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Performance Analysis of Beacon-Enabled IEEE 802.15.4 MAC for Emergency Response Applications

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***Abstract*—IEEE 802.15.4 standard provides a viable MAC and PHY specification for wireless sensor networks. Performance evaluation of these networks has been reported in literature. Previous works focus largely on analyzing the CSMA/CA traffic and frame delay due to Guaranteed Time Slots (GTS) allocations. In this work, we propose a analytical model to understand and characterize the performance of GTS traffic in IEEE 802.15.4 networks for emergency response situations. We study two crucial performance metrics, latency and frame drop rate, for GTS frames. The results from our analysis closely match with those from simulations of IEEE 802.15.4 MAC reported earlier.**

I. Introduction

With rapid improvements in wireless technologies, wireless sensor networks (WSN) are attracting growing attention from both research communities and vendors. IEEE 802.15.4 standard offers a MAC and PHY specification for short range and multi-hop wireless mesh networks [2]. Several works analyze the performance of IEEE 802.15.4. MAC. Its transmission delay and node lifetimes under single hop and multi-hop scenarios has been studied [3]. Discrete Markov chains are used in [4] to characterize system throughput and energy consumption. Simulation results are presented to characterize and compare the performance of GTS traffic in IEEE 802.15.4 networks and a few of its variants [1]. [5] analyzes transmission delay due to GTS allocation between nodes. In our work, we focus on formulating an analytical model to study the network performance for transmission delay and frame drop rate for GTS traffic in emergency response scenarios, typically characterized by very low-latency requirements, which, to the best of our knowledge, has not been done before. Comparison is drawn with simulation results to validate the performance results of our analysis. Future work can extend this model to analyze CSMA/CA as well, for emergency response applications.

II. System description

We consider a beacon-enabled star network configuration according to the IEEE 802.15.4-2006 spec [2]. A central node, called a coordinator, owns a superframe which specifies the periods and modes of channel access by neighboring nodes. The superframe consists of active and in-active periods as shown in Fig.1. The length of these periods is specified by two system parameters i.e. beacon order (BO) and superframe order (SO). During the in-active period a node can switch over to power-saving mode. The active period is divided into sixteen equal sized time slots. It consists of a contention access period (CAP) and a contention free period (CFP). A CSMA/CA mechanism is employed for channel access in the CAP. The time slots in the CFP are allocated on demand for exclusive channel access. Data frames transmitted in the CFP have better chance for a successful transmission. The GTS transmissions are well suited for regular periodic sensor data and latency sensitive alert messages.

GTS traffic is considered independent of CSMA traffic in the IEEE 802.15.4 standard. Hence, in our delay analysis, we ignore contention due to CSMA/CA traffic in the CAP. Moreover, in our model, if a node has multiple GTS frames for transmission at the start of a GTS, it transmits the most recent frame and discards the older ones. We make this assumption as we are studying emergency response situations which, unlike data collection applications, require latest information about the phenomenon of interest so that the emergency being sensed can be responded to.

Our WSN is based on the model described in [1]. In that model, the simulated system consists of a PAN coordinator and 27 sensor nodes. Only 7 of these nodes have statically been allocated a GTS each, this is the maximum allowed by IEEE 802.15.4 standard, [2]. The allocation of these 7 time slots in CFP remains unchanged for duration of the simulation. All data frames are acknowledged by the receiver and an error-free transmission of ACK frames is assumed. The data frames, however, encounter an error-prone channel having a certain probability of channel error. In our analysis we use same values of BO, SO and probability of frame error P_e as used in [1]. We vary the average GTS arrival rate λ over 3 values.

III. Mathematical Formulation

Consider the superframe structure shown in Fig. 1. Beacon Interval is given as $BI = 2^{BO} * 960$ and is the time between two successive beacons transmitted by the coordinator and measured in symbol time. The active period has a duration of $2^{SO} * 960$ symbols. The remaining time is considered as in-active period. Note that since we assume that GTS allocations stay unchanged across the superframes the time between two successive guaranteed time slots, allocated to the same node, is equal to BI.

A. Transmission delay of IEEE 802.15.4 MAC

First, without loss of generality, we only consider the transmission delay for successfully transmitted GTS frames. We, therefore, ignore the delay caused by the dropped frames.

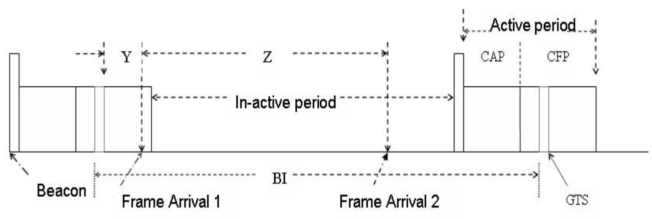

Fig. 1. superframe structure of IEEE 802.15.4 MAC

The average transmission delay, Δ can be expressed as

$$\Delta = \sum_{i=0}^{\infty} P_i^f(\epsilon + iBI) \qquad (1)$$

where $P_i^f, 0 \leq i \leq \infty$, is the probability that a GTS frame is successfully transmitted in its i^{th} superframe after its arrival at a node and ϵ is the round trip delay. In order to calculate these probabilities we observe a WSN in its steady state. We then categorize every successfully transmitted GTS frame based on the delay it encounters before its transmission. Let X^s be the total number of successfully transmitted GTS frames during the observation period and X_i^s be the number of GTS frames that had to wait i superframes before succeeding in their transmission. P_i^f can be expressed as

$$P_i^f = \frac{X_i^s}{X^s} \qquad (2)$$

such that

$$\sum_{i=0}^{\infty} P_i^f = 1 \qquad (3)$$

Let X_0^s denote the number of GTS frames that are successfully transmitted in the first GTS after their arrival at any node. Note that these frames need zero retransmission attempts. It can be written as

$$X_0^s = X(1 - P_e)$$

where X is the total number of GTS frames that get at least one transmission attempt. A frame that fails in its first GTS transmission attempt must wait until the next superframe for a retransmission attempt, subject to the condition that it does not get dropped due to a new arrival. Let the number of successful GTS frames with one superframe delay be denoted by X_1^s, which is given by

$$X_1^s = (P_e e^{-BI\lambda})X(1 - P_e) \qquad (4)$$

where $P_e e^{-BI\lambda}$ specifies the probability that a frame fails transmission in a superframe and no new frames arrive in time interval BI, at a specific node. Let $K = P_e e^{-BI\lambda}$, so we have

$$X_1^s = KX(1 - P_e) \qquad (5)$$

We now generalize the expression for i^{th} superframe. It is given by

$$X_i^s = K^i X(1 - P_e) \qquad (6)$$

Hence X^s can be written as

$$X^s = \sum_{i=0}^{\infty} K^i X(1 - P_e) = \frac{1}{1-K} X(1 - P_e) \qquad (7)$$

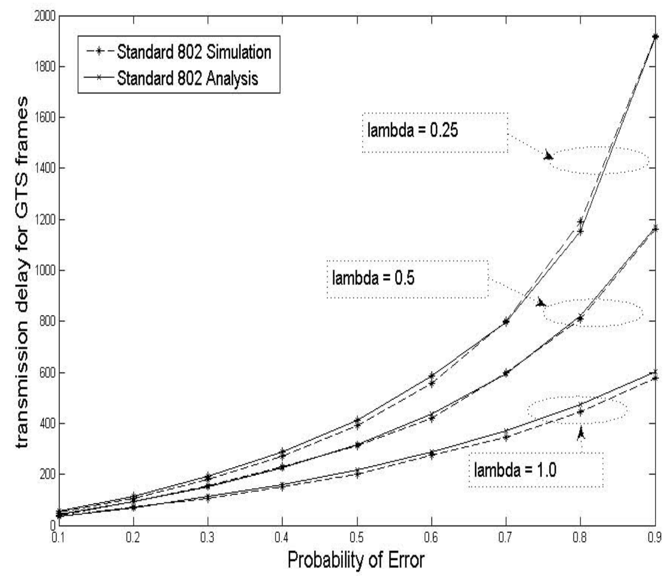

Fig. 2. GTS frame transmission delay vs Pe

Using (6) and (7), (2) can be rewritten as

$$P_i^f = \frac{XK^i(1 - P_e)}{X(1 - P_e)\frac{1}{(1-K)}} = (1 - K)K^i \qquad (8)$$

Substituting (8) into (1) the average delay encountered by any CFP frame is given as

$$\Delta = \epsilon + \frac{K}{1-K} BI \qquad (9)$$

Fig. 2 gives comparison of (9) with the simulation results. The three curves are for $\lambda = 0.25, 0.5$, and 1.0 whereas $BO = 5$ and $SO = 2$. For all values of λ we note that average delay goes up with increasing value of P_e with $\lambda = 0.5$ being the middle case. For $\lambda = 0.25$ we observe a significantly higher transmission delay for high values of P_e than for $\lambda = 0.5$ or 1.0. This is because at low values of λ the interarrival times are longer and frames survive a longer time on average at their respective nodes. This increases the number of frames transmitted successfully albeit with higher delays, which increases average transmission delay. For the case where $\lambda = 1.0$, interarrival times are shorter and more frames are dropped due to new arrivals. That results in a lower average delay but increased drop rate as will be seen in next section. From Fig. 2 we see the analytical and simulation results match closely.

B. Frame drop rate for IEEE 802.15.4 MAC

In this sub-section, we derive an expression for average GTS frame drop rate, P_{drop}. A frame is dropped after either it gets the maximum number of transmission attempts or a new frame arrives at the node while it was still waiting for its transmission. There is a frame drop rate associated with each node for a given λ, BO and SO. These parameters decide how long, on the average, a frame will have to wait for its turn for transmission and be susceptible to be dropped as newer frames arrive.

Let a random variable Z represent the interarrival duration of GTS frames. Assume that Z is exponentially distributed with mean $1/\lambda$. To calculate P_{drop}, we first calculate the probability, P_{di}, that a frame is dropped in i^{th} superframe after its arrival. Summing P_{di} over $0 \leq i < \infty$ gives us the closed form expression for P_{drop}. We first derive the expression for P_{d0} and then the expression is generalized for P_{di}.

Let Y be the random time difference between a frame arrival at a node and start instance of its immediately previous GTS. For P_{d0}, we need to consider the arrival instance, i.e. y_0, of the frame within the BI interval. The frame under consideration will be dropped in its 1^{st} superframe if there is at least one frame arrival in the interval ($BI - y_0$). The corresponding probability is given by

$$P_{d0|Y=y_0}(y_0) = 1 - e^{-(BI-y_0)\lambda}, 0 < y_0 < BI \tag{10}$$

Due to memoryless property, arrivals in ($BI - y_0$) interval are independent of the duration prior to the interval.

The conditional CDF of Y is found as follows

$$P(Y \leq y_0 | Y \leq BI) = \frac{P(Y \leq y_0, Y \leq BI)}{P(Y \leq BI)} \tag{11}$$

where the condition $Y \leq BI$ ensures at least one arrival in BI. Simplifying (11) results in

$$P(Y \leq y_0 | Y \leq BI) = \frac{P(Y \leq y_0)}{P(Y \leq BI)} = \frac{1 - e^{-y_0\lambda}}{1 - e^{-BI\lambda}} \tag{12}$$

The conditional PDF of Y is given as

$$p(Y = y_0 | Y \leq BI) = \frac{\lambda e^{-y_0\lambda}}{1 - e^{-BI\lambda}}, 0 < y_0 \leq BI \tag{13}$$

The expression for P_{d0} is given by

$$P_{d0} = \int_0^{BI} P_{d0|Y=y}(y) p_{Y|Y \leq BI}(y) dy \tag{14}$$

Using (10) and (13) we have

$$P_{d0} = 1 - \frac{\lambda BI e^{-BI\lambda}}{1 - e^{-BI\lambda}} \tag{15}$$

The probability that a GTS frame will be dropped in its 2^{nd} superframe $i = 1$ is given by

$$\begin{aligned} P_{d1} &= (1 - P_{d0}) P_e P(BI - y_0 < Z < 2BI - y_0) \\ &= (1 - P_{d0}) P_e (1 - e^{-BI\lambda}) \end{aligned} \tag{16}$$

where$(1 - e^{-BI\lambda})$, is the probability of at least one arrival within BI. The $(1 - P_{d0})$ term represents no arrivals in the 1^{st} superframe, which implies the frame is not dropped in its 1^{st} superframe.

Similarly, this analysis can be extended to superframe i. Expressions for P_{di} and P_{drop} are given by

$$P_{di} = (1 - P_{d0}) P_e^i (1 - e^{-BI\lambda}) e^{-(i-1)BI\lambda} \tag{17}$$

$$P_{drop} = P_{d0} + (1 - P_{d0}) \sum_{i=1}^{\infty} P_{di} \tag{18}$$

where $e^{-(i-1)BI\lambda}$ represents no arrivals in the previous $i - 1$ superframes and $1 - e^{-BI\lambda}$ represents at least one arrival in superframe i. Fig. 3 illustrates comparison of (18) with

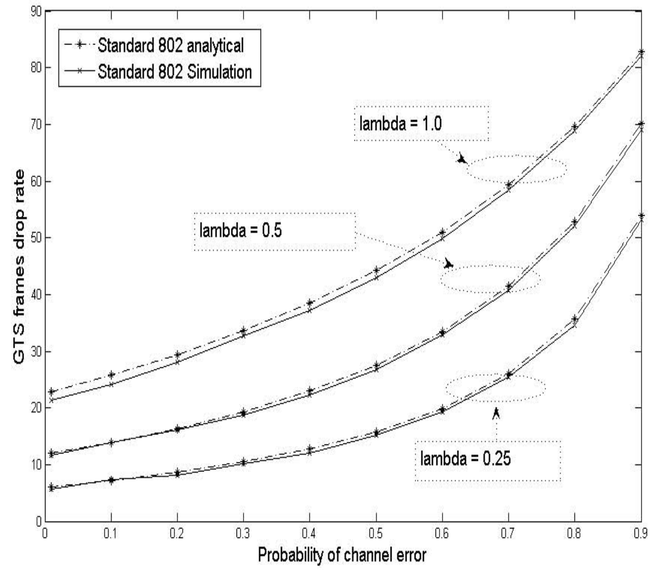

Fig. 3. GTS frame drop rate vs Pe

simulation results. Once again, we use $\lambda = 0.5$ as a reference and see that the frame drop rate increases with P_e. The reason being that frames take longer to transmit and are more likely to be dropped. It is also interesting to see that the frame drop rate is not zero even at low values of P_e. This is because frames can be dropped within their superframe of arrival as depicted by P_{d0} in (10). When $\lambda = 0.25$, the drop rate goes down as the average interarrival times get longer. This is in sync with the increase in transmission delay for $\lambda = 0.25$. Finally, for $\lambda = 1.0$, we see the drop rate increases as the frames arrive in quick succession. This increases the probability of a new frame arrival while older frames are still waiting for transmission, which in turn increases the drop rate. The analytical derivation and simulation results match for the average drop rate.

IV. Conclusion

The paper presented a statistical model for IEEE 802.15.4 MAC to study latency and frame drop rate performances for GTS traffic for emergency response applications with low-latency requirements. The analysis focuses on a single-hop star network operating in beacon-enabled mode. Comparison to simulation results validates our analysis.

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