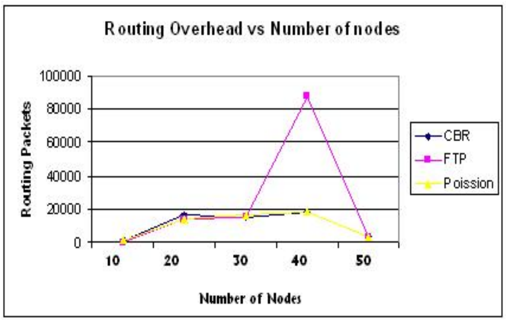

Figure 1.3. Routing Overhead vs Number of nodes

In the figure 1.3, the routing overhead is depicted with changing node density. Since there is no much exchange of control or routing packets as in case of 802.11, all the traffic type will almost maintain the steady stage. Due in burst in application traffic, there is a huge rise (almost 80%) in routing overhead packets at node density 40. Further due to adjustment in the traffic load, the routing overhead drops to normal and continues at node density 50.

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 star topology with beacon enabled mode. The specifications used for the experiment are shown in appendix-3.

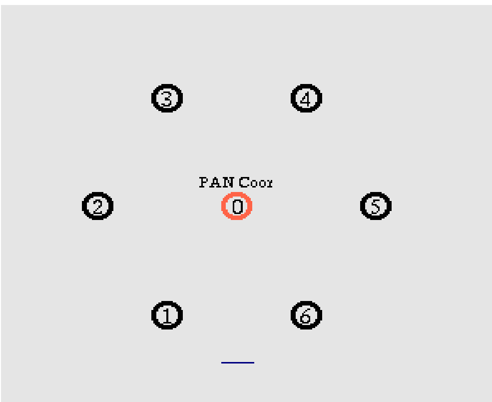

Figure 1.3 Piconet

This topology is known as one-hop star or piconet, which consists of one coordinator and up to seven devices. In a piconet, 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.

Traffic Type	No of Packets sent	No of Packets received	No of Packets Dropped	PDR (Packet Delivery Ratio)	Hop Delay	Routing Overhead
CBR	24195	25503	16529	94.87	0.0039	66231
FTP	17463	24553	19213	71.12	0..0040	61231
Poisson	24627	25623	16782	96.11	0.0039	67036

Table 1.6 Simulation data for Piconet

The table 1.6 shows the captured simulation data from the Piconet WPAN. The number of packets dropped very high in all the cases. This is due to uniform generation of packets with respect to adaptability of network. But the application traffic FTP generates less routing overhead compared with CBR and Poisson also low PDR (78%). The Hop Delay of CBR and Poisson is almost nearer and FTP has recorded high delay. This is because of flow of traffic in Poisson uses probability distribution function makes packet generation and transmission time consuming.

Scenario-3

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. This is also target the collision behaviour of 802.15.4. The following specifications are used for the experiment are depicted in Appendix-4.

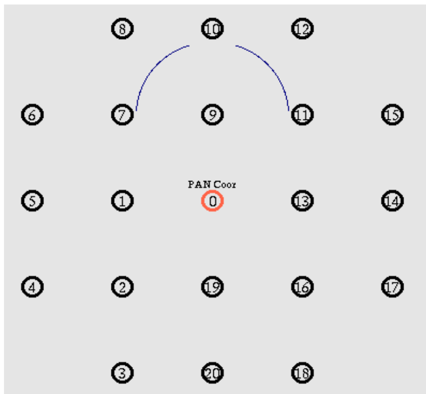

Figure 1.7. Peer-to-peer beacon enabled Network

The topology is shown in figure 1.7 is known as Peer-to-peer beacon enabled network, which consists of one coordinator and up to twenty one devices. In a piconet, 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.

Traffic Type	No of Packets sent	No of Packets received	No of Packets Dropped	PDR (Packet Delivery Ratio)	Hop Delay	Routing Overhead
CBR	24195	25503	16529	94.87	0.0039	66231
FTP	17463	24553	19213	71.12	0..0040	61231
Poisson	24627	25623	16782	96.11	0.0039	67036

Table 1.7 Simulation data for Peer to peer network

The table 1.7 shows the captured 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. But the CBR, application traffic FTP and Poisson generates huge routing overhead with also high PDR (96%-94%). But there is slight drop in the PDR for FTP (71%). The Hop Delay of CBR and Poisson is almost same and FTP has recorded slight high delay. This is because of flow of traffic in Poisson uses probability distribution function for generating packets and transmission.

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 three sets of experiments, that is, experiments of Comparing the performance of 802.15.4 between CBR, FTP and Poisson traffic with varying node density considering ScatterNet topology, PicoNet with PAN Coordinator and Peer-to-peer beacon enabled Network (21 Nodes including one PAN Coordinator). Detailed experimental results are presented, and analyses and discussions are given.

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.

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. 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 favoring low data rate and low power consumption applications.

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APPENDIX-1

Parameter	Value
Link BER	10-6 to 10-5
Packet Error Rate	0.2%
Simulation Duration	1000 seconds
Application Traffic	20 to 900 seconds
Traffic Type	CBR/FTP/Poisson
Radio Propagation Model	Two-ray ground reflection
Application Packet Size	90 bytes

APPENDIX-2

Parameter	Value
Node Density	10,20,30,40,50
Simulation Area	50 x 50 m2
Traffic flow	9->6, 4->2 and 3 -> 2
Transmission Range	15 meters
Traffic Type	CBR/FTP/Poisson
Routing Protocol	AODV
Duration	900 seconds

APPENDIX-3

Parameter	Value
Node Density	07 (including PAN Coordinator)
Simulation Area	50 x 50 m2
Traffic flow	0 to all other devices
Transmission Range	10 meters
Traffic Type	CBR/FTP/Poisson
Routing Protocol	AODV
Duration	900 seconds
Beacon order	0 to 8
Data rate	250 kbps

APPENDIX-4

Parameter	Value
Node Density	21 (including PAN Coordinator)
Simulation Area	80 x 80 m2
Traffic flow	0 to all other devices
Transmission Range	15 meters
Traffic Type	CBR/FTP/Poisson
Routing Protocol	AODV
Duration	900 seconds
Beacon order	0 to 20
Data rate	250 kbps

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