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Enhanced Beacon Enabled Mode For Improved IEEE 802.15.4 Low Data Rate Performance

Xiaoyun Li, Chris Bleakley, Wojciech Bober

Abstract— This paper proposes enhancements to IEEE 802.15.4 Beacon-Enabled Mode that provide improved network performance and lower power consumption for low data rate applications. The proposed mode utilizes a Synchronous Low Power Listening technique that allows nodes to sleep for multiple Beacon Intervals and subsequently recover Beacon synchronization in a power efficient manner. The proposed mode also incorporates a Periodic Wakeup scheme that allows nodes to transmit at scheduled times during the inactive period. The proposed Enhanced Mode is backward compatible and inter-operable with the original standard. Simulation results show that the proposed Enhanced Mode reduces the power consumption overhead of synchronization by more than 50% for applications with low data rates compared with standard Beacon-Enabled mode. End-to-end delay and data loss rate are reduced by more than 90% compared with standard Beacon-Enabled mode. Duty cycle is reduced by 20% ~ 80% compared with standard Beacon-Enabled mode and by more than 90% compared with non-Beacon-Enabled mode in low and moderate traffic conditions.

***Index Terms*— IEEE 802.15.4, Beacon-Enabled mode, Power saving, Low Power Listening, synchronization, MAC layer, protocol design.**

I. INTRODUCTION

IN many envisaged Wireless Sensor Networks (WSNs) applications, such as environmental monitoring [1]-[5], it is planned to deploy large numbers of sensor nodes in the target area for months, or even years, without maintenance. In these circumstances, battery replacement and manual recharging are impossible. Hence, energy efficiency is essential. In practice in many of these applications, sensor measurements were only downloaded from the motes once a few hours or even every few days [1][2][3]. In addition, the measurements themselves, for example temperature and humidity, have only a low data rate.

The IEEE 802.15.4 protocol [6] specifies the Medium Access Control (MAC) sub-layer and physical layer for Low-Rate Wireless Private Area Networks (LR-WPAN). It targets low-data rate, low power consumption, low cost wireless networking applications. The IEEE 802.15.4 protocol is closely associated with the ZigBee protocol [7]. In fact, the ZigBee Alliance, which is an organization with over 150 member companies [7], is working in conjunction with the IEEE Task Group 4 in order to specify a full protocol stack. The Zigbee protocol's application and network layers are based on the 802.15.4 standard's MAC and Physical layers. It is expected that the IEEE 802.15.4 standard will be commonly used in current and future WSN products.

The 802.15.4 standard provides a Beacon-Enabled Mode that allows for period wakeup and synchronization of nodes. The mode enables power savings for low duty cycle applications in which nodes can save energy by being switched off most of the time.

This paper proposes a new Enhanced IEEE 802.15.4 Beacon-Enabled Mode. The proposed Enhanced mode improves on performance of the standard IEEE 802.15.4 MAC protocol for low rate applications by means of Synchronized Low Power Listening (S-LPL) and Periodic Wakeup (PW) mechanisms. S-LPL allows nodes to be inactive to longer periods of time than is supported by the standard. The increased clock drift that arises is compensated for uses a Low Power Listening and Virtual Preamble communication scheme for synchronization. PW allows nodes the option of communicating more frequently than allowed in the standard. Overall, the new Enhanced Mode significantly reduces power consumption, data transmission end-to-end delay and data loss rate for low duty cycle and low date rate applications. The mode is compatible and inter-operable with the original standard.

This paper is structured as follows. Section 2 introduces the IEEE 802.15.4 standard. Related works on improving the IEEE 802.15.4 MAC protocol are presented in Section 3. The proposed Enhanced IEEE 802.15.4 Beacon-Enabled Mode is introduced in Section 4. The results of performance comparisons with the standard using OPNET simulations are discussed in Section 5. Section 6 concludes the paper.

II. IEEE 802.15.4 OVERVIEW

According to the IEEE 802.15.4 standard, a LR-WPAN contains two different types of devices - Full Function Devices (FFDs) and Reduced Function Devices (RFDs). FFDs can support three operational modes: Personal Area Network

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(PAN) Coordinator, Coordinator or simple device. RFDs operate with minimal implementations of the IEEE 802.15.4 protocol. A LR-WPAN must include at least one FFD acting as a PAN Coordinator that provides services to the network and manages FFDs and RFDs. Two basic types of network topologies are defined in the IEEE 802.15.4 standard: - star topology and peer-to-peer topology.

A. IEEE 802.15.4 Medium Access Control

The IEEE 802.15.4 MAC protocol supports two operational modes that may be selected by the Coordinator:

- Non Beacon-Enabled Mode. In this mode, devices can simply send their data using unslotted CSMA/CA (Carrier Sense Multiple Access With Collision Avoidance). No superframe structure is used in this mode.
- Beacon-Enabled Mode. In this mode, Beacon frames are periodically generated by the Coordinator to synchronize associated devices and to identify the PAN. A Beacon frame is the first part of a superframe. During the active period of a superframe, all data is exchanged between the nodes and the PAN coordinator using slotted CSMA/CA.

In the IEEE 802.15.4 standard, every PAN Coordinator must choose either Beacon-Enabled mode or non-Beacon-Enabled mode, and cannot support both modes at the same time. When the Coordinator selects Beacon-Enabled Mode, it forces the use of a superframe structure to manage communication between devices that are associated to the PAN. The format of the superframe is defined by the PAN coordinator and is broadcast periodically to the other devices. The superframe is divided into 16 equally sized slots and is followed by a predefined inactive period. During the inactive period the PAN Coordinator may switch to a low power mode in order to save energy. An example of a superframe structure is shown in Fig 1.

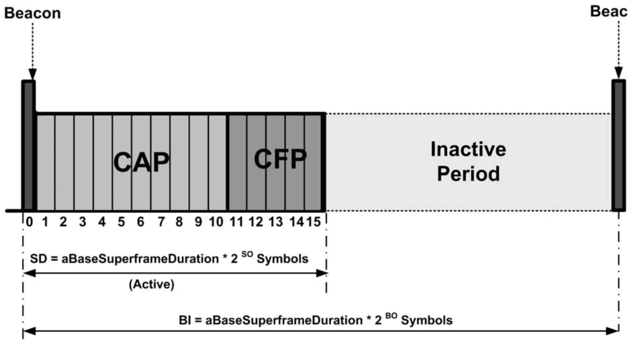

Fig. 1. Example of the Structure of a Superframe

B. Structure and Parameters of a Superframe

The structure of a superframe is defined by two parameters:

The parameter macBeaconOrder (BO) defines the interval at which the coordinator must transmit Beacon frames. The Beacon Interval (BI) is the time, in symbols, between two adjacent broadcasted Beacon frames. All binary data is encoded and mapped into data symbols in the IEEE 802.15.4 Physical layer. For example, in the IEEE 802.15.4 (2450 MHz) PHY layer, each symbol is mapped to 4 bits data.

$$\mathrm{BI} = \mathrm{aBaseSuperframeDuration} * 2^{\mathrm{BO}} \text{ symbols}$$

where for $0 \leq \mathrm{BO} \leq 14$ and aBaseSuperframeDuration equals 960 symbols.

The parameter macSuperframeOrder (SO) defines the length of the active portion of the superframe. The Superframe Duration (SD) is the active period of a superframe in symbols.

$$\mathrm{SD} = \mathrm{aBaseSuperframeDuration} * 2^{\mathrm{SO}} \text{ symbols}$$

where $0 \leq \mathrm{SO} \leq \mathrm{BO} \leq 14$. The PAN operates in Non Beacon-Enabled mode if macBeaconOrder and macSuperframeOrder are equal to 15.

The active portion of each superframe is divided into aNumSupeframeSlots (default 16) equally spaced slots of duration $2^{\mathrm{SO}} *$ aBaseSlotDuration. The attribute aBaseSlotDuration represents the number of symbols forming a superframe slot when the superframe order is equal to zero. The standard value of aBaseSlotDuration is equal to 60 symbols.

The active portion of the superframe structure is composed of three parts - Beacon frame, CAP (Contention Access Period) and an optional CFP (Contention-Free Period). The CAP has a minimum length of aMinCAPLength (default 440) symbols. In a CAP, associated nodes can communicate with PAN Coordinator using slotted CSMA/CA. The CFP starts immediately after the end of the CAP and must complete before the start of the next Beacon frame. All of the Guaranteed Time Slots (GTSs) that may be allocated by the PAN coordinator are located in the CFP and must occupy contiguous slots.

C. CSMA/CA Mechanisms

The IEEE 802.15.4 standard defines two CSMA/CA mechanisms:

- Slotted CSMA/CA is used in Beacon-Enabled Mode
- Unslotted CSMA/CA is used in Non Beacon-Enabled Mode

In both cases, the CSMA/CA algorithm is based on backoff periods, where one backoff period is equal to aUnitBackoffPeriod (20 Symbols). aUnitBackoffPeriod is the basic time unit of the MAC protocol. In slotted CSMA/CA the backoff period boundaries must be aligned with the superframe slot boundaries. While in unslotted CSMA/CA, the backoff periods of one device are completely independent of any other device in a PAN.

D. Synchronization

The standard defines mechanisms to synchronize the Coordinators with their associated devices. This procedure is particularly important in Beacon-Enabled Mode where each associated device must synchronize its transmission with the Beacon transmissions from its Coordinator.

A synchronization problem arises if a device is not able to receive the Beacon from its Coordinator. When the number of missed Beacons reaches aMaxLostBeacons, or if aMaxFrameRetries attempts of transmissions come to failure, the device must consider itself an orphan and either perform the orphaned device realignment procedure or reset the MAC sub-layer and perform the association procedure again.

To acquire Beacon synchronization, a device must enable its receiver and search for at most aBaseSuperframeDuration * (2^n +1) symbols, where n is the macBeaconOrder.

E. Problems to Be Addressed

For low duty cycle applications, Beacon-Enabled Mode is much more energy efficient than Non Beacon-Enabled Mode. In Beacon-Enabled Mode, the PAN coordinator only switches on during the active period and can sleep during the inactive period to save power. In order to communicate with the PAN Coordinator, nodes must synchronize with it and communicate with it only during the active period.

Unfortunately, the degree of power saving is limited. Beacon-Enabled Mode only supports a Beacon Order of between 0 and 14. Thus a Beacon frame must be transmitted at least every 251.6 seconds for the 2.4 GHz band Physical layer. For applications with low duty cycles, in which, for example, a node may only transmit 1 data packet every 24 hours, the node still has to wakeup and receive a Beacon frame every 251.6 seconds or less, which is inefficient in energy critical WSN applications.

Additionally, the use of Beacon-Enabled Mode can lead to substantial data transmission latency. Data generated during the inactive period must be sent in the next active period. In order to save power, the active period may only occupy a very small proportion of the Beacon Interval. Hence the mean transmission delay is approximately half of the Beacon Interval, which can be more than 1 minute for BO>11. For smaller values of BO, the mean transmission delay can be reduced using smaller BO or by increasing the proportion of the active period. However there is a penalty in terms of increased energy consumption. This increase in energy consumption is especially significant for low data rate applications. Long transmission latency is a particularly significant problem in multi-hop networks because latency is introduced at each hop of the transmission.

An associated problem with Beacon-Enabled Mode is that it cannot adapt to varying traffic loads. A short active period can result in a high data loss rate under high data rate conditions. There is simply not enough time to transmit all of the date. Conversely, a long active period can result in low energy inefficiency under low data rate conditions. Again, this is an issue for some low rate applications which use thresholding to detect events. Normally the traffic load is low but when an event is detected, the traffic load is temporally high. To avoid a high date loss during an event, power must be wasted in maintaining a high active period even when the traffic load is light.

III. RELATED WORK

Due to importance of power saving, WSNs community proposed a number of energy efficient MAC protocols. Researchers proposed asynchronous protocols like B-MAC [8] which offer simplicyty, but suffer from overhearing. Also synchronous protocols like S-MAC [9] were proposed to reduce idle listening and collisions, but have higher control overhead. An energy-efficient long-term time synchronization algorithm [10] adapting to clock drift was integrated with B-MAC to reduce transmission energy consumption. Hybrid protocols like Z-MAC [11] combine both approaches to alleviate abovementioned issues. Although, protocols proposed so far perform well in terms of energy conservation, they are proprietary solutions and are not compatible with the IEEE 802.15.4 standard.

Previous work by other authors has addressed the problems described in the last section, especially in relation to improving the performance of IEEE 802.15.4 Beacon-Enabled mode in meeting the requirements of various applications.

TEA-15.4 [12] utilizes two techniques: Arbitrary Traffic Signal (ATS) and Traffic Time-Out (TTO), which allow a PAN coordinator to adjust its active period during CAP according to the traffic volume from its children nodes. Hence TEA-15.4 can support high data throughput and offer lower energy consumption. However, TEA-15.4 does not solve the problem of long latency for data generated during the inactive period of the PAN coordinator. TEA-15.4 can only adapt to queued traffic, so that queued data packets can be sent before the next superframe with short latency. Traffic generated during the inactive period has to bear long latency until the next superframe.

The AGA (Adaptive GTS Allocation) scheme for IEEE 802.15.4 [13], provides GTS Allocation with low latency and fairness. In the IEEE 802.15.4 standard, seven nodes at most can be allocated to a GTS in one superframe on a first-come-first-served basis. Using AGA, each child node is assigned a priority number according to the importance of the node. Nodes with the highest priority (smallest priority number) are allocated to a GTS first. Fairness is also considered, so that the priority of a node is decreased after being allocated to a GTS, while nodes with lower priority get higher priority if they were refused allocation to a GTS. AGA [13] does not consider GTS allocation for nodes with very low data rates. For nodes with very low data rates, e.g, 1 data packet per 100 superframes, AGA does not provide higher priority in such cases, although a GTS is required before 100 Beacon Intervals. A node has to request a GTS every time it wants to send a packet during CFP, which is energy inefficient.

Centralized [14] and distributed [15] Beacon scheduling algorithms have been proposed, such that Beacons can be scheduled to avoid overlapped active periods between adjacent PAN Coordinators in multi-hop networks. Hence

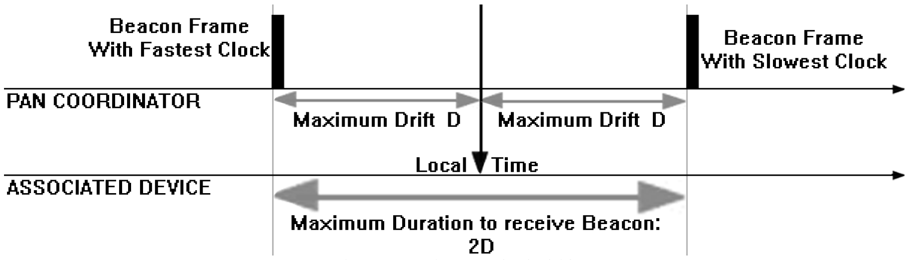

Fig. 2. Maximum Clock drift

Beacon frame collisions can be avoided. If the network topology changes frequently due to node mobility, node failure or active node rotation in high density networks, the overhead of Beacon scheduling [14][15] could be significant. The IEEE 802.15.5 Task Group 5 is discussing a proposal for Beacon scheduling for mesh topologies [16], to avoid Beacon collisions. It involves making fundamental changes to the superframe structure on the MAC to provide a Beacon-only timeslot in which Beacons of neighbours and neighbours' neighbours are transmitted. The Beacon scheduling algorithm [16] involves changing the MAC superframe structure of IEEE 802.15.4, hence it is incompatible with the current standard.

IV. ENHANCED IEEE 802.15.4 BEACON-ENABLED MODE

Enhanced Beacon-Enabled Mode includes two optional functions - Synchronized Low Power Listening (S-LPL) [17] to reduce synchronization overhead for low data rate applications, and Periodic Wakeup (PW) during the inactive period of a superframe to reduce data transmission latency and data loss rate.

A. Synchronization for Low Data Rate Applications

The IEEE 802.15.4 standard Beacon-Enabled mode supports a Beacon Order of between 0 and 14. This limits the power saving which is possible in low duty cycle applications. Standard Beacon-Enabled Mode cannot support larger BOs (BO > 14) for two main reasons.

The first reason is due to the synchronization overhead when a device associates with a PAN coordinator. It may search for aBaseSuperframeDuration*(2^n+1) symbols at most and may spend an average of aBaseSuperframeDuration*2^{n-1} symbols to receive a Beacon frame, where n is equal to macBeaconOrder. If n is too large, a device may run out of energy before it associates with the PAN Coordinator.

The second reason is due to synchronization difficulties when the Beacon Interval grows because of clock drift between devices. The main causes of clock drift are temperature variation and differences in crystal oscillator cut angles [18]. The IEEE 802.15.4 standard requires that all devices have a maximum drift of ±50ppm. Therefore, the maximum drift D between any two 802.15.4 compliant devices is given by:

$$D = 2 \times 50 \times 10^{-6} \times \mathrm{BI} \qquad (1)$$

where BI is the Beacon Interval.

The IEEE 802.15.4 standard requires an associated device to wakeup earlier than the expected Beacon arrival time to avoid missing the Beacon frame. As shown in FIG. 2, a node associated with a PAN coordinator must wakeup D seconds before the expected Beacon arrival time in case the PAN coordinator's clock is D seconds faster than the node's clock and might have to listen to the channel for up to $2D$ seconds before receiving the Beacon frame, because it is possible that the PAN coordinator's clock is D seconds slower than the node's clock.

Thus for larger BOs than allowed by the standard (BO>14), the Beacon Interval would be at least 503 seconds and the maximum drift between any two devices would be 50.3 ms or more. Hence a device would have to wakeup more than 50.3 ms earlier than the predicted time for the next Beacon frame to ensure receipt of the Beacon frame.

The proposed Enhanced Mode allows for longer synchronization periods for certain nodes. These nodes only receive a Beacon every K Beacon frames. We refer to the time K x BI at the Extended Beacon Interval (EBI). This longer synchronization period can lead to large clock drift between the Controller and the associated node. In this case, the maximum clock drift is:

$$D' = 2 \times 50 \times 10^{-6} \times K \times \mathrm{BI} \qquad (2)$$

For example, when the data rate of an application is around one packet per 4 hours, the PAN Coordinator sets BO = 14 and K = 56 (for the 2.4 GHz band physical layer), such that an associated node only needs to wakeup and synchronize with the PAN coordinator every 56 Beacon frames (equal to K×BIs). In this case, the maximum clock drift is 1.41 seconds. If the associated node had to listen to the channel for 1.4 seconds before receiving the next Beacon frame, it would quickly run out of energy. To reduce the synchronization overhead, Enhanced Beacon-Enabled Mode performs S-LPL, which uses Virtual Preambles (VPs) at the PAN coordinator and Low Power Listening [19] at associated node at the beginning of every Extended Beacon Interval. At the start of the EBI, the Coordinator transmits a series of Virtual Preambles, each separated by the duration of a Virtual Preamble itself. An example of S-LPL is shown in FIG 3. The associated node starts LPL D' seconds before the expected Beacon broadcast time [19]. LPL lasts for $2D'$ seconds, at most, if no VP frame is received. The VP frame length is set to the minimum frame length according to the standard (39 bytes). The VP contains the Controller Id and the time stamp of the Controller. LPL is periodic at the associated node until a Virtual Preamble is received. Listening is on for two times the duration of a single VP frame and then off for the duration of one VP. This ensures that the VP is detected while minimizing power consumption.

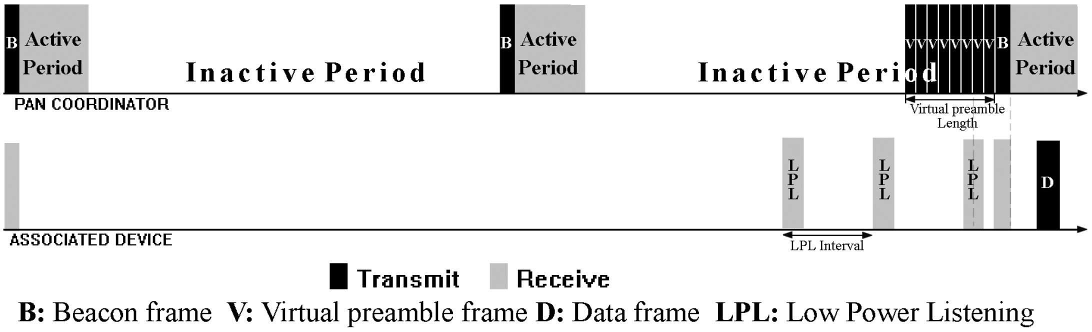

Fig. 3. Example of synchronized Low Power Listening in Enhanced Beacon-Enabled mode

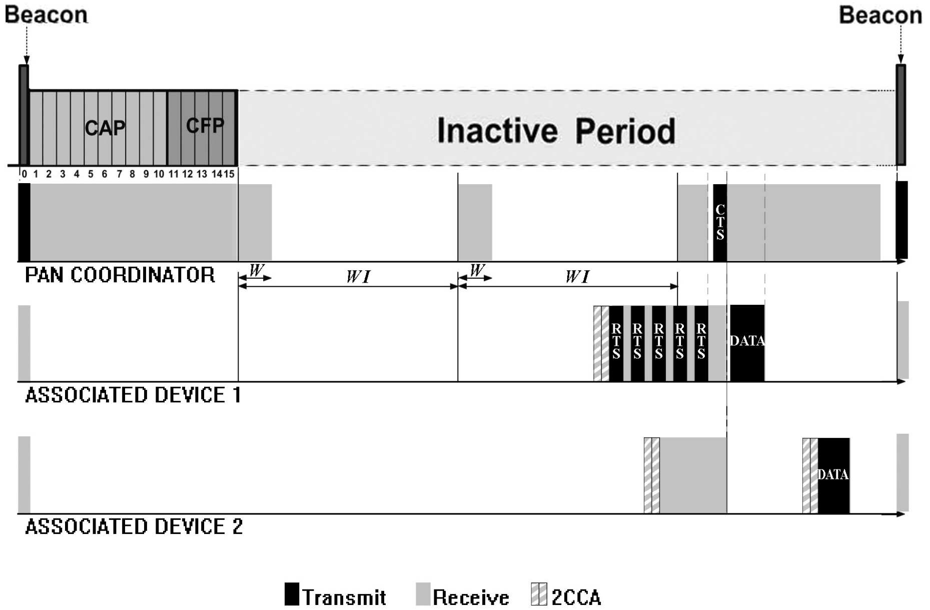

Fig. 4. An example of periodic wakeup during the inactive period

If the node receives a VP frame during LPL, it synchronizes according to the PAN Coordinator's time stamp and adjusts its clock to receive the following Beacon frame. After this, the associated node can send data to the PAN Coordinator during the active period of the superframe, either during CAP or CFP. The value of K and the VP length are defined in the Beacon frame.

If a number of associated nodes share the same EBI then VP reception can be shared, reducing energy consumption.

If the associated node wants to transmit data to the PAN coordinator using GTS during CFP, the GTS allocation procedure should be adjusted accordingly because the node only requires the GTS slot every K superframes. Details for the adjustment of the GTS allocation procedure are not presented here, since this paper focuses on reducing the synchronization overhead for low data rate applications.

Using S-LPL, the synchronization overhead is significantly reduced compared to standard Beacon-enabled mode for low data rate applications, as shown Section 5.

B. Reliability for S-LPL

If an associated node cannot receive any VP frames during the Synchronized LPL period, due to collision or any other reason, then the node may not be able to receive the following beacon frame from the PAN Coordinator and synchronize with it.

In the case of VP collision, the associated node either receives a packet other than the VP frame or detects noise during the Synchronized LPL period. If this happens, the node stops LPL and switches on the receiver during the remaining Synchronized LPL period to acquire the correct VP frame or Beacon frame.

If no virtual preamble frame or beacon frame is received during the Synchronized LPL period then the node will send a data frame requesting acknowledgement using CSMA/CA to the PAN Coordinator during the estimated CAP of the superframe. If the node receives an acknowledgement or any other message from the Coordinator, then it synchronizes with the PAN Coordinator. Otherwise the next higher layer will be notified of a loss of synchronization after the Superframe Duration, and the node will perform an orphan scan to relocate its Coordinator according to the IEEE 802.15.4 Beacon Enabled mode standard [6].

C. Periodic Wakeup

To solve the problem of long latency for data generated during the inactive period of a superframe and to adapt to changing traffic loads, the proposed Enhanced Beacon-

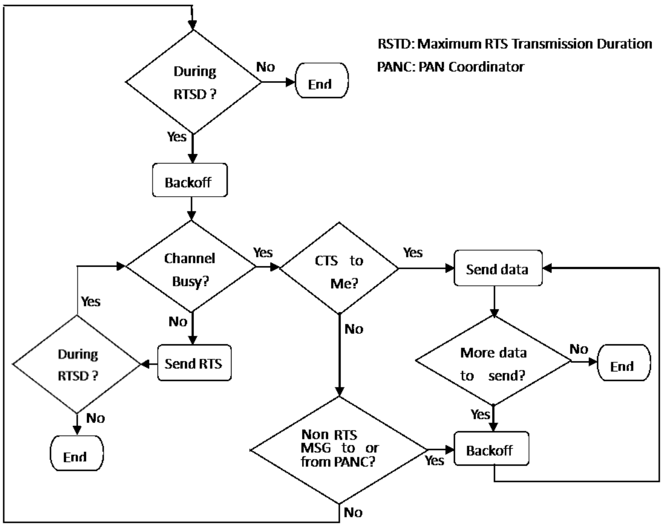

Fig. 5. State graph for an associated node to send data during inactive period

Enabled Mode incorporates optional Periodic Wakeup (PW) by the associated nodes and listening by the PAN Coordinator during the inactive period. Hence not only queued data, but also newly generated data during the inactive period can be sent to the PAN coordinator with low latency.

Usually in networks requiring low latency, Beacon Order (BO) is set to 6 or 7, such that nodes communicate with the PAN Coordinator every 1 or 2 seconds. However, this increases power consumption. Additionally, in multi-hop networks, frequently broadcast Beacon frames have a high probability of collision. In such cases, nodes may lose synchronization with the PAN Coordinator, resulting in transmission failure.

In Enhanced Beacon-Enabled Mode, Beacon broadcast can be reduced significantly using a larger value of BO. Thus BO can be set to a sufficiently large value, e.g. BO>10, so as to reduce the probability of collision. Hence the high probability of Beacon collision, especially in multi hop networks can be avoided. Using PW, the mean transmission delay using Enhanced Beacon-Enabled mode is still comparable to that obtained using standard Beacon-Enabled mode with a smaller value for BO, e.g. BO = 6.

During the inactive period in Enhanced mode, the PAN coordinator can optionally support PW for a short duration (W symbols) at the start of every Wakeup Interval (WI). If no data is received during the wakeup duration, the PAN coordinator will go to sleep until the next WI. If a data frame is received during the wakeup, the PAN coordinator will stay awake for the maximum backoff units until no data is received. It will then return to sleep until the next WI. An example is shown in FIG 4. In this way, the mean transmission delay can be shortened from around BI/2 to WI/2. Thus the network can adapt to traffic load variation with a very low data loss rate even when the active period is very short (e.g. SO=2), as shown in Section 5.

Because the PAN coordinator needs to wakeup periodically during the inactive period even if no data transmission occurs, the wakeup duration should be as short as possible to save power. The minimum wakeup duration W is set to 2 times the RTS duration + aUnitBackoffPeriods, which is the minimum duration to guarantee receiving a whole RTS message.

If a node wants to communicate with the PAN coordinator during the inactive period, firstly it sends RTS (Ready To Send) messages continuously using CSMA/CA. The first RTS message is sent $D+T_{backoff}$ seconds before the next expected PAN coordinator wakeup time, and the maximum RTS transmission duration lasts for $\min(2D+T_{backoff}, WI)$ seconds at most before receiving a CTS (Clear To Send) from the PAN coordinator. $T_{backoff}$ is a random backoff period between 0 and $(2^{macMinBE}-1)$ aUnitBackoffPeriods. aUnitBackoffPeriods equals to 20 symbols. If the channel is clear, it sends the first RTS message. Then it switches on the receiver for aUnitBackoffPeriods to receive the preamble of the CTS message. If the channel is idle, it then transmits the next RTS. If a preamble (preamble length = 8 symbols) is received, it then continues to receive the whole packet. If the packet is CTS from the Coordinator, it sends the data frame immediately. Otherwise it continues to send RTS messages. If the node has more than one packet to send, after transmitting the first data frame, it will wait for a random backoff period to listen to the channel for 2CCA (Clear Channel Assessment). One CCA duration equals aUnitBackoffPeriods. If the channel is clear, it then sends the second data frame without sending any more RTS messages.

If another node has detected that the channel is busy after one or two CCA, it switches on the receiver to overhear the media. If it receives a RTS message, it listens to the channel until it receives a CTS message from the PAN coordinator. Then it waits for a random backoff period and performs 2CCA again. If the channel is clear, it then sends a data frame immediately without sending a RTS message, as shown in FIG 4. The state graph for an associated node to send data using S-LPL is shown in FIG. 5.

Once the PAN coordinator wakes up and receives a RTS message, it responds with a CTS message after *aTurnaroundTime* (12 symbols), and then waits to receive the data frame. After receiving a data frame, it switches on the receiver for a period of $2^{macMaxBE} \times$ aUnitBackoffPeriod in order to receive another data frame. If no data is received during this period, the PAN coordinator will go to sleep until the next wakeup time. If an associated node receives or overhears a CTS from the PAN Coordinator, it then synchronizes with the PAN Coordinator. Hence the node adjusts its clock to compensate the time drift before sending one or more data frames. The process for an associated node to send data is shown in FIG 4.

D. *Reliability for PW*

It is difficult for the associated nodes to detect whether the PAN Coordinator is awake or not during the inactive period since the PAN Coordinator listens to the channel passively. If an associated node has not received any CTS after sending RTS messages or overhearing the channel during the maximum RTS transmission duration $\min(2D+T_{backoff}, WI)$ then the node has to wait until the next wakeup duration of the PAN Coordinator to send its data. To avoid long end-to-end delay the following mechanism is implemented.

If an associated node receives a non-RTS message to or from the PAN Coordinator during the maximum RTS transmission duration, the node will wait for a random backoff period to send its data packet. Otherwise the node will send RTS messages until the end of the maximum RTS transmission duration as shown in FIG. 5. In this way, the mean transmission end to end delay is restricted to around WI/2 thus most of the data frames generated during a WI can be transmitted at the following wakeup duration of the PAN Coordinator.

If two adjacent PAN Coordinators' wakeup timeslots overlap, the collision is not an issue because a PAN coordinator can simply discard a RTS message if it is not the correct destination.

V. EXPERIMENTS

Simulations of standard IEEE 802.15.4 Beacon-Enabled Mode and the Enhanced Beacon-Enabled Mode were performed using OPNET. Various numbers of associated nodes, traffic models (Poisson distribution and constant distribution) and different traffic loads were used to compare the performance of the protocols. The simulation code for the Enhanced mode was developed from open source code for the IEEE 802.15.4 standard Beacon-Enabled Mode [20].

Using the Enhanced mode, the synchronization overhead is significantly reduced for low data rate applications because for each associated device, the Beacon frame is only received once every K superframes. There is a minor overhead of S-LPL for each associated device and VP broadcast by the PAN coordinator once every K superframes.

In contrast in the standard Beacon-Enabled Mode, each associated node has to receive every Beacon frame, and should wakeup earlier than the expected Beacon arrival time. Because the IEEE 802.15.4 standard does not explicitly define the offset time before receiving the next Beacon frame, in order to compare the synchronization overhead with standard Beacon-Enabled mode, it is assumed in this paper that in standard Beacon-Enabled Mode (for BO $\leq$ 14), if an associated node wakeups one tenth of Maximum Drift ($D/10$) earlier than the next expected Beacon arrival time, it can keep synchronization with the PAN Coordinator. Because for a short period of time (BI $<$ 5 minutes for BO $\leq$ 14) the temperature variation is relatively small to affect the clock drift, and the IEEE 802.15.4 standard allows aMaxLostBeacons of missed Beacons before claiming synchronization failure as mentioned in Section II. Hence an associated node can keep synchronization with the PAN Coordinator using wakeup offset time of $D/10$. Therefore $D/10$ is the mean Synchronization overhead for each associated node in standard Beacon-Enabled mode according to this assumption. For BO=14, $D/10$ is 2.5ms. While for BO<12, $D/10$ is less than 0.32 ms. Such synchronization overhead is very small. But for a long duration such as a few hours, the accumulated synchronization overhead is large especially for low data rate applications.

Simulation of Enhanced Beacon-Enabled Mode was performed using OPNET within various data rates and K values (BI=251.6 seconds). The reduction of synchronization overhead is shown in FIG. 6. In the simulation, BO is 14 and the VP (including 16 VP frames) length is 15.36 ms. When the data rate is 1 packet every 4 hours (K=56), the synchronization overhead is reduced by more than 50% when the number of associated nodes is more than 1, compared with standard Beacon-Enabled mode. When the data rate is even lower (1 packet per 24 hours), the synchronization overhead is reduced by around 60%.

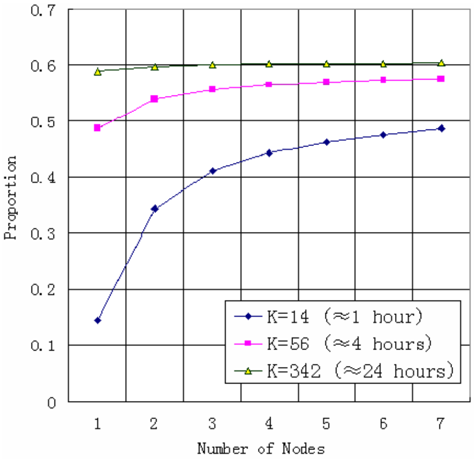

Fig. 6. . The reduced synchronization overhead using Synchronized LPL compared to the standard Beacon-Enabled mode

In the standard Non Beacon-Enabled Mode, the duty cycle of the PAN coordinator is always 100% no matter whether the network is busy or not, even if the duty cycle for each associated node is close to 0.

The mean duty cycle equals to the total wakeup time of all nodes (PAN Coordinator and all associated nodes) divided by the total simulation time (wakeup time plus sleeping time) of all nodes. Wakeup time includes the time when a node is receiving or transmitting, or in idle listening. Therefore the mean duty cycle for Non Beacon-Enabled Mode is almost fixed as 1/(N+1) (N+1 includes N associated nodes and the PAN Coordinator) regardless of traffic variation.

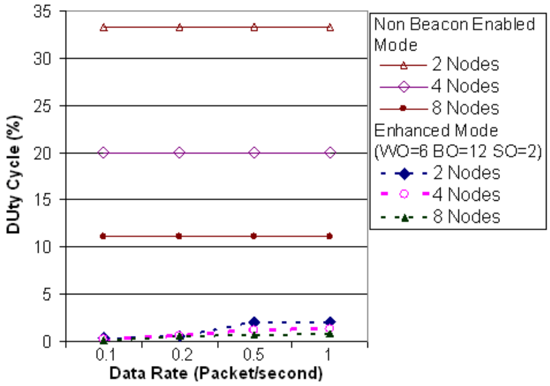

Fig. 7. . Comparison of mean duty cycle

In the Enhanced Beacon-Enabled Mode with WO (Wakeup Order) = 6, the reduction in duty cycle is between 90% and 98% compared with Non-Beacon-Enabled Mode for a range of associated nodes (2, 4 and 8 nodes) as shown in FIG. 7. The duty cycle is adaptive to traffic load (data rate and number of associated nodes),

where $WI = aBaseSuperframeDuration * 2^{WO}$ symbols.

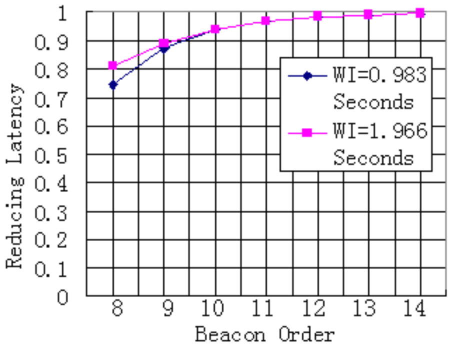

Fig. 8. . Reduced end to end delay compare to Beacon Enabled mode

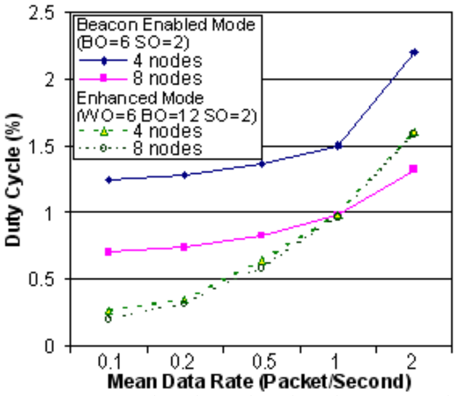

Fig. 9. . Mean Duty Cycle Enhanced mode and Beacon-Enabled mode (Poisson traffic)

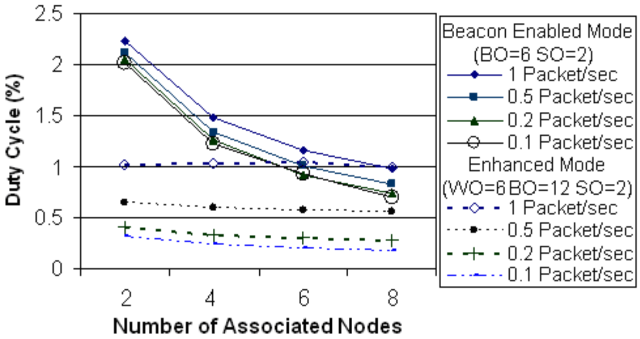

Fig. 10. . Mean Duty Cycle Enhanced mode and Beacon-Enabled mode (Constant traffic)

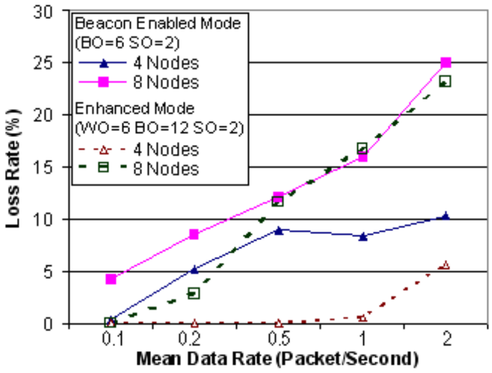

Fig. 11. . data loss Enhanced mode and Beacon-Enabled mode (Poisson traffic)

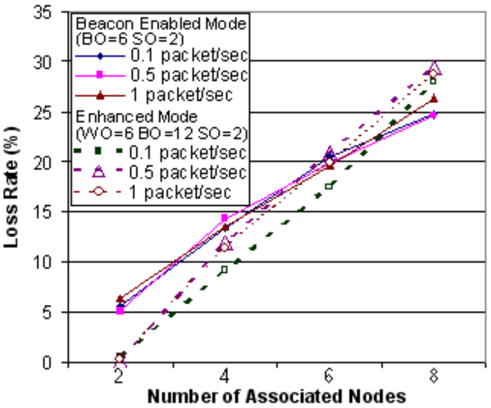

Fig. 12. . Mean data loss Enhanced mode and Beacon-Enabled mode (Constant traffic)

Using standard Beacon-Enabled Mode, the mean end-to-end delay is around BI/2 if data is generated randomly at any time in the active or inactive period of a superframe and the active period only occupies a small proportion of a BI. For the Enhanced Beacon-Enabled Mode, the mean transmission latency is reduced to around WI/2 if the traffic load is small with almost no collision, because the PAN coordinator wakeups every WI seconds.

FIG 8 shows that, in Enhanced Mode, the end to end delay is reduced by more than 90% while the wakeup interval is 0.983 and 1.966 seconds respectively, compared to Beacon-Enabled mode with BO>9, when traffic load is low without serious collision.

In Enhanced Mode, the mean end to end delay (data receive time – data generation time) is slightly longer than WI/2, which is comparable with standard Beacon-Enabled Mode for any number of associated nodes and traffic load, when WO (in Enhanced mode) is the same as BO (in standard Beacon-Enabled mode) and the value of BO in Enhanced mode is much larger. The end to end delay only increases between 10% and 20% compared to standard Beacon-Enabled Mode when the data rate is constant and all associated nodes generate data simultaneously. The simulation result is similar for Poisson distribution traffic, where all associated nodes have the same mean data rate and data is generated randomly by each node at any time in a superframe.

FIGs 9 and 10 show that, in the Enhanced Mode, when the total traffic in the network is less than 4 packets per second (total traffic is equal to nodal data rate times the number of associated nodes), the mean duty cycle is reduced by 20% ~ 80% compared to standard Beacon-Enabled Mode.

FIG. 9 and 10 also show that, in the Enhanced Mode the mean duty cycle is almost fixed for various numbers of associated nodes with the same traffic load, which indicates that duty cycle is adaptive to traffic load, such that when number of associated nodes or traffic load decreases, the duty cycle of the PAN Coordinator also decreases to save energy. While in standard Beacon Enabled Mode, the duty cycle for the PAN Coordinator is fixed, therefore the mean duty cycle for smaller numbers of associated nodes or low traffic load is much higher than that in the enhanced mode.

FIG 11 and 12 show that in Enhanced Mode, for low data rate with total traffic in the network of less than 6 packets per second, the data loss rate is reduced by 10% ~ 99% compared to Beacon-Enabled Mode when WO (in Enhanced mode) is equal to BO (in Beacon-Enabled mode), and BO (12) in

Enhanced mode is much larger than the BO (6) in Beacon-Enabled mode.

FIG 11 and 12 also show that, in Enhanced Mode, when mean data rate is low without serious collision for random data traffic with Poisson distribution in FIG 11 (number of associated nodes ≤ 4 and mean data rate ≤ 1 packet/sec), or for constant traffic with the number of associated nodes ≤2 in FIG 12, the data loss rate is less than 1%, while for the same parameters in Beacon-Enabled mode, the data loss rate is between 5% and 10%. This is because of the RTS/CTS mechanism in Enhanced mode. When collision occurs and no CTS is received, the sender will try to send another RTS. Hence data loss is reduced compared to Beacon-Enabled mode with unacknowledged data traffic. While for higher data rate with total traffic in the network of more than 6 packets per second, in the Enhanced mode, the data loss is slightly higher (≤ 5%) than in Beacon-Enabled mode, because the RTS/CTS mechanism results in more retransmission of RTSs and more collision and higher probability of channel busy compared to Beacon-Enabled Mode, hence it causes slightly more data loss.

In the Enhanced Mode, if the value of BO (12) is the same as that in Beacon-Enabled mode with random data traffic of Poisson distribution, the mean duty cycle increases by –3% ~ 45% when traffic load increases. The increased duty cycle in Enhance Mode grows according to the increase in traffic load, in order to adapt to the traffic load and reduce the data loss rate. The data loss rate is reduced significantly by 80% ~ 100% in Enhanced Mode as shown in FIG. 13 with 6 associated nodes, because in Beacon Enabled Mode with the same BO (=12), queued data generated during inactive period results in heavy traffic in the active period, which causes collisions and loss, especially at the beginning of a superframe, even when the active period (SO=6) is sufficient to receive all the packets.

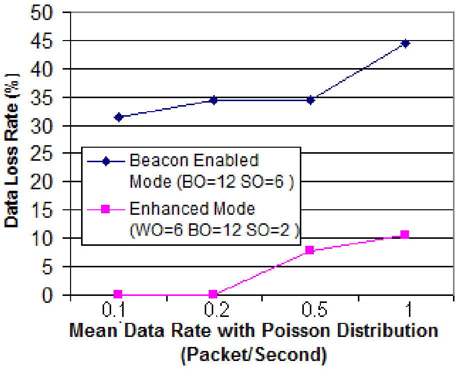

Fig. 13. . Mean Data loss Enhanced mode and Beacon-Enabled mode with the same BO (6 Associated nodes)

Furthermore, in Enhanced Mode the end-to-end delay is much shorter (<1 second) than in standard Beacon-Enabled Mode with the same BO (BO = 12) (mean delay ≈ 29 seconds), when the nodal data rate is no more than 0.5 packets per second. But for a higher data rate of 1 packet per second, the mean end to end delay increases dramatically to 230 seconds in Beacon-Enabled Mode for SO=6, because the active period is not sufficient to transmit all queued data generated during the last superframe. When SO is increased to 7 in Beacon-Enabled Mode, the end-to-end delay drops to 28.8 seconds. But the data loss rate is still very high (44.5%), and the mean duty increases accordingly because the active period is double.

VI. CONCLUSION

This paper proposed an Enhanced IEEE 802.15.4 Beacon-Enabled Mode. The mode incorporates Synchronized Low Power Listening and Periodic Wakeup during the inactive period, while still being compatible and interoperable with the original standard. Hence nodes supporting the original standard can join the network without modification. The proposed Enhanced Mode improves on performance of the standard IEEE 802.15.4 MAC protocol significantly reducing power consumption, data transmission end-to-end delay and data loss rate.

Simulations using OPNET were performed for the proposed Enhanced Mode. The simulation results show that the energy consumption of the synchronization overhead is reduced by more than 50% for applications with low data rate compared to standard Beacon-Enabled mode. The average nodal duty cycle is reduced by more than 90% compared to Non-Beacon-Enabled mode. It was found that the transmission end to end delay is reduced by more than 90% compared to standard Beacon-Enabled Mode for BO>9 in scenarios without significant numbers of collisions. Data loss rate is decreased by more than 90% compared to standard Beacon-Enabled Mode in non-saturated scenarios, with a slight increase in duty cycle (10% ~ 30%) compared to standard Beacon-Enabled Mode when the traffic load is high.

Simulation results indicate that the proposed Enhanced Mode improves the performance of the standard IEEE 802.15.4 MAC protocol significantly for low duty cycle and low data rate applications, reducing power consumption, data transmission latency and data loss rate.

The proposed Enhanced IEEE 802.15.4 Beacon-Enabled Mode requires a minor adjustment of the MAC layer of the standard, without impacting on the upper layers. So it is easy to implement on existing commercial IEEE 802.15.4 and Zigbee products.

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