Energy efficiency of different data transmission methods in IEEE 802.15.4: study and improvement

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Abstract— **IEEE 802.15.4 is a new standard intended to serve a set of simple but important applications with very low power consumption and relaxed data rate requirements. Among these applications are residential networks, medical sensor networks, and industrial monitoring networks. In this paper, we propose new mechanisms to reduce the energy consumption of IEEE 802.15.4 devices further. Analysis results show that our schemes can improve energy efficiency of the devices, and save up to 47% energy in tracking beacons. Thus it can extend the lifetime of the entire personal area network.**

I. INTRODUCTION

IEEE 802.15.4 is a new standard designed to support short-distance networking with very low power consumption and relaxed data rate requirements [1] [2]. It can be used in home automation and networking, industrial monitoring, medical sensor networking, and precise agriculture. The wireless link of IEEE 802.15.4 (referred to as 802.15.4 hereinafter) is operated in license free industrial scientific medical (ISM) 2.4GHz band that is publicly available worldwide.

In the literature, a great number of existing 802.15.4 work focused on performance evaluation and analysis either through simulations or through experiments [3] [4] [5] [6] [7]. Their evaluation metrics are throughput (or goodput), packet delivery ratio, energy consumption and packet delay. Several others studied 802.15.4 MAC protocol from the prospect of power consumption. In [8], an energy model of 802.15.4 was proposed, while the power consumption of slotted CSMA-CA was analyzed in [9]. The energy efficiency analysis of 802.15.4 was presented in [10]. It proposed an energy-aware radio activation scheme to minimize the energy consumption. Based on the energy breakdown, the authors suggested several possible ways, such as reducing the state transition time and transmitting larger packets, to improve the overall energy efficiency of 802.15.4 in wireless sensor networks. However, these approaches to improving energy efficiency either depend on the electrical characteristics of 802.15.4 RF transceivers, or are only applicable to certain application scenarios.

In this paper, we compare the energy efficiency of different data transmission methods (direct, indirect, and Guaranteed Time Slot (GTS)). From the close examination of the procedures of the three supported transmission methods, we propose several new schemes to reduce power consumption of 802.15.4 devices in a personal area network (PAN).

The remainder of the paper is organized as follows. Section II provides a brief overview of the 802.15.4 standard. Our simulation experiments with the analysis for various transmission methods are presented in Section III. Section IV presents the proposed solutions to improve energy efficiency with some discussions. Finally, we summarize the paper and describe the future work in Section V.

II. IEEE 802.15.4 OVERVIEW

IEEE 802.15.4 standard is designed for low-power low-rate wireless PANs. It defines the physical layer and medium access control layer specifications. For energy efficiency, the physical layer supports activation and deactivation of the radio transceiver, energy detection, link quality indication, and clear channel assessment (CCA). The MAC protocol of 802.15.4 can operate in either beacon mode or beaconless mode. In the beaconless mode, it is a simple unslotted CSMA-CA protocol. We focus on beacon mode in the remainder of this paper because there exist many unique features that we are able to exploit. The typical operating range of 802.15.4 is approximately 10 to 20 meters, and the raw data rate is 250kb/s in the 2.4GHz band. In this section, we introduce the features of the MAC layer.

A. Superframe structure

IEEE 802.15.4 supports low-rate wireless personal area networks working in beacon mode through superframe. The structure of a superframe, bounded by beacon frames, is shown in Figure 1. The coordinator of the PAN defines the format of the superframe.

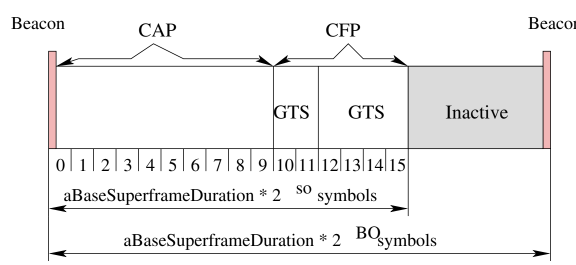

Fig. 1. The typical structure of a superframe

The superframe beacons are transmitted periodically by the coordinator and are used to identify the PAN and synchronize the attached devices. The transmission frequency of beacons is determined by the *macBeaconOrder* ranged from 0 to 14.

Within the superframe structure, the coordinator may choose to enter sleep mode during the inactive portion. The length of the inactive portion depends on the *macSuperframeOrder* (SO) and *macBeaconOrder* (BO). As shown in Figure 1, the active portion of the superframe is divided into 16 time slots. It may consist of two periods, namely contention access period (CAP) and contention free period (CFP). The CAP immediately follows the superframe beacon and completes before the CFP begins. All frames except acknowledgement frames are transmitted in this period using a slotted CSMA-CA mechanism. In slotted CSMA-CA, the backoff period boundaries are aligned with the superframe slot boundaries of the PAN coordinator. Unlike in CAP, channel access in CFP is based on reservations and is free of contention. One part of the CFP is allocated for a particular device, which is denoted as a guaranteed time slot (GTS). The GTS direction, which is relative to the data flow from the device that owns the GTS, is specified as either transmit or receive. A maximum of seven GTSs are allowed to be allocated in a PAN.

B. Transfer model

Three types of data transfer models are supported in 802.15.4. The first one is the data transfer from a device to a PAN coordinator. In a beacon-enabled PAN, the device has to synchronize to the superframe structure. Then the device can transmit a data frame using slotted CSMA-CA at the appropriate time. The coordinator returns an acknowledgement (ACK) when receiving the frame. The transaction is now completed. This type of transfer is called direct transfer model.

The second type is the data transfer from a coordinator to a device. In a beacon-enabled PAN, the PAN coordinator stores the data frame in a transaction list, and notifies the device through beacons. After the device decodes the beacon, it transmits a data request to the coordinator if there is a transaction pending for it. The coordinator acknowledges the reception of the request and the pending data frame is transmitted at the appropriate time using slotted CSMA-CA. The pending data frame is removed from the transaction list only after the acknowledgement for this frame is received or the data frame remains unhandled in the list over the maximal transaction persistence time. Because the data transfer is instigated from the destination (device) instead of the data source (coordinator), this type of transfer is called indirect transfer model.

The third type is the peer-to-peer data transfer between two devices in a peer-to-peer PAN. This type of transfer model allows devices to communicate with each other directly through unslotted CSMA-CA or some synchronization mechanisms.

III. EXPERIMENT AND ANALYSIS

In this section, we evaluate the ideal energy efficiency of the three transmission modes of 802.15.4 using the simulation tool [11]. The experiments are conducted in a simple beacon-enabled PAN, consisting of a PAN coordinator *node(0)* and a PAN device *node(1)*. We choose BeaconOrder = 7 and SuperframeOrder = 7, thus the duty cycle is 100%. The active potion of the superframe is 1.98114 seconds. *Node(1)* is the traffic source with a simple exponential on-off pattern. The on period only occupies 5% of the time. The traffic rate is 1000 bits/sec and the packet size is 20 bytes. One hundred and eighty bytes of data flows from the source to the destination.

Due to the fact that devices in a PAN are usually simpler and more power-constrained compared to the coordinator, we focus on the energy consumed at a device side when sending/receiving a data packet. Our goal is to determine schemes to reduce energy consumption further in order to extend the lifetime of devices. For the GTS transmission mode, GTS request procedure is the overhead. We assume that the energy consumption in the GTS request is negligible in the case that the device has a substantial amount of data to transmit.

TABLE I
TRANSCEIVER PARAMETERS

Item	Value
Voltage supply	1.8 v
Receiver current	19.7 mA
Idle current	0.426 mA
Transmitter current (-10dBm)	11 mA

The only variance is that the data source is different in direct, indirect and GTS data transmission. In direct and GTS data transmission, *node(1)* is the data source while it is the data destination in indirect mode. For each method, we run 10 simulations with different seeds. The transceiver characteristics of the commercial transceiver CC2420 [12] as shown in Table I are used for energy calculations.

We define the energy efficiency as

$$\rho = \frac{p_{data}}{\sum_{k=1}^{n} p_k} \tag{1}$$

, where p_{data} is the power spent on the raw data transmission, and p_k is the power consumed on the beacon, acknowledgement, idle state, data frame and other command frames. The energy consumed in turning on/off the transceiver is fixed, thus excluded from the calculation. The energy efficiency of the three modes are shown in Table II.

TABLE II
POWER EFFICIENCY

Transmission method	Efficiency	Energy spent on tracking beacons
Direct transmission	38.08%	37.02%
Indirect transmission	40.87%	24.52%
Transmission through GTS	39.45%	38.35%

From Table I, we can see that the cost of receiving one byte is relatively high compared to that of transmission of one byte. Moreover, the current in idle state is about 2% of the current in receive state and the backoff periods are very short. Thus the indirect transmission has the highest efficiency although it involves more complicated procedures. However, the rank of its efficiency is conditional. The condition is that the device knows that a pending data packet for it is available in the upcoming superframe. Direct transmission method ranks the lowest in energy efficiency due to similar reasons. Transmission through GTS is a very efficient method with guaranteed service although it may waste some bandwidth if no data transmission takes place in the allocated slots. Surprisingly, the cost of tracking beacons is almost $1/3$ of energy consumption in all three transmission methods as shown in Table II. Although the transmission of short data packets is a partial reason, tracking beacons is still a big overhead. Thus, we will investigate how to improve energy efficiency in the next section. We acknowledge the three transmission methods serve different purposes. Our objective is to show which method favors low power devices, and examine the procedures of each transmission method in order to propose new mechanisms to improve their efficiency.

IV. Improvement and Discussion

As we discussed in Section III, the indirect transmission method has the conditional highest energy efficiency. The condition is that a device turns on its transceiver upon knowing there is a data packet pending for it. In practice, it is usually impossible. Waking-up frequently would lower the efficiency. On the other hand, waking-up rarely would incur the risk of losing packets because the pending packet is discarded if not fetched within the maximal transaction persistence time. However, a suboptimal solution exists. Devices can wake up periodically (maximal transaction persistence time) to check whether there is a transaction pending. If there is, the devices will try to fetch the packet. And the devices should continue to track the next superframe beacon to check again. If there is no indication of packets pending, the device turns off its transceiver. Otherwise, the fetch procedure continues.

(a)

Octs:2	1	4/10	2	1	0/1	var	var	var	2
Frame control	Seq No	Address –ing fields	Superframe Spec	GTS Spec	GTS directions	GTS list	Pending address fields	Beacon payload	FCS

(b)

Bits: 0–3	4–7	8–11	12	13	14	15
Beacon order	Superframe order	Final CAP slot	Battery life extension	Reserved	PAN coordinator	Association permit

Fig. 2. (a) Beacon frame format (b) Superframe specification

One similarity shared among the three transmission methods is that the device has to track at least one beacon before it can prepare for its data transmission. As shown in Table II, the power consumption for receiving a beacon is about 37% in direct transmission mode, 24% in indirect transmission mode and 38% in transmission through GTS. In a large size PAN, multiple devices have to receive the same beacon and decode it although they do not have any data to transmit/receive, which cause a substantial amount of energy waste. By examining the beacon frame structure in Figure 2 closely, we find that it has much space to minimize its length. A beacon contains at least 1 byte GTS field – *GTS specification* all the time regardless of whether valid GTS information is included. Figure 2(b) shows there is a bit *Reserved* in superframe specification. Therefore it can be used to make the GTS field as an option in the beacon frame. In this case, the GTS field is included only when necessary, so higher energy efficiency can be achieved. The modification and the interpretation are as follows:

GTSIndication(Reserved)	Description
0	no GTS spec
1	GTS spec

Another unnecessary energy drain is when the coordinator disseminates the GTS allocation information – GTS descriptor. The GTS descriptor remains in the beacon frame for *aGTSDescPersistenceTime* (default: 4) superframes. When the device, which has requested for GTS slot, receives the first beacon containing the descriptor, the information in the beacons received afterwards become redundant. Note: other devices accessing wireless channel in CAP do not need to know this information. Instead, it is sufficient for them to know the *Final CAP slot* through superframe specification. Based on the analysis above, we propose the following mechanism to make the dissemination of GTS descriptor more efficient.

Scheme IV.1 GTS information distribution

```
1:  The coordinator allocates GTS slots for devices
2:  The coordinator transmits a beacon including the GTS descriptors
3:  Turn on the receiver and keep it on in all allocated GTS slots
4:  The devices requesting the GTS slot receive the beacon.
5:  if The GTS slot is of transmit type then
6:      if The device has data to send then
7:          Transmit data in the GTS slot allocated for this device
8:      else
9:          Transmit an ACK to the coordinator in the GTS slot
            allocated for this device. The seq number in ACK uses
            the seq of the beacon
10:     end if
11: else if The GTS slot is of receive type then
12:     The device transmits an ACK to the coordinator in the GTS
        slot allocated for this device. The seq number in ACK uses
        the seq of the beacon
13:     Turn receiver on
14: end if
15: if The coordinator receives the ACK/data in the dedicated GTS
    slot then
16:     It stops the dissemination of the GTS descriptor in beacons
17: else
18:     The coordinator repeats the above procedure from step 2
19: end if
```

For simplicity, we use the same ACK frame format as the 802.15.4 specification. Since each device that requests a GTS slot returns an ACK or implicit ACK in its own allocated slot, no collision occurs at the coordinator. During the GTS period, each device is expected to turn on its receiver or transmitter only at its designated slot for energy saving. We assume that the acknowledgment and data transmission in GTS slots are reliable due to the exclusive usage. In order to analyze the net energy saving of the proposed GTS allocation distribution algorithm, the following variables are defined. Let E_t and E_r be the energy for transmitting and receiving one byte respectively. N is the total number of devices in a PAN, and ρ is the percentage of devices waking-up. n_{ack} is the length of an ACK frame measured in terms of bytes, $n_{ack} = 11$. n_{bytes} is the bytes saved for a GTS descriptor, $n_{bytes} = 3$. Compared with the scheme defined in 802.15.4 specification, the extra energy cost by the proposed algorithm comes from the transmission and reception of ACKs to GTS descriptors. As indicated in the proposed algorithm, the illustration and analysis for the energy cost are discussed as below.

Case 1: the GTS slot is of transmit type and the device has data to send at time-being. The device can utilize the allocated slot to transmit the data to the coordinator. The reception of data at the coordinator implicitly acknowledges the successful reception of the GTS descriptor from the specific device. Due to the fact that the data transmission is necessary regardless of whether the proposed algorithm is deployed or not, the extra energy cost is:

$$E_{cost} = 0 \tag{2}$$

Case 2: the GTS slot is of transmit type and the device has no data to send at time-being. In this case, the device transmits an ACK to the coordinator to notify its successful reception of the GTS descriptor. Note: the transmission takes place in the designated GTS slot, so no other devices in the PAN receive the packet. The extra costs are only at the specific device and the coordinator. The energy cost is:

$$\begin{aligned} E_{cost} &= E_{cost_{device}} + E_{cost_{coord}} \\ &= (E_r + E_t)n_{ack} \end{aligned} \tag{3}$$

Case 3: the GTS slot is of receive type. It is similar to the scenario of Case 2. And the cost is the same as that of the Case 2.

$$\begin{aligned} E_{cost} &= E_{cost_{device}} + E_{cost_{coord}} \\ &= (E_r + E_t)n_{ack} \end{aligned} \tag{4}$$

Assume there are k devices requesting GTS slots in a PAN, of which m devices fall into Case 1. $0 \leqslant m \leqslant k \leqslant 7$. Thus, the extra energy cost for the entire PAN is:

$$E_{cost} = (k - m)(E_r + E_t)n_{ack} \tag{5}$$

The energy savings of our proposed schemes are from reception and transmission of smaller size beacons at the devices and the coordinator respectively. The acknowledged GTS descriptors are excluded in the next beacons. For example, if 3 of the k devices acknowledged the receptions of their descriptors, only $k - 3$ descriptors will be included in the remaining beacons. The coordinator distributes GTS descriptors at most *aGTSDescPersistenceTime* (4) times. Table III shows the example of how to calculate the energy saving compared with the original scheme. The fourth column is the number of devices requesting GTS receiving their own descriptors in the beacon. If x devices receive their descriptors in the 1st beacon, their descriptors will not be included in the next three beacons.

TABLE III
EXAMPLE FOR CALCULATION

Beacon Seq	**# descriptors** inclded(original)	**# descriptors** included(proposed)	**# devices recv their** descriptors in the beacon
1	k	k	x
2	k	k-x	y
3	k	k-x-y	z
4	k	k-x-y-z	k-x-y-z

Note: in the PAN, not only these devices requesting for GTS track the beacons, all waking-up devices are tracking the beacons. Therefore, the energy saving is:

$$\begin{aligned} E_{saving} &= E_{devices} + E_{coord} \\ &= (3xE_r n_{bytes} + 2yE_r n_{bytes} + zE_r n_{bytes}) \times N\rho \\ &\quad +(3xE_t n_{bytes} + 2yE_t n_{bytes} + zE_t n_{bytes}) \times 1 \\ &= (3x + 2y + z)(E_r N\rho + E_t)n_{bytes} \end{aligned} \tag{6}$$

Alternatively, the above equation could be obtained in another way. Let P_1, P_2, P_3, and P_4 be the probabilities that the 1st, 2nd, 3rd and 4th beacon be the first successfully received one containing the descriptor by a device. The requesting devices can only receive one copy of their descriptors, either in the 1st beacon, or in the 2nd/3rd/4th beacon. Thus, the two conditions:

$$P_j = \begin{cases} 1 & \text{, a device receives its descriptor in } j\text{th beacon} \\ 0 & \text{, otherwise} \end{cases}$$

$$\sum_{j=1}^{4} P_j = 1 \tag{7}$$

are satisfied. The number of requesting devices that receive their descriptors in the 1st, 2nd, 3rd beacon are

$$\sum_{i=1}^{k} P_1^{(i)} = x \tag{8}$$

$$\sum_{i=1}^{k} P_2^{(i)} = y \tag{9}$$

$$\sum_{i=1}^{k} P_3^{(i)} = z \tag{10}$$

Therefore, Equation (6) can be rewritten in the following format.

$$\begin{aligned} &E_{saving} = E_{devices} + E_{coord} \\ &= (3\sum_{i=1}^{k} P_1^{(i)} E_r + 2\sum_{i=1}^{k} P_2^{(i)} E_r + \sum_{i=1}^{k} P_3^{(i)} E_r) n_{bytes} N\rho \\ &+(3\sum_{i=1}^{k} P_1^{(i)} E_t + 2\sum_{i=1}^{k} P_2^{(i)} E_t + 1\sum_{i=1}^{k} P_3^{(i)} E_t) n_{bytes} \\ &= (3\sum_{i=1}^{k} P_1^{(i)} + 2\sum_{i=1}^{k} P_2^{(i)} + \sum_{i=1}^{k} P_3^{(i)})(E_r N\rho + E_t) n_{bytes} \end{aligned} \tag{11}$$

So the condition for energy saving in the entire PAN is

$$E_{saving} > E_{cost} \tag{12}$$

Plugging Equation (5) and (11) into (12), we have

$$(3\sum_{i=1}^{k} P_1^{(i)} + 2\sum_{i=1}^{k} P_2^{(i)} + \sum_{i=1}^{k} P_3^{(i)})(E_r N\rho + E_t)n_{bytes} > (k-m)(E_r + E_t)n_{ack} \tag{13}$$

It is obvious that the PAN always benefits from the proposed scheme if all the GTS processing scenarios are of transmit type, and devices have data to send when they acknowledge the reception of descriptors. This case is very common in sensor networks where most data flows are from sensor devices to the sink (coordinator). The worst case is that all the requesting devices receive their descriptors in the fourth beacon. The proposed algorithm would result in a little energy waste due to the transmission of ACKs at the requesting devices and reception of ACKs at the coordinator.

The proposed mechanism has two merits. The first is power efficiency. A typical sensor network usually consists of a large number of devices with dense deployment. With our mechanism not only the energy of the coordinator and the targeted device is saved, the energy consumption of other devices which are tracking network beacons is also reduced. The second merit is that the proposed mechanism is compatible with the implementation of the existing specification without introducing extra complexity. In addition, the proposed mechanism can also be applied to deallocate GTS initialized by the PAN coordinator.

To investigate the performance of proposed beacon structure and the innovated GTS descriptor distribution, we perform some evaluations. The characteristics of CC2420 in Table I are used. In a typical dense microsensor network, a large number of nodes are deployed as redundant nodes. We consider a scenario where 1000 nodes are distributed around a sink. The sink acts as the coordinator, while the sensor nodes are PAN devices. We assume that all the nodes are within the communication range of the coordinator. In normal operation, among the 1000 nodes some of them are in sleep mode and others are awake, transmitting packets or waking up to check whether there are data pending at the coordinator for them. We focus on the energy consumed at devices when receiving beacons because devices are usually more power-constrained than the coordinator in a PAN.

The evaluation of modified beacon structure is straightforward. When no GTS descriptor is present in beacons, the one byte *GTS specification* is excluded. For one device, the energy used to receive 17 standard beacons is sufficient to receive 18 modified beacons. That is to say a device can save 5.6% energy in tracking beacons. Therefore adopting the modified beacon structure favors very low power devices.

In order to evaluate the performance of the innovated GTS allocation distribution algorithm, we assume only one device

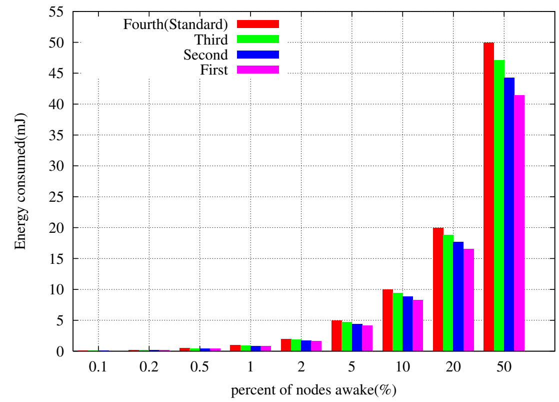

Fig. 3. Energy for tracking the four beacons at devices when applying modified beacon structure and innovated GTS descriptor distribution scheme

in the PAN requests for GTS and it is approved. This is the simplest case. The coordinator disseminates the allocated GTS descriptor in beacons. The energy consumed by PAN devices to track the four beacons with the modified beacon structure and the GTS distribution mechanism simultaneously is shown in Figure 3. The *fourth*, *third* and *second* represent the target device receiving the GTS descriptor in the fourth, third, and second beacon respectively, which indicates the previous beacons are missed due to various reasons such as sleeping. The *first* represents the target device receiving the GTS descriptor in the first beacon. From the figure, in the case of *fourth*, the PAN always consumes much more energy than in other cases. It is because the coordinator has to disseminate the GTS descriptor in four beacons due to no ACK from the target device. This is the worst case. If the device receives and acknowledges the first beacon, the coordinator will transmit the remaining three beacons with modified beacon structure. In this case, the PAN saves the largest amount of energy, which is about 17% saving compared with the standard protocol. This amount of energy saving is vital to significantly extend the lifetime of low power wireless sensor networks.

The scenario becomes complicated when multiple devices request GTS, and some of them may receive their GTS descriptors in the first beacon while others receive them in the remaining beacons. The energy consumption for tracking these beacons depend on the variances. There exist 120 combinations. Instead, a simplified case is considered here. Seven devices in the PAN request GTS. The requesting devices receive their descriptors either all in the first beacon, or all in the 2nd/3rd/4th beacon. Figure 4 show the energy consumption by PAN devices to track the four beacons with the modified beacon structure and the GTS distribution mechanism. Compared with the mechanism in 802.15.4 standard, our proposed algorithm can save up to 47.3% energy in tracking the four beacons if the requesting devices can receive their descriptors in the first beacon. When they receive their descriptors in the second and third beacon respectively, 31.5% and 15.8% energy saving could be achieved. Considering that the GTS is requested on demand and is deallocated when not used, a PAN can benefit significantly from the proposed algorithm and the modified beacon structure.

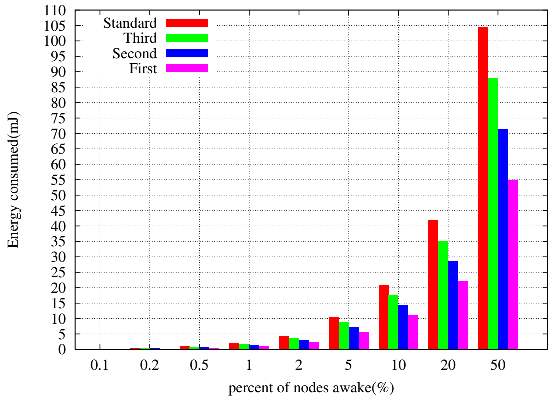

Fig. 4. Energy for tracking the four beacons at devices when applying modified beacon structure and innovated GTS descriptor distribution scheme

It is interesting to investigate the conditions for achieving energy saving in a PAN. Figure 5 shows the simplified cases, where all requesting devices receive their GTS descriptor in the first, second or third beacon. Note: this figure does not depend on the number of devices requesting for GTS. As shown in the figure, the PAN can achieve energy saving as long as there is another device tracking beacons if the requesting devices can receive their GTS descriptors in the first beacon. The PAN can always benefit from energy savings if 60% of the GTS requests fall into case 1 (GTSs are of transmit type and requesting devices have data to send). If all requesting devices receive their descriptors in the second beacon, two other waking-up devices are needed for net energy saving. In case of requesting devices receiving descriptors in the third beacon, there only needs four of devices to track the beacons in order to achieve net energy savings. The conditions are easy to be satisfied in wireless sensor networks, where a large number of redundant nodes are deployed.

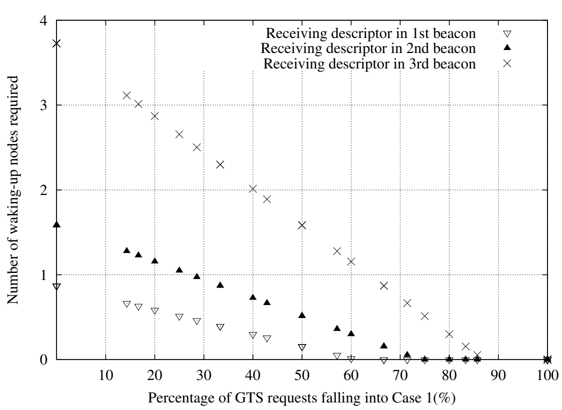

Fig. 5. The number of waking-up nodes required for energy saving in a PAN

V. Conclusion

IEEE 802.15.4 standard targets a wide variety of applications, which require simple short-range wireless communications with limited power and relaxed throughput needs. It offers device-level wireless connectivity at low cost.

In this paper, we investigate the performance of different data transmission methods in terms of power efficiency. Simulation results show that although superframe beacons from the PAN coordinator play the key role in channel access synchronization, they are also the overhead contributing to lower power efficiency. By examining the procedure of the three transmission methods closely, we streamline the size of network beacons to save the energy consumed by the devices which are tracking the beacons. In addition, a simple but efficient mechanism is proposed for a coordinator to disseminate GTS descriptors. The conditions for net energy saving are discussed. Evaluation results show that these solutions can reduce up to 47.3% energy consumption in tracking beacons at devices, and thus extend the lifetime of the entire PAN.

Our future work includes implementation of the proposed energy efficient mechanisms in 802.15.4 RF chips, and employing real experiments to test their performance.

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