Performance Analysis of Time-Critical Peer-to-Peer Communications in IEEE 802.15.4 Networks

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***Abstract*—Existing works on the performance analysis of IEEE 802.15.4 networks with peer-to-peer (P2P) topologies assume the non-beacon unslotted mode in the MAC layer, which is not suitable for time-critical communications required by many applications, such as control, actuation and monitoring applications. In this paper, we introduce an enhanced guaranteed timeslot (GTS) mechanism which can support time-critical P2P communications in wireless sensor networks (WSNs). A Markov chain that takes into account retransmission limits, acknowledgements, unsaturated traffic and packet delivery ratios of links is proposed to model P2P communications using this enhanced GTS mechanism. Based on this model, we analyze the expected reliability and energy consumptions under various traffic conditions. In addition, the impacts of MAC parameters on these performance indexes are analyzed. Monte Carlo simulations show that our theoretical analysis is quite accurate, and thus can be used as guidance for networks configuration in WSNs.**

I. Introduction

The IEEE 802.15.4 standard [1] has received considerable attentions in both academy and industry as a low date rate and low power protocol for WSNs. It is essential to understand the latency, reliability and energy consumption in order to characterize the fundamental limitations of this protocol, optimize the MAC layer parameters and design optimal cross-layer protocols. The problem will be studied in this paper is defined as follows. Given an IEEE 802.15.4 sensor network that consists of a Personal Area Network coordinator (PANC) and a number of associated devices, supposing a device needs to send a time-critical packet to another device, which MAC layer mechanism should be used if we want to increase the reliability and reduce the latency and energy consumption. More importantly, their accurate values should be analyzed.

Several works (e.g., [2]–[8]) have investigated the performance of data transmissions in the Contention Access Period (CAP) in IEEE 802.15.4 networks by Markov chain models. However, for time-critical applications, packets are not suitable to send in the CAP. Thus, the IEEE 802.15.4 standard specifies the GTS mechanism in the Contention Free Period (CFP). Some works (e.g., [9], [10]) analyzed the performance of the GTS allocation. However, they did not study the performance when devices actually use GTSs to send packets.

The works mentioned above only considered data transmissions between the PANC and devices, and did not study P2P communications between devices. If a device wants to send a packet to another device, then two GTSs will be required: one is for the transmission from the source to the PANC, and the other is for the transmission from the PANC to the destination. This will reduce the reliability and increase the latency. In the current standard, in order to achieve P2P communications, the devices will need to either receive constantly or synchronize with each other. In the former case, the device can simply transmit its data using unslotted CSMA/CA, which is not suitable for time-critical applications. In the latter case, other measures need to be taken in order to achieve synchronization, which is not specified in the current standard.

In this paper, we introduce an enhanced GTS mechanism which is proposed for the IEEE 802.15.4e standard [11] and can support time-critical P2P communications in WSNs. A Markov chain that takes into account retransmission limits, acknowledgements, unsaturated traffic and packet delivery ratios of links is proposed to model P2P communications using this enhanced GTS mechanism. Based on this model, we analyze the expected reliability and energy consumptions under various traffic conditions. In addition, the impacts of MAC parameters on these performance indexes are investigated. Monte Carlo simulations show that our theoretical analysis is quite accurate. To our best knowledge, this is the first work on P2P communications using GTS mechanism.

Our contributions are three-folded in this paper. Firstly, with our Markov chain model, we analyze the performance during a complete P2P data transmission process using the enhanced GTS mechanism, from the very beginning when the source generates a packet, until the destination receives it. Secondly, we consider the unreliability of wireless channels and integrate packet delivery ratios of links in our model. Finally, we investigate the impacts of IEEE 802.15.4 MAC parameters on the performance, which can serve as guidance for networks configuration.

The remainder of this paper is organized as follows. We introduce the IEEE 802.15.4 MAC layer protocol in Section II, describe our system model in Section III and propose our Markov chain model for P2P communications in Section IV. In Section V, we present an accurate analysis of the reliability and energy consumptions. We validate our analysis by Monte Carlo simulations and discuss the impact of protocol parameters in Section VI. Finally, Section VII concludes this paper and discusses the future work.

II. Overview of The IEEE 802.15.4 Standard

In this section, we first give an overview of the key characteristics of the IEEE 802.15.4 standard related to our analysis. Then we introduce an enhancement proposed for IEEE 802.15.4e to support P2P communications.

A. Basic Standard

The IEEE 802.15.4 standard supports beacon enabled and non-beacon enabled modes. In the beacon enabled mode, the PANC periodically sends beacon framess in every beacon interval (BI) to identify its PAN and synchronize devices associated with it. The PANC and devices can communicate during the active period, called the superframe duration (SD), and enter the low-power mode during the inactive period. The length of the superframe (BI) and the length of its active period (SD) are determined by two parameters: the beacon order (BO) and the superframe order (SO), respectively. The superframe structure of the beacon enabled mode is described in Fig. 1.

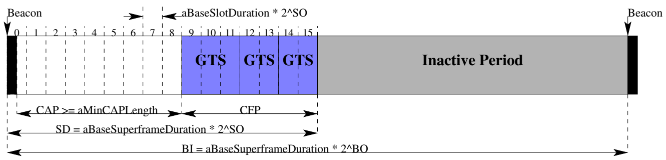


Fig. 1. Superframe structure in IEEE 802.15.4

The *aBaseSuperframeDuration* and *aBaseSlotDuration* denote the minimum length of the superframe and the number of symbols forming a superframe slot, respectively. The active period consists of 16 equally sized time slots, which are divided into a CAP and an optional CFP consisting of GTSs. In this paper, the GTS mechanism is considered, which is only available in the beacon enabled mode.

A slotted CSMA/CA mechanism is used to access the channel for non-time critical data transmissions and GTS requests during the CAP. In the CFP, the dedicated bandwidth is used for time critical data frames. The PANC is responsible for the GTS allocation and determines the length of the CFP. A single GTS can extend over one or more superframe slots. The PANC may allocate up to seven GTSs at the same time, provided there is sufficient capacity in the superframe.

To request a new GTS, the device sends the GTS request command to the PANC. On receipt of this command, the PANC shall send an ACK within the CAP. Then the PANC shall first check if there is available capacity in the current superframe based on the remaining length of the CAP and the desired length of the requested GTS. The superframe shall have available capacity if the maximum number of GTSs has not been reached, and allocating a GTS of the desired length would not reduce the length of the CAP to less than *aMinCAPLength*. The PANC determines GTS allocations in a first-come-first-served fashion and shall make its decision within *aGTSDescPersistenceTime* superframes.

On receipt of the ACK from the PANC, the device shall continue to track the beacons and wait for at most *aGTSDescPersistenceTime* superframes. If there is sufficient bandwidth in the next superframe, the PANC allocates the GTSs with the desired lengths and includes the GTS descriptor in the next beacon to announce the allocation information. A device uses the dedicated bandwidth to transmit or receive data. In addition, a transmission must complete one interframe spacing (IFS) period before the end of its GTS. Each device can choose whether the MAC sublayer enables its receiver during idle periods or not. By setting the value of *macRxOnWhenIdle* to *FALSE*, a device can disable its receiver and enter the low-power mode in idle periods.

B. IEEE 802.15.4 Enhancement

Current GTS mechanism limits that a GTS can be used only for communications between the PANC and a device. To our best knowledge, non-beacon unslotted mode is currently supposed to be used in mesh topologies [12]. However, this mechanism suffers from uncertain delay and high energy consumption, which is not suitable for time-critical applications.

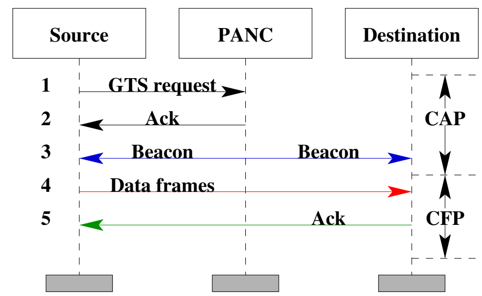


Fig. 2. GTS Allocation and Data Transfer during the CAP and CFP

A modification is proposed in [11] to enhance IEEE 802.15.4 to support P2P communications, which is described in Fig. 2. When the source sends the GTS request command to the PANC, it also includes the destination address. When the PANC announces the allocation information, it indicates that the assigned GTS is one transmitting GTS for the source, and one receiving GTS for the destination. Then the source can send data frames to the destination in this GTS from the next superframe. Although this enhancement can support multi-channels, we only consider the single-channel case.

III. System Model

We consider a *pseudo-star* WSN consisting of a PANC and n devices associated with it, as shown in Fig. 3. The network operates in the beacon-enabled slotted CSMA/CA and ACK mode. We assume that only n_0 ($n_0 \leq \Delta$) devices will generate time-critical packets and each of them needs exactly one GTS, while the other $n-n_0$ devices will generate ordinary traffic transmitted in the CAP. Here, the maximum number of GTSs Δ that can be allocated to devices in a superframe can be calculated as in [9]. In this case, all GTS requests can be served in the following superframe.

For P2P communications, if the destination is the PANC or another device out of its transmission range, the source will send a normal GTS request command to the PANC. Otherwise, the enhanced GTS mechanism will be used and a GTS request command with the destination address will be sent to the PANC. In this paper, we only consider the latter case.

Due to the unreliability of wireless channels, packets sent along links may be lost due to link failures. The bit error rate (BER) along link i is denoted by b_i. The BERs of links between the PANC, source and destination are shown in Fig. 3. Existing works have not considered this characteristic yet.

Time-critical packets sent during GTSs require ACKs. If the source does not receive the ACK from the destination within its GTS, it will retransmit in the same GTS in the following superframes, until it receive the ACK. We assume the retransmission limit to be m.

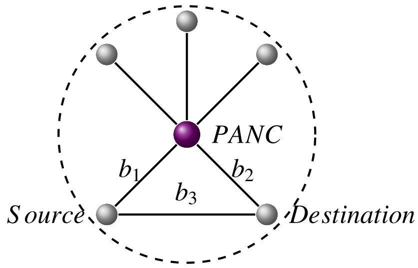


Fig. 3. Pseudo-star Wireless Sensor Network

For the sake of energy efficiency, we let devices enter the low-power mode in idle periods by setting *macRxOnWhenIdle* to be *FALSE*. Thus, a device will wake up only when it tracks beacons, has data to send, or needs to receive data in the allocated receiving GTS indicated in beacons.

IV. Markov Chain Model

In this section, we propose a Markov chain model for P2P communications as described above and analyze its stationary distribution. The Markov chain is shown in Fig. 4.

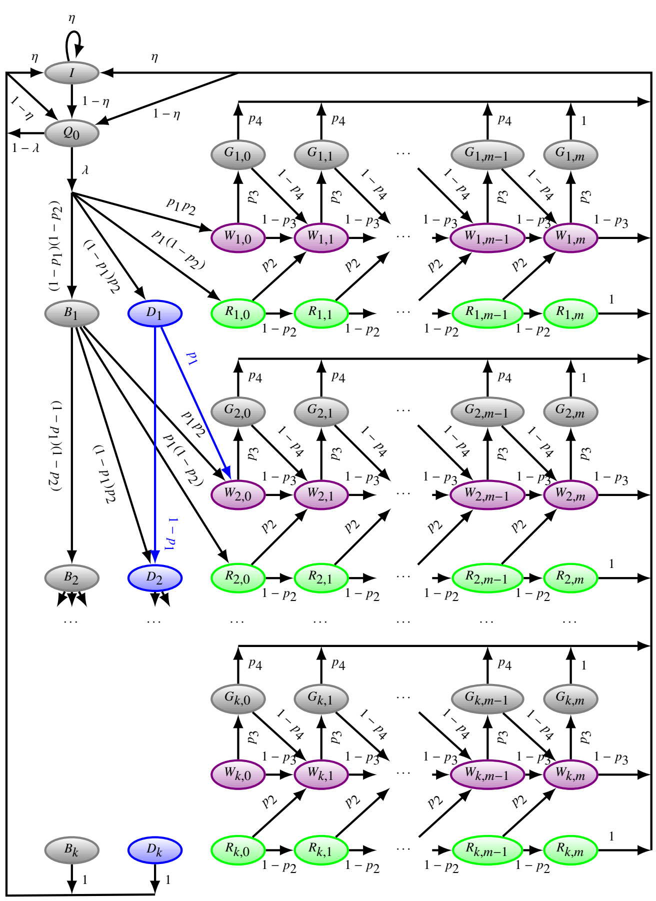


Fig. 4. Markov Chain Model for Peer-to-Peer Communications

Let $k \triangleq aGTSDescPersistenceTime$ and η be the probability that no packet is generated. States I and Q_0 represent the idle state and that a GTS request command is sent in the CAP because a packet is generated, respectively. We denote the probability that the PANC receives this request successfully by λ. State B_i $(1 \le i \le k)$ represents that both the source and destination fail to track the GTS allocation information in beacons in the first i superframes due to link failures. Similarly, state D_i $(1 \le i \le k)$ represents that the destination has got this information but the source has not. State $R_{i,j}$ $(1 \le i \le k, 0 \le j \le m)$ represents that the source has got the GTS information in the i^{th} superframe and is transmitting $(j = 0)$ or retransmitting at the j^{th} time $(j \ge 1)$. However, the destination cannot receive the packet because it has not got the GTS information yet and is still staying in the low-power mode. State $W_{i,j}$ $(1 \le i \le k, 0 \le j \le m)$ represents almost the same case, except that both the source and the destination have got the GTS allocation information. In this case, the source will transmit or retransmit and the destination will wake up to receive the packet in the assigned GTS. State $G_{i,j}$ $(1 \le i \le k, 0 \le j \le m)$ represents that the destination has received the packet successfully. p_i $(1 \le i \le 4)$ is the packet delivery ratio that can be calculated as follows:

$$p_1 = (1-b_1)^{l_b}, p_2 = (1-b_2)^{l_b}, p_3 = (1-b_3)^{l_{data}}, p_4 = (1-b_3)^{l_{ACK_2}}$$

where l_b, l_{data}, l_{ACK_2} are the length of beacons, data packets and ACKs in the CFP, respectively. The state transition probabilities in this the Markov chain are:

$$P[B_{i+1}|B_i] = (1-p_1)(1-p_2) \quad (1)$$
$$P[D_{i+1}|B_i] = (1-p_1)p_2 \quad (2)$$
$$P[D_{i+1}|D_i] = 1-p_1 \quad (3)$$
$$P[W_{i+1,0}|B_i] = p_1 p_2 \quad (4)$$
$$P[W_{i+1,0}|D_i] = p_1 \quad (5)$$
$$P[R_{i+1,0}|B_i] = p_1(1-p_2) \quad (6)$$
$$P[R_{i,j+1}|R_{i,j}] = 1-p_2 \quad (7)$$
$$P[W_{i,j+1}|W_{i,j}] = 1-p_3 \quad (8)$$
$$P[W_{i,j+1}|G_{i,j}] = 1-p_4 \quad (9)$$
$$P[W_{i,j+1}|R_{i,j}] = p_2 \quad (10)$$
$$P[G_{i,j}|W_{i,j}] = p_3 \quad (11)$$

for $1 \le i \le k$, $0 \le j \le m-1$. Eqs. (1)–(6) are obvious according to our state definitions. Eqs. (8) and (11) represent the probability that the source sends the data packet, but the destination fails or successes to receive it, respectively. Eq. (9) gives the probability of unsuccessful transmission of the ACK replied by the destination. In this case, the source still needs to retransmit although the destination has received the data packet successfully. Eqs. (7) and (10) represent the probability that the destination fails or successes to track the beacon at the beginning of retransmission superframes, respectively. For other state transition probabilities, please refer to Fig. 4.

Let Π be the stationary distribution of the Markov chain. We will derive the probability for each state using the global balance equations. From Eq. (1), we have

$$\Pi[B_i] = \lambda\left[(1-p_1)(1-p_2)\right]^i \Pi[Q_0] \quad 1 \le i \le k \quad (12)$$

From Eq. (2) and (3), we obtain

$$\begin{aligned}\Pi[D_i] &= (1-p_1)\Pi[D_{i-1}] + p_2(1-p_1)\Pi[B_{i-1}] \\ &= (1-p_1)^{i-1}\Pi[D_1] + \sum_{j=1}^{i-1} p_2(1-p_1)^{i-j}\Pi[B_j] \\ &= \lambda(1-p_1)^i\left[1+p_2-(1-p_2)^i\right]\Pi[Q_0]\end{aligned} \tag{13}$$

for $1 \le i \le k$. From Eqs. (4) and (5), we get

$$\begin{aligned}\Pi[W_{i,0}] &= p_1p_2\Pi[B_{i-1}] + p_1\Pi[D_{i-1}] \\ &= \lambda p_1(1-p_1)^{i-1}\left[1+p_2-(1-p_2)^i\right]\Pi[Q_0]\end{aligned} \tag{14}$$

for $1 \le i \le k$. From Eq. (6) and (7), we have

$$\begin{aligned}\Pi[R_{i,j}] &= (1-p_2)^j\Pi[R_{i,0}] \\ &= (1-p_2)^j \cdot p_1(1-p_2)\Pi[B_{i-1}] \\ &= \lambda p_1(1-p_1)^{i-1}(1-p_2)^{i+j}\Pi[Q_0]\end{aligned} \tag{15}$$

for $1 \le i \le k$, $0 \le j \le m$. From Eqs. (8)–(10), we can get

$$\begin{aligned}\Pi[W_{i,j}] &= (1-p_4)\Pi[G_{i,j-1}] + (1-p_3)\Pi[W_{i,j-1}] + p_2\Pi[R_{i,j-1}] \\ &= (1-p_3p_4)^j\Pi[W_{i,0}] + \sum_{k=0}^{j-1} p_2(1-p_3p_4)^{j-k-1}\Pi[R_{i,k}] \\ &= \lambda p_1(1-p_1)^{i-1}\Pi[Q_0]\Big\{\left[1+p_2-(1-p_2)^i\right](1-p_3p_4)^j \\ &\quad + \frac{p_2}{p_2-p_3p_4}(1-p_2)^i\left[(1-p_3p_4)^j-(1-p_2)^j\right]\Big\}\end{aligned} \tag{16}$$

for $1 \le i \le k$, $0 \le j \le m$. From Eq. (11), we obtain

$$\Pi[G_{i,j}] = p_3\Pi[W_{i,j}] \tag{17}$$

for $1 \le i \le k$, $0 \le j \le m$. Finally, for the idle state we have

$$\begin{aligned}\Pi[I] &= \frac{\eta}{1-\eta}\Big\{(1-\lambda)\Pi[Q_0] + \Pi[B_k] + \Pi[D_k] + p_4\sum_{i=1}^{k}\sum_{j=0}^{m-1}\Pi[G_{i,j}] \\ &\quad + \sum_{i=1}^{k}\left[(1-p_3)\Pi[W_{i,m}] + \Pi[G_{i,m}] + \Pi[R_{i,m}]\right]\Big\} \qquad (18) \\ &= \frac{\eta\Pi[Q_0]}{1-\eta}\left[1+\lambda p_2 - \lambda p_1(1-p_2)^{m+1}\frac{1-[(1-p_1)(1-p_2)]^k}{1-(1-p_1)(1-p_2)}\right]\end{aligned}$$

By the normalization condition, we know that

$$\begin{aligned}&\Pi[I] + \Pi[Q_0] + \sum_{i=1}^{k}\Big(\Pi[B_i] + \Pi[D_i]\Big) \\ &+ \sum_{i=1}^{k}\sum_{j=0}^{m}\Big(\Pi[W_{i,j}] + \Pi[G_{i,j}] + \Pi[R_{i,j}]\Big) = 1\end{aligned} \tag{19}$$

by replacing Eqs. (12)–(18) in Eq. (19), we can obtain

$$\begin{aligned}\Pi[Q_0] = \Big[&\lambda p_1(1+p_2)(1+p_3)x_1x_4 + \lambda(1-p_1)(1+p_2)x_1 \\ &+ \frac{\lambda p_1p_3p_4(1-p_2)(1+p_3)}{p_2-p_3p_4}x_3x_4 + \frac{1+\lambda\eta p_2}{1-\eta} \\ &+ \frac{\lambda p_1p_3(1-p_2)(p_2+p_4)}{p_2-p_3p_4}x_2x_3 - \frac{\lambda\eta p_1(1-p_2)^{m+1}}{1-\eta}x_3\Big]^{-1}\end{aligned} \tag{20}$$

where

$$x_1 \triangleq \frac{1-(1-p_1)^k}{p_1} \qquad x_2 \triangleq \frac{1-(1-p_2)^{m+1}}{p_2}$$
$$x_3 \triangleq \frac{1-[(1-p_1)(1-p_2)]^k}{1-(1-p_1)(1-p_2)} \qquad x_4 \triangleq \frac{1-(1-p_3p_4)^{m+1}}{p_3p_4}$$

V. Performance Analysis

In this section, we derive the expressions of the reliability and energy consumptions based on our Markov chain model developed in the previous section.

A. Reliability

In this enhanced GTS mechanism, packets may be discarded due to three reasons: (*i*) GTS request transmission failure, (*ii*) GTS allocation information reception failure, and (*iii*) retransmission limit. GTS request transmission failure happens when the PANC fails to receive the GTS request command, due to link failures or collisions with other nodes. GTS allocation information reception failure happens when the source fails to track the beacons to get the GTS allocation information within *aGTSDescPersistenceTime* superframes. In addition, a packet will be discarded if the source has retransmitted it for m times and got no ACK from the destination. Note that a packet is considered to be transmitted successfully if and only if the source receives the ACK from the destination. Therefore, based on our model, the reliability is given by

$$\begin{aligned}\mathbb{R} &= 1 - \underbrace{(1-\lambda)\Pi[Q_0]}_{(i)} - \underbrace{(\Pi[B_k] + \Pi[D_k])}_{(ii)} \\ &\quad \underbrace{- \sum_{i=1}^{k}\left(\Pi[R_{i,m}] + (1-p_3)\Pi[W_{i,m}] + (1-p_4)\Pi[G_{i,m}]\right)}_{(iii)} \\ &= 1 - \Big[\lambda p_1(1-p_3p_4)^{m+1}(1+p_2)x_1 + 1 - \lambda \\ &\quad + \frac{\lambda p_1p_3p_4}{p_2-p_3p_4}(1-p_2)\left[(1-p_3p_4)^{m+1}-(1-p_2)^{m+1}\right]x_3 \\ &\quad + \lambda(1-p_1)^k(1+p_2)\Big]\Pi[Q_0]\end{aligned} \tag{21}$$

B. Energy Consumption

In this paper, we only consider the energy consumed specifically by P2P communications. Other energy (e.g., consumed in the low-power mode or used for beacon tracking) are not counted. Based on our Markov chain model, the expected energy consumption of the source is given as follows:

$$\begin{aligned}\mathbb{E}_{src} &= \sum_{i=1}^{k}\sum_{j=0}^{m}\left[(R_{i,j}+W_{i,j})\mathbb{P}_{tx}l_{data} + G_{i,j}\mathbb{P}_{rcv}l_{ACK_2}\right] \\ &\quad + \sum_{i=1}^{k}\sum_{j=0}^{m}\left[(R_{i,j}+W_{i,j})(l_{GTS}-l_{data}) - G_{i,j}l_{ACK_2}\right]\mathbb{P}_{idle} \\ &\quad + \mathbb{P}_{CAP}\Pi[Q_0]\end{aligned} \tag{22}$$

where $\mathbb{P}_{tx}$, $\mathbb{P}_{rcv}$ and $\mathbb{P}_{idle}$ are the average energy consumption for transmitting, receiving and idle-listen for one bit, respectively. As mentioned, l_{data}, l_{ACK_2} and l_{GTS} are the length (in bits) of data packet, ACK packet in the CFP and the allocated GTS. In Eq. (22), the first term considers the energy consumption of the data packet transmission and the ACK packet reception, while the second term takes into account the energy consumption during the idle stage in the rest of GTS, and the third term is the energy consumption for the GTS request command transmission in the CAP, which is given in the appendix.

Similarly, the expected energy consumption of the destination is given as follows:

$$\mathbb{E}_{dst} = \sum_{i=1}^{k}\sum_{j=0}^{m}\Big(W_{i,j}\mathbb{P}_{rcv}l_{data} + G_{i,j}\mathbb{P}_{tx}l_{ACK_2}\Big) + \sum_{i=1}^{k} D_i\mathbb{P}_{idle}l_{GTS} + \sum_{i=1}^{k}\sum_{j=0}^{m}\Big[W_{i,j}(l_{GTS} - l_{data}) - G_{i,j}l_{ACK_2}\Big]\mathbb{P}_{idle} \qquad (23)$$

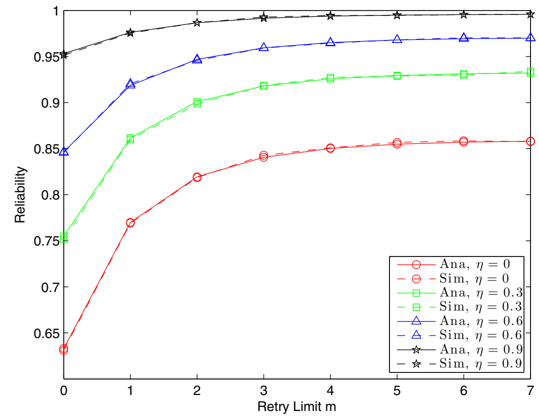
where the first term considers the energy consumption of the data packet reception and the ACK packet transmission, the second and the third terms take into account the energy consumption during idle stage in the rest of GTS.

VI. Numerical Results

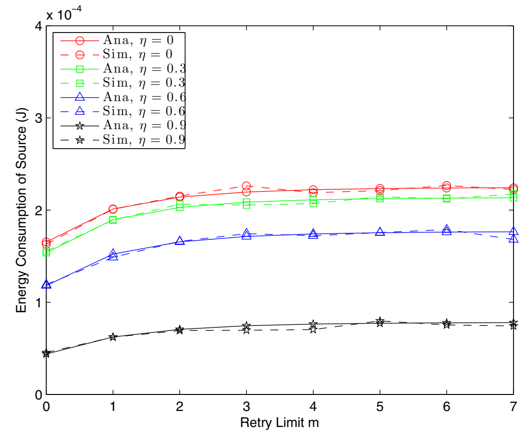
In this section, we first present Monte Carlo simulations of the enhanced GTS mechanism to validate our analytical expressions of the reliability and energy consumptions. Then we investigate the impacts of MAC parameters m, k and the traffic condition η on the performance indexes.

Based on the IEEE 802.15.4 specifications [1] and CC2420 datasheet [13], parameters are set as follows: $l_b = 20\ bytes$, $l_{ACK_2} = 5\ bytes$, $l_{data} = 256\ bytes$, the data rate is $250\ kbps$, $l_{GTS} = 484\ bytes$, $b_1 = b_2 = b_3 = 3.2053 \times 10^{-4}$, $\mathbb{P}_{tx} = 2.5056 \times 10^{-7} J/bit$, $\mathbb{P}_{rcv} = 2.8368 \times 10^{-7} J/bit$ and $\mathbb{P}_{idle} = 6.1344 \times 10^{-9} J/bit$. Based on these values, we can derive that $p_1 = p_2 = 0.95$, $p_3 = 0.5186$ and $p_4 = 0.9873$. For simplicity, we assume that other devices in the network will generate ordinary packets sent in the CAP with probability $1 - \eta$ as well, and the size of ordinary packets is also l_{data}.

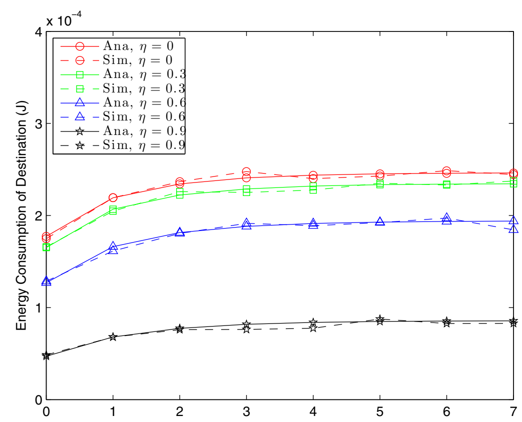
Fig. 5 illustrates the reliability, energy consumptions of the source and destination obtained by our analytical expressions Eqs. (21)–(23) and Monte Carlo simulations with 3000 steps. Different traffic conditions ($\eta = 0, 0.3, 0.6, 0.9$) are investigated. These figures show that our analysis matches the simulation results very well. We observe that retransmissions can improve the reliability significantly and increase the energy consumption only slightly if $m \leq 3$. When $m \geq 4$, both the reliability and energy consumptions will converge to certain values. Thus, large retransmission limit will not improve the performance. The performance differences between high traffic scenarios and low traffic scenarios are mainly caused by the performance in the CAP (i.e., λ and $\mathbb{P}_{CAP}$). In high traffic scenarios, it is more difficult for the PANC to receive the GTS request commands successfully and thus the CAP becomes a bottleneck. This implies that for time-critical applications with high reliability requirement, it is preferable to limit the number of devices associated with each PANC.



(a) Reliability



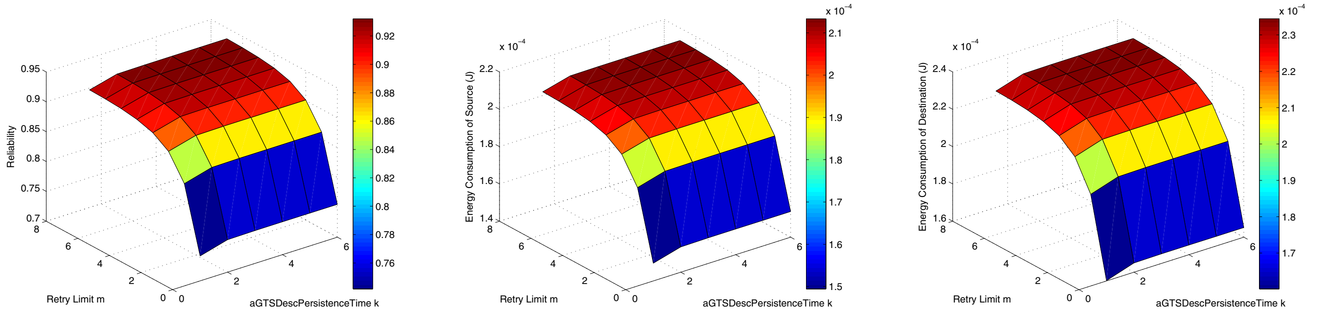
(b) Energy Consumption of Source



(c) Energy Consumption of Destination

Fig. 5. Analysis validation by Monte Carlo simulations with 3000 steps on the traffic condition $\eta = 0, 0.3, 0.6, 0.9$ and $k = 4$

Fig. 6 shows the impacts of MAC parameters m and k under the traffic condition $\eta = 0.3$. Besides similar observations as in Fig. 5, we notice that the value of k does not have much impact on the performance if $k \geq 3$. The reason is that all GTS requests are assumed to be served in the first superframe. Due



(a) Reliability (b) Energy Consumption of Source (c) Energy Consumption of Destination

Fig. 6. Impacts of MAC parameters ($\eta = 0.3$)

to the low probability of beacon tracking failures, both the source and destination are very likely to get the GTS allocation information in the first two superframes. These figures can be used to decide the values of MAC parameters. In this scenario, we can set $k = 2$ and $m = 3$.

VII. Conclusion and Future Work

In this paper, we modeled and analyzed the performance of the enhanced GTS mechanism in IEEE 802.15.4 networks. We derived the expressions for the reliability and energy consumptions of both the source and destination, and validated their accuracy by Monte Carlo simulations. The impacts of MAC parameters are also investigated. Our future work includes: (*i*) analyze the latency and extend our model to consider the case $n_0 > \Delta$, and (*ii*) design protocols based on our model with optimized performance and integrate them into a system level design framework for specific application requirements.

Appendix
Calculation of λ and $\mathbb{P}_{CAP}$

For State Q_0 (i.e., the transmission in the CAP), we need to calculate the probability λ that the PANC can receive the GTS request command successfully and the energy consumption $\mathbb{P}_{CAP}$ in this state. We will make use of the results in [5], which analyzed the performance of data transmissions in the CAP in the beacon-enabled CSMA/CA mode. Observing that the state probabilities in the case of single transmission are the same as that in the case of saturated traffic, we set $q_0 = 0$ and $L_0 = 0$ in their model to calculate λ and the energy consumption $\mathbb{P}_{CAP}$ in State Q_0 as follows:

$$\lambda = 1 - \frac{x^{m'+1}(1-y^{n+1})}{1-y} - y^{n+1} \tag{24}$$

$$\begin{aligned}\mathbb{P}_{CAP} &= \mathbb{P}_{idle}\sum_{i=0}^{m'}\sum_{k=0}^{W_i-1}\sum_{j=0}^{n} b_{i,k,j} + \mathbb{P}_{sc}\sum_{i=0}^{m'}\sum_{j=0}^{n}(b_{i,0,j} + b_{i,-1,j}) \\ &+ \mathbb{P}_{tx}\sum_{j=0}^{n}\sum_{k=0}^{L-1}(b_{-1,k,j} + b_{-2,k,j}) + \mathbb{P}_{idle}\sum_{j=0}^{n}(b_{-1,L,j} \\ &+ b_{-2,L,j}) + \sum_{j=0}^{n}\sum_{k=L+1}^{L+L_{ack}+1}(\mathbb{P}_{rcv}b_{-1,k,j} + \mathbb{P}_{idle}b_{-2,k,j}) \end{aligned} \tag{25}$$

where $x = \alpha + (1-\alpha)\beta$ and $y = p_c(1-x^{m+1})$. Due to the limited space, please refer to [5] for more details.

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