Performance Degradation of IEEE 802.15.4 Slotted CSMA/CA due to Hidden Nodes

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***Abstract*—As sensor nodes are subject to strict power limitations and often deployed in harsh environments, there is significant potential for a node to be hidden from another node. The impact of hidden nodes on performance of the IEEE 802.15.4 Low-Rate Wireless Personal Area Network protocol is evaluated. At lower Tx power, as a result of hidden nodes, there are more collisions in the network increasing the cost of packet delivery. The simulation results indicate that there exists an optimum transmission power that minimizes the impact of hidden nodes, and it depends on factors such as network load, desired throughput and beacon order. Results indicate that additional throughput gain and lower cost per packet delivered can be achieved by increasing the beacon order at higher Tx power.**

I. INTRODUCTION

IEEE 802.15.4 Low-Rate Wireless Personal Area Network (LRWPAN) standard [7] defines the Physical Layer (PHY) and Medium-Access Layer (MAC) for sensor networks. This paper evaluates the impact on performance of hidden nodes on the performance of LR-WPAN based on energy cost of per packet delivery and throughput as metrics. Simulation based performance results relating the cost per packet delivered with load and Tx power, for example, indicate the importance of taking into account the impact due to hidden terminals in evaluating power control strategies. We address how changing different operating parameters of IEEE 802.15.4 protocol may reduce the adverse effects of hidden nodes in the network. We explain what factors influence such a behavior in the LR-WPAN.

We focus our study on the beacon-enabled mode in a star network where the central personal-area network coordinator is within a hop from every node. In a beacon-enabled network, each device uses slotted CSMA/CA mechanism to access the channel [2, 3, 4, 7].

II. EXPERIMENTAL SETUP

An event driven simulator was developed for IEEE 802.15.4 LR-WPAN to study its behavior in the presence of hidden nodes. We consider 100 randomly distributed nodes on a square grid of size (14m x 14m) as shown in Fig. 1. Simulator allows the change of radio output Tx power level for each node, and different power levels result in different percentages of hidden nodes in the network. Wireless loss channel is simulated using the model presented in [5] which specifies the packet reception (PRR) rate as a function of distance from the transmitter. When Manchester encoding and NCFSK modulation schemes are used, PRR is given by Eq. 1

$$p_{RR}[d] = \left(1 - \frac{1}{2}\exp^{-\frac{\gamma(d)}{2}\frac{1}{0.64}}\right)^{16f-8l} \quad (1)$$

where, $\gamma(d)$ is the SNR at a distance d between source node and the sink node, f is the frame size, and l is the preamble length. SNR at a distance d is a function of transmission power. Using Eq. (1), network packet loss probability between a source node and a sink node separated by distance d is determined as:

$$p_N = 1 - p_{RR}[d] \quad (2)$$

The PAN coordinator, PANC, is selected such that PRR between PANC and each of the nodes in the network is greater than zero. Thus, each node in the sensor network is able to communicate with the PANC in a single hop. A node is never disassociated from the PAN, i.e., nodes are never orphaned. The percentage of hidden nodes is defined to be the mean of number of nodes hidden from each node expressed as a percentage of the total number of nodes in the network.

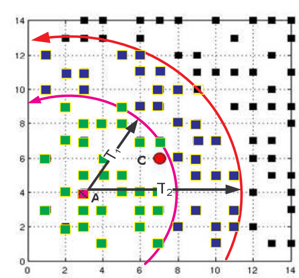

Figure 1. Example network topology (14m x 14m) of 100 nodes configuration with average 20% hidden nodes

The percentage of hidden nodes varies with the change in output transmission power as shown in Fig. 1. In Fig. 1, Node C indicates the PANC at the centre of the network grid. Consider two values for output transmission power for node A, P1 and P2 corresponding to transmission ranges T1 and T2, with T1<T2. The nodes outside the corresponding arc in Fig. 1 indicate the nodes hidden from A (PRR <= 0) for the given transmit power. Each node generated packets of length 54 bytes, 13 of which are used for MAC header and remaining 41 bytes for the data payload. Each node in the network generates messages to be sent to the PANC according to a Poisson process. The mean message generation rate is the same for all

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the nodes unless otherwise specified. Each data point contains mean values obtained over a period of 60 minutes of network time. Although we present results for the case when the network operates at 100% duty cycle without any sleep period between two successive beacons, the performance trends for different duty cycles can be derived directly by scaling the performance characteristics presented.

TABLE I. RADIO PARAMETERS [6]

Radio bandwidth	40Kbps
Power consumption (PT in mW) for RF output PTx (dBm)	50.4mW at 0dBm 57.6mW at 3dBm 76.2mW at 5dBm
Receiver Power (PR)	28mW
Idle Power (PI)	28mW

III. PERFORMANCE METRICS

Following performance metrics are used in the evaluation:

Throughput is defined as the number of bits successfully received per unit time by the PAN coordinator.

Cost per packet delivered (CPD) is defined as the ratio of the total energy consumed by all the nodes in the network to the number of packets successfully delivered to PANC. Total energy consumed by all the nodes in the network is the sum of useful energy and wasted energy. Useful energy is the energy spent by all the nodes to successfully transmit packet to the PAN. The energy spent includes the energy of the transmitted signal as well as the energy consumed by the transmitter/receiver electronics. Wasted energy is the energy spent by all the nodes either in the case of a collision or a packet drop due to channel being busy or due to packet error.

A. Energy Model

We use the energy model as proposed in [1] for the performance evaluation. Let the output transmit power of the node to transmit the data frame be PT, power spent while in idle mode be PI, and power spent while in receive mode be PR. If T_D, T_I, and T_R are the times to send the data frame, time the node was in idle mode, and the time the node was in receiving mode respectively. For a node to transmit a packet successfully to the PANC, it must receive the beacon first (corresponding to an energy consumption of P_R x T_R) and perform back-offs (P_I x T_I) till the channel becomes idle to transmit the packet. Once the channel is available, the node transmits the packet to the PANC (requiring an energy of P_T x T_D). We can calculate the total energy spent by the node for successful transmission of packets, $E_{Success}$, as

$$E_{Success} = P_R \times T_R + P_I \times T_I + P_T \times T_D \quad (3)$$

The same amount of energy is spent by the node in the case of a collision ($E_{Collision}$ = $E_{Success}$) as collision interval is equal to that for successfully packet delivery. If the channel is found to be busy, a node randomly backs off according to the NB parameter[7]. If the node backs off more than maximum number of retries (> 4 from [7]), it fails and drops the message. The amount of power spent during this interval is given by

$$E_{DropPacket=} P_R \times T_R + P_I \times T_I \quad (4)$$

We consider MICA2 hardware platform for evaluating the LR-WPAN performance. The corresponding values of the radio parameters for CC1000 radio [6] are shown in Table 1. MICA2 platform does not support IEEE 802.15.4, however the wireless model used in the paper is valid for MICA2. The simulator used in the study operates at 915MHz, the frequency at which MICA2 platform can operate. Note that the output transmit power PT corresponds to the power consumption for transmission, and it is significantly greater than the actual transmitter output power.

IV. PERFORMANCE RESULTS

The impact of different percentages of hidden nodes on network throughput and cost per packet delivered is evaluated by varying the output transmission power (PTx). The percentages of hidden nodes for different PTx are as follows: For PTx = 0dBm (32% hidden nodes), PTx=3dBm (20% hidden nodes), and PTx=5dBm (12% hidden nodes). Since LR-WPAN is not expected to operate close to its capacity in normal sensor network applications, we show results only for load ranges below 40%. Fig. 2 and Fig. 3 show the impact of hidden nodes on the cost per packet delivery and throughput for beacon orders, BO=0 and BO=8 respectively. As seen in Fig. 2 the cost per packet delivered at low loads (e.g., 5% of 40Kbps) is lower for higher PTx. We have observed that at lower beacon order, the wasted energy (energy spent due to collision, packet loss, and drop packets) is high for PTx=0dBm. This is due to the fact that the number of collisions is more at transmission power PTx=0dBm. As a result, the cost per packet delivered increases significantly.

LR-WPAN supports different BO, which can be efficiently configured to reduce the network degradation due to the hidden nodes. For higher BO (=8) as seen in Fig. 3, operating the network at higher PTx at low loads is better in terms of throughput. However, in terms of cost per packet delivered, illustrated in Fig. 3, lowest occurs for PT = 3dBm. This indicates that the beacon order has a significant effect on the performance characteristics. As the load increases (20% and 40% of 40Kbps), illustrated in Fig. 2 and Fig. 3, the cost per packet delivered varies about 2-10% at higher PT compared to lower PT. The results indicate that there exists an optimum transmission power that reduces the impact of hidden nodes, and which depends on factors such as network load, desired throughput and beacon order.

Fig. 2 and Fig. 3 indicate that as transmission power PTx increases for different loads (5%, 20% and 40% of 40Kbps) the throughput increases. This indicates that operating at lower PTx (=0dBm), the number of hidden nodes is more, effectively decreasing the throughput. Although results are shown only for BO=0 (lower BO, Fig 2) and BO=8 (higher BO, Fig 3), this observation is true independent of BO. However by operating at higher beacon order the throughput attainable increases and

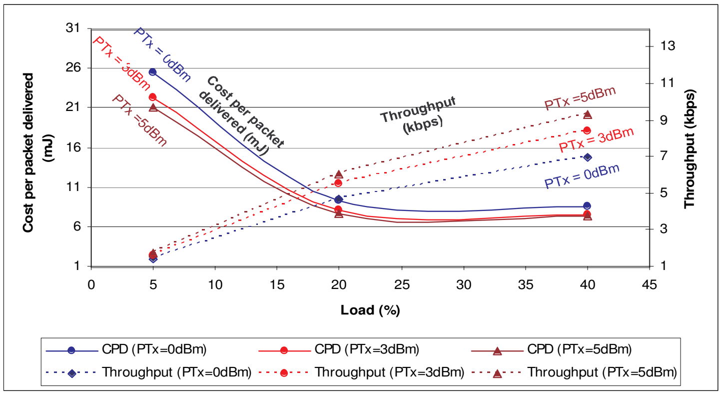

Figure 2. Impact of network traffic load on Throughput and Cost per packet delivered at BO=0

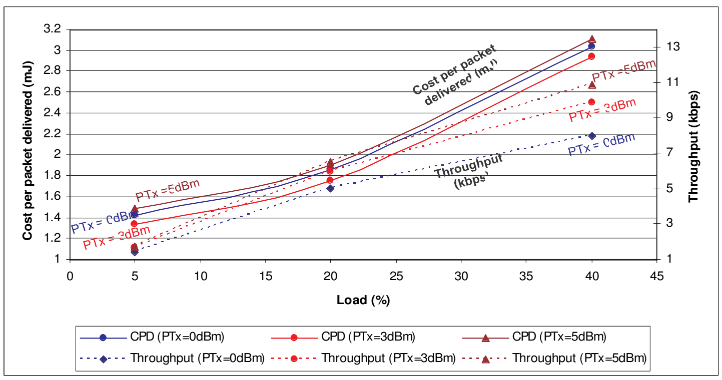

Figure 3. Impact of network traffic load on the Throughput and Cost per packet delivered for BO=8

we also verified that throughput becomes less sensitive to the beacon order when it is greater than 8.

V. CONCLUSIONS

Performance results for IEEE 802.15.4 MAC protocol shows that hidden nodes can have a significant effect on the performance. Operating the radio at higher power level results in increased network throughput, but it does not guarantee a lower cost per packet delivered. At high percentages of hidden nodes, operating the network at higher BO promises higher throughput and lower energy consumption than at lower BO. Operating at lower BO introduces more collisions due to Clear channel assessment, CCA deference [2] and results in more energy consumption in the network. Results presented above illustrates that parameters such as beacon order and transmit power, as well as impact due to hidden terminals affect the performance of the network in a complex manner. Such affects have to be taken into account by various optimization algorithms associated with sensor networks. Analysis of power control strategies for sensor networks, for example, usually ignore the impact it has on hidden nodes and resulting impact on performance. However, the results shown here suggest that gains made in terms of power can be negated due to additional collisions introduced as a result.

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