Service Differentiation based on Contention Window with Enhanced Collision Resolution LR-WPANs

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***Abstract*— The IEEE 802.15.4 MAC [1] standard defines the channel access for low-rate, low-power communication applications such as Wireless Sensor Networks but does not differentiate between high or low priority data. We study few priority based service differentiation mechanisms which distinguish between such data for each and every device, and also let high priority have better channel access as compared to low priority. We also study a mechanism, which improves collision resolution in CSMA algorithms for 802.15.4.**

In this paper, we propose a service differentiation mechanism for IEEE 802.15.4 based on varying Contention Window parameter and enhance collision resolution. Our proposed algorithm not only deliver service differentiation according to class priority, but also adapts to the backoff exponent according to the channel contention information collected during CCA.

***Keywords*— IEEE 802.15.4, Service Differentiation, Contention Window, Enhanced Collision Resolution, LR-WPAN.**

I. Introduction

The recent advent in wireless communications elicited the development of standard protocols explicitly designed for a particular range of applications. In that direction, the IEEE 802.15.4 protocol [1] has been proposed as a wireless communication standard which specifies the physical layer and media access control for Low-Rate Wireless Personal Area Networks (LR-WPANs). LR-WPAN is used in a diverse variety of embedded applications, including home automation, environmental monitoring and sensing, industrial sensing and control.

The IEEE 802.15.4 defines the protocols used for the physical (PHY) and medium access control (MAC) layer functionality. It is composed of various components like nature of devices, topologies supported by the network, types of frames that can be exchanged in the network among different nodes, techniques involved for handling all nodes and coordinator issues in the network. All these components will be discussed one by one before we proceed with multi-level differentiated services of LR-WPANS.

In 802.15.4, two different types of devices can exist in a network i.e. Full Function Device (FFD) and Reduced Function Device (RFD). A FFD is a node with full levels of functionality which is not only used for sending and receiving data, but is also used for routing data from other data. A RFD is a node with reduced levels of functionality. Stereotypically, it is an end node with no routing functionality. Also, there exists a Coordinator which is special form of FFD that controls and manages the network.

A personal area network (PAN) is composed of numerous nodes, which transmit data to a PAN coordinator through direct links or multiple hops. Depending on the needs of an application, 802.15.4 supports two types of topologies in a PAN: the star topology and the peer-to-peer topology. In the star topology, communication links are established between wireless sensor nodes and a single centralized controller, called the PAN coordinator. In this topology, all the communication happens via the PAN coordinator only. In a peer to- peer topology, every sensor node can communicate with every other sensor node within its transmission range without the involvement of the PAN Coordinator.

The LR-WPAN defines four frame structures: i.e. data frames, acknowledgement frames, beacon frames and MAC command frame. A data frame is used for all transfers of data and an acknowledgement frame is used for confirming effective frame reception. A Beacon frame is used by the PAN coordinator to transmit beacons while a MAC command frame is used for managing all MAC peer entity control transfers.

Also 802.15.4 network can provide channel access at MAC layer either in beacon-enabled or in non-beacon-enabled mode. Beacon-enabled PAN uses a slotted CSMA/CA channel access mechanism while Non-beacon enabled PAN uses an unslotted CSMA/CA mechanism.

In the beacon mode, the PAN coordinator transfers the beacon frames periodically to all nodes within its coverage. All the nodes within the PAN are synchronized by these beacon frames. In Beacon-enabled mode, the nodes communicate over the network through a superframe structure. The non-beacon mode does not support time-sensitive applications since it allows only contention-based access through unslotted CSMA/CA. In addition, with no use of the beacons, all nodes in a wireless network are not synchronized.

The rest of the paper is organized as follows. Section II of our paper presents an overview of superframe structure and slotted CSMA/CA mechanism of IEEE 802.15.4. In Section III, we study the few available Priority Based Service Differentiation schemes and Section IV discusses our Proposed Algorithm: Service Differentiation based on Contention Window with Enhanced Collision Resolution. And, finally Section V concludes our paper.

II. OVERVIEW OF IEEE 802.15.4

A. Superframe Structure

In Beacon-enabled mode, the nodes uses a superframe structure to communicate over the network. Each superframe has an active period, during which the nodes can attempt to communicate using slotted CSMA/CA, and an inactive period during which the devices may enter in a sleep mode in order to conserve energy.

The active period of a superframe is further divided into 16 equally time slots and is composed of three parts: a Beacon, a contention access period (CAP) and a contention free period (CFP).

This CFP is only present if guaranteed time slots (GTS) are allocated by the PAN coordinator to the sensor node in need of communication. Each GTS consists of some integer multiple of CFP slots and upto 7 GTS are allowed in CFP.

In beacon-enabled mode, beacon frames are periodically sent by the PAN coordinator in the first slot of each superframe. The beacons are used to identify its PAN, synchronize the associated nodes and describe the structure of the superframes.

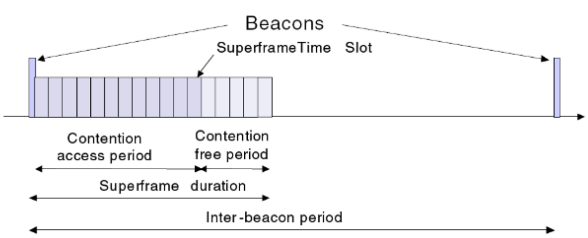

Fig. 1 IEEE 802.15.4 Superframe Structure in Beacon-Enabled Mode [7]

The Contention Access Period shall start immediately following the beacon and complete before the Contention Free Period on a superframe boundary. All activities for nodes contending to access the channel are within this stage. The Contention Free Period, whose slots are referred to as Guaranteed Time Slots are reserved by the PAN Coordinator for dedicated access by some sensor nodes to ensure time-critical transmission i.e. contention-free activities.

If a node has been allocated a GTS, it sends its data during the Contention Free Period, otherwise, it sends its data using CSMA/CA in the Contention Access Period. The CSMA/CA algorithm used in the CAP portion of the superframe is implemented using units of time called Backoff Period (BP).

B. Slotted CSMA/CA Mechanism

Each operation of slotted CSMA/CA i.e. channel access, backoff count, CCA can only occur at the boundary of a Backoff Period.

The slotted CSMA/CA backoff algorithm mainly depends on three variables:

1. The Backoff Exponent (BE) enables the computation of the backoff delay, which is the time before performing the CCAs. The backoff delay is a random variable between 0 and (2BE – 1).

2. The Contention Window (CW) refers to the number of backoff periods during which the channel must be sensed idle before accessing the channel. The standard set the default initialization value to CW=2 (corresponding to two CCAs).

3. The Number of Backoffs (NB) represents the number of times the CSMA/CA algorithm was required to backoff while attempting to access the channel. This value is initialized to zero (NB = 0) before each new transmission attempt.

CSMA/CA algorithm works as follows:

Initialization (Step 1): The Number of Backoffs (NB) and the Contention Period (CW) are initialized as NB = 0 and CW = 2. The backoff exponent is also initialized to BE = 2 or BE = min (2, macMinBE) depending on the value of the Battery Life Extension MAC attribute. macMinBE is a constant defined in the standard [1], which is by default equal to 3.

Backoff (Step 2): Before a station attempts to send a frame, it waits for a random number of Backoff Periods uniformly generated within [0, 2BE -1]. The first backoff period of each superframe starts with the transmission of the beacon.

Clear Channel Assessment (CCA) (Step 3): After completing its backoff, the station performs one CCA operation at the backoff period's boundary to assess channel activity. If the channel is assessed to be busy (Step 4), CW is re-initialized to 2, NB and BE are incremented. BE must not exceed aMaxBE (default value equal to 5) [1]. Incrementing BE increases the probability for having greater backoff delays. If the maximum number of backoffs (NB = macMaxCSMABackoffs = 5) is reached, the algorithm reports a failure to the higher layer, otherwise, it goes back to (Step 2) and the backoff operation is restarted.

If the channel is sensed as idle, CW is decremented (Step 5). The CCA is repeated if CW $\neq$ 0. This ensures performing two CCA operations to prevent potential collisions of acknowledgement frames.

Starting the transmission: In slotted CSMA/CA, a transmission can only start at a backoff period boundary and only if all steps (two CCAs, frame transmission and acknowledgement) can be completed at least one inter-frame space period before the end of CAP.

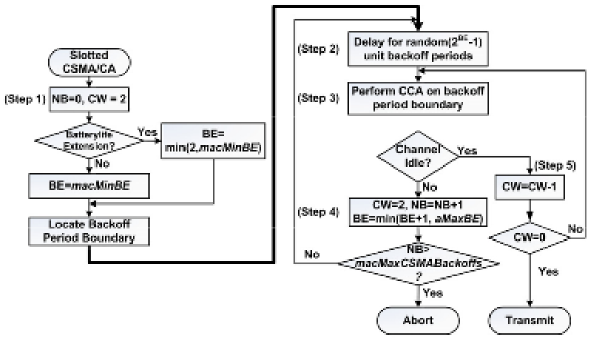

Fig. 2 Slotted CSMA/CA Mechanism [5]

III. PRIORITY BASED SERVICE DIFFERENTIATION SCHEMES

IEEE 802.15.4 standard defines the channel access mechanism that does not differentiate based on traffic priority. There are certain applications that require time-critical messages across the network before other traffic. We study two mechanisms that propose to provide service differentiation to high priority traffic. We also study an enhanced collision resolution mechanism that aims to enhance throughput and energy efficiency of the channel.

A. Service Differentiation by Contention Window Size and Backoff Exponent [2]

Kim et. al. in [2] propose a mechanism where different data packets transmitted by different devices have different priorities. This mechanism focuses on beacon enabled mode with slotted CSMA/CA under saturation conditions. Also, if a packet encounters collision, it is dropped and device tries to transmit a new packet.

When the network is setup, a priority is assigned to each sensor node depending on its functional importance. This differentiation is done based on CW value or BE value or both. The process is described as follows. According to its priority CW or BE value for a device is set to CW[q] or BE[q]. For example, let there be three priorities high, middle and low with corresponding values 0, 1 or 2. So for a high priority device CW or BE will be set to CW [0], BE [0]; CW [1], BE [1] for device with middle priority; CW [2], BE [2] for low priority device. The relations CW [0] < CW [1] < CW [2]; BE [0] <BE [1] < BE [2] hold to ensure service according to priority. Consider a scenario with two devices with CW[a] and CW[b] and a<b, and same BE parameter. During CCA procedure the device with CW = a will have a high transmission probability than the device with CW = b as, device with CW[b] will refrain from transmission when the device with CW[a] attempts to transmit.

The proposed backoff mechanism deviates from standard 802.15.4 backoff procedure. At stage 0 of backoff procedure, the backoff counter, a random number generated from the range of [0, W0 − 1], W0 = 2 BE[q], is chosen. If the channel is sensed busy, both the backoff stage and the BE value are increased by one and the backoff counter is randomly chosen in [W0, W1 − 1], W1 = 2 W0. Thus ensuring that a higher priority device is served, when the channel is heavily loaded. A small value of backoff counter, it gives better service. Let X and Y (X<Y) be two uniformly distributed random variables in range [0, X − 1] and [0, Y − 1]. E[X] = X/2 < E[Y] = Y /2, given X<Y. Thus the device with small BE will have higher probability of transmission. If channel is sensed busy, BE value is increased by one in next stage and the range of the backoff counter becomes [X, 2X − 1] and [Y, 2Y − 1], respectively. The expectation of X and Y are given by E[X] = X + X/2 < E[Y] = Y + Y /2.As the backoff stage grows, higher priority device will have better service as difference of BE values in later stages is larger as compared to those in earlier stages.

B. Backoff Exponential Range Modifications [3]

Jeong-Gil Ko, Yong-Hyun Cho and Hyogon Kim in [3] propose a modification to IEEE 802.15.4 MAC to support different capacity to individual nodes in a wireless sensor network, by dynamically adapting minBE. Standard [1] defines choosing BE value randomly in the range [minBE, aMaxBE].The backoff exponent can take a maximum value of aMaxBE (limited to 5). minBE can be chosen from set {0, 1, 2, 3}, and default value of minBE is set to 3. minBE value may be adapted to differentiate amongst nodes. Decreasing the lower boundary of backoff by setting the BE value to a value less than the default value 3. This will reduce the waiting time after collision. The node will try CCA more frequently, as the probability of choosing a shorter backoff period is increased. Performing frequent CCA, chances of making a successful transmission increase, thus increasing the throughput as compared to nodes which have longer waiting time. The value of minBE changes as the nodes' state changes. The nodes can transition to three states, noData, postData, sendData, with minBE values 3, 2, 1 respectively. minBE value can change according to following steps:

For every node,

1. Initialise state to noData, minBE = 3.

2. When a packet is ready to be transmitted, state is changed to postData and minBE takes the value 2. Probability of transmission will increase because a smaller value of minBE will increase the chances of choosing a lower back off period.

3. After two continuous transmissions, the state is changed to sendData and minBE is set to 1. If the node does not transmit anything and two consecutive beacon frames are detected, change state to noData and modify minBE to 3.

4. If node is in sendData state and no transmission has been done for two beacon frames, node state transits to postData and minBE = 2.

There will be no fairness problem as if node does not have a packet to transmit it can exclude itself from being in a high priority list by changing its minBE value. Throughput values of nodes with differentiated minBE values $minBE_\alpha$: $minBE_\beta$ = 2 $minBE_\beta$: 2 $minBE_\alpha$, where minBEα and $minBE_\beta$ are minBE values of differentiated nodes derived in Kim et al [5].

C. Enhanced CSMA/CA Algorithm [4]

Ha, Kim et al in [4] argue that collision resolution mechanism in legacy 802.15.4 does not effectively reflect the degree of channel contention. The BE adjustment mechanism is so sensitive that BE is increased when CCA finds the channel busy, easily reaches its maximum value and then is reset to the initial value. Also, the 802.15.4 CSMA-CA does not utilize information acquired from expensive CCA, that there is ongoing transmission and proceeds with un-necessary backoff.

1) *Enhanced Collision Resolution Mechanism*: ECR mechanism proposed in [4] adjusts the BE value based on CCA information as well as packet transmission. A CCA busy result does not necessarily indicate channel contention. The suggested mechanism makes BE adjustment less sensitive and BE is increased when the number of consecutive CCA busy results reaches macMAXCSMABackoffs in [1]. BE value is not reset after reaching a maximum, but is adapted. Secondly, instead of resetting the BE after a transmission, the ECR mechanism adjusts the BE according to based on the result of the transmission. If there is a collision, or transmission failure BE value is increased. In case of successful transmission, ECR decreases the value of BE instead of resetting it. Packet collision and consecutive CCA busy results increase BE, and gradual decrease of BE because of successful transmission, reflect overall network contention better, thus enhancing 802.15.4 CSMA/CA performance.

2) Enhanced Backoff Mechanism: The Enhanced Backoff mechanism utilizes ongoing transmissions information acquired from expensive CCA and attempts to reduce redundant backoffs. The range of backoff counters is shifted to avoid unnecessary backoffs and CCAs when there is already a transmission progressing on channel. This approach is similar to the policy of IEEE 802.11, in which a node freezes its backoff counter during other's transmission. Since 802.15.4 node assesses channel irregularly, it cannot determine the exact remaining time of the ongoing transmission. An expected number, Dccax, to avoid an ongoing transmission is introduced in [4]. After the x^{th} (x = 1 or 2) CCA reports the busy channel, the EB mechanism randomly picks a backoff counter in the range from Dccax to Dccax + 2BE −1, where Dccax is the expected number of busy BPs that follows the current busy BP, as confirmed by the x-th CCA.

$$Dcca1 \sim \lceil \tfrac{1}{2} \cdot \{E[L]-1\} + Lack + \delta 1 \rceil ,$$

$$Dcca2 \sim \lceil \{E[L]-1\} + \delta 2 \rceil$$

where δx is effect of pc (probability of collision) and pidle (probability that an idle BP exists between data and corresponding ACK.)

Therefore, only with the average packet length of a network, Dcca1 and Dcca2 can be properly set for the EB mechanism, which facilitates the reduction of unnecessary backoffs and CCA operations of the 802.15.4 CSMA-CA.

IV. SERVICE DIFFERENTIATION BASED ON CONTENTION WINDOW WITH ENHANCED COLLISION RESOLUTION

Service differentiation based on CW, BE in [2] drops a packet in case of an unsuccessful transmission. There can be a scenario, where two high priority devices have same BE value. Small value of BE will result in a smaller range to choose a backoff counter. This increases the probability of two devices choosing the same random number; result in increased chance of collision. Whether the transmission succeeds or fails the algorithm moves to the next packet in queue.

Using [4] as reference we propose modifications to service differentiation based on CW suggested in [2].

The algorithm can operate as follows:

1. Initialize NB to 0 and set the values of CW according to priority classes. (Based on numerical results in [2] we do not choose BE as parameter for service differentiation).

2. A random number is chosen from the range [0 – 2BE – 1] as backoff counter and algorithm tries to avoid collision for this period.

3. MAC layer performs first CCA to sense if channel is busy. If the channel is sensed busy for macMAXCSMABackoffs CCAs, BE and NB values are increased by 1; CW value is set to CW[q]. If the channel is sensed idle go to step 6.

4. If NB < macMAXCSMABackoffs it goes to step 5, else report a failure.

5. The algorithm backoffs of for a random unit in range [2(BE-1), 2BE-1]. Once this delay has been observed, it goes to step 3.

6. CW value is decreased by 1 and channel is assessed again. If the channel is idle in subsequent slots and CW value becomes 0, the node transmits (provided remaining number of backoff periods are sufficient to handle both packet and subsequent acknowledgment). If backoff periods are not sufficient packet transmission is postponed till beginning of next superframe.
   If the channel is busy for next slots, go to step 3.

7. If an ACK comes back; i.e. successful transmission, BE = BE -1 (to avoid resetting information by channel contention). If there was a collision, BE = min(BE+1, aMaxBE).

The proposed algorithm not only provides service differentiation according to class priority; but it also adapts BE according to the channel contention information collected during CCAs.

V. CONCLUSIONS

The high priority class with lower contention window value will have a higher chance of transmission [2] and enhanced collision resolution [4] makes good use of information about ongoing transmissions and packet collisions acquired by CCA, and adjusts BE thereby enhancing performance. In future, we can study how the proposed mechanism effects power consumption of device. Also throughput, delay, packet drop probability of this scheme can be analysed using mathematical model.

REFERENCES

[1] IEEE Standard for Part 15.4: Wireless Medium Access Control Layer(MAC) and Physical Layer(PHY) Specifications for Low Rate Wireless Personal Area Networks (LR-WPANS), Oct 2003.

[2] Eui-Jik Kim, Meejoung Kim, Sung-Kwan Youm, Seokhoon Choi, Chul-Hee Kang, Priority – based service differentiation scheme for IEEE 802.15.4 networks.

[3] Jeong-Gil Ko, Yong-Hyun Cho and Hyogon Kim, Performance Evaluation of IEEE 802.15.4 MAC with Different Backoff Ranges in Wireless Sensor Networks.

[4] Jae Yeol Ha, Tae Hyun Kim, Hong Seong Park, Sunghyun, Choi and Wook Hyun Kwon, An Enhanced CSMA-CA Algorithm for IEEE 802.15.4 LR-WPANs

[5] Marco Naeve, Eaton Corp., IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

[6] Chonggang Wang, Bo Li and Lemin Li, A new collision resolution mechanism to enhance the performance of IEEE 802.11 DCF.

[7] Iyappan Ramachandran, Arindam K.Das and Sunit Roy, Analysis of the Contention Access Period of IEEE 802.15.4 MAC.