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Beacon scheduling for broadcast and convergecast in ZigBee wireless sensor networks

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ABSTRACT

Broadcast and convergecast are two fundamental operations which often happen simultaneously in a wireless sensor network. Previous works have addressed energy-efficient, low-latency scheduling but they only try to optimize the traffic in one direction (broadcast or convergecast). This work defines a *low-latency two-way beacon scheduling (LTBS)* problem for ZigBee tree-based networks, where beacons stand for timing for nodes to deliver broadcast and convergecast traffics. We formulate the problem as a slot assignment problem where each node needs to obtain slots for upstream and downstream transmissions while avoiding interferences. We propose two efficient slot assignment algorithms based on the concept of sequencing nodes' slots to facilitate two-way traffics. We show the advantages of these schemes through extensive simulations. The results indicate that these two slot assignment algorithms can indeed achieve low-latency in ZigBee networks.

1. Introduction

The rapid progress of wireless communication and embedded micro-sensing MEMS technologies has made *wireless sensor networks* (*WSNs*) possible. A WSN normally consists of many inexpensive wireless nodes, each capable of collecting, processing, and storing environmental information, and communicating with neighboring nodes. Many WSN applications have been developed, such as emergency guiding [6,18], object tracking [14,24], and environment monitoring [3,20].

Recently, several WSN platforms have been developed, such as MICAz [2], Tmote [4], and Dust Network [1]. To ensure interoperability of different platforms, the ZigBee/IEEE 802.15.4 standards [9,26] are proposed, which define physical, MAC, and network layers for low-rate, low-power wireless communications.

Broadcast and convergecast are two common operations, and they are often executed simultaneously in a wireless sensor network. However, most existing works only consider one way (broadcast or convergecast) communication. The goal of this work is to design an efficient beacon scheduling solution for ZigBee tree-based networks to support low-latency transmissions for broadcast and convergecast. Fig. 1(a) shows the problem scenario. The network contains one sink (ZigBee coordinator), some *full-function devices* (ZigBee routers), and some *reduced-function devices* (ZigBee end devices). In the network, the sink broadcasts regular announcements or commands to all or to some network nodes, and routers and end devices report their data to the sink. According to the IEEE 802.15.4 specification, a router can announce a beacon to start a superframe. Each superframe consists of an *active portion* followed by an *inactive portion*. On receiving its parent router's beacon, a child device needs to wake up for an active portion and can communicate with its parent. However, to avoid collision with its neighbors, a router should shift its active portion by a certain amount. Fig. 1(b) shows a possible allocation of active portions for the sink c, routers R_A, R_B, and R_C. In this example, the sensory data reported from ED_1 and ED_2 can reach to the sink within three active portions (because the report from R_C to R_A and R_A to the sink need to wait 2 and 1 active portions, respectively). But, using the above schedule, the transmission latency from the sink to network nodes will be high. Assume that the sink is going to send a command to ED_1. The latency will be up to almost two superframes (because that both the downstream transmissions from R_A to R_C and R_C to ED_1 need almost one superframe to complete). The transmission latency is not negligible when the network is run under a low duty cycle. For example, in 2.4 GHz PHY, with 3.13% duty cycle, a superframe can be up to 251.658 seconds with an active portion of 7.88 seconds.

The above observation indicates that the original design of ZigBee networks cannot handle broadcast and convergecast simultaneously in an efficient way. Motivated by the two-ladders idea in [12], we propose to modify the original superframe structure of IEEE 802.15.4 to allow each router to broadcast two beacons in a

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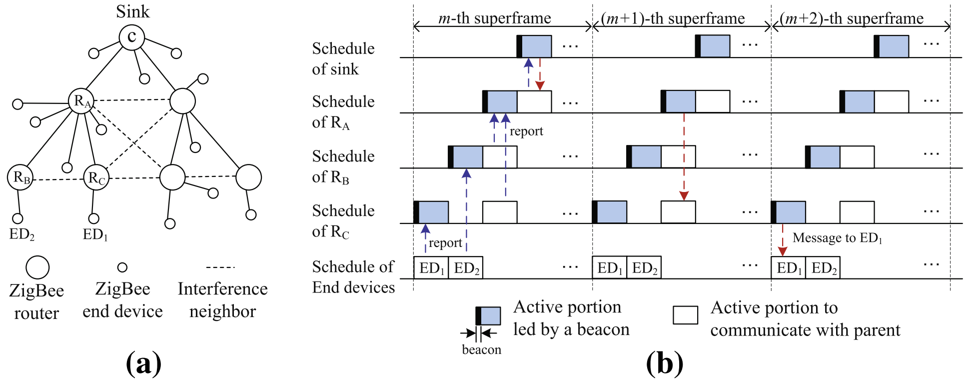

Fig. 1. (a) A ZigBee tree-based network. (b) A two-way transmission example using the ZigBee superframe structure.

superframe. Two beacons will form two active portions. In our design, one active portion is for the upstream (convergecast) direction and the other is for the downstream (broadcast) direction. This modification can significantly reduce the latencies of both broadcast and convergecast. The new superframe structure is backward compatible with the original one. Moreover, based on the modified superframe structure, we formulate a *low-latency two-way beacon scheduling (LTBS)* problem, where each node needs to obtain some slots for upstream and downstream transmissions while avoiding interferences. We propose two efficient slot assignment algorithms based on the concept of sequencing nodes' slots to facilitate broadcast and convergecast traffics. We also observe that some interferences may be avoided if some specific ZigBee end devices can be re-associated to another ZigBee routers. We show the advantages of our schemes through extensive simulations.

The rest of this paper is organized as follows. Section 2 introduces ZigBee/IEEE 802.15.4 standards, our proposed superframe structure, and some related works. Section 3 formally defines the LTBS problem. Section 4 presents our observations and algorithms for the LTBS problem. Simulation results are given in Section 5. Finally, we give our conclusions in Section 6.

2. Preliminaries

2.1. Overview of IEEE 802.15.4 and ZigBee

IEEE 802.15.4 [9] specifies the physical and data link protocols for *low-rate wireless personal area networks (LR-WPAN)*. IEEE 802.15.4 devices are expected to have limited power, but need to operate for a longer period of time. Therefore, energy conservation is a critical issue. Devices are classified as *full function devices* (FFDs) and *reduced function devices* (RFDs). IEEE 802.15.4 supports star and peer-to-peer topologies. In each PAN, one device is designated as the *coordinator*, which is responsible for maintaining the network. A FFD has the capability of becoming a coordinator or associating with an existing coordinator. A RFD can only associate with a coordinator.

The ZigBee alliance [5] defines the communication protocols above IEEE 802.15.4. In [26], *star*, *tree*, and *mesh* topologies are supported. A ZigBee coordinator is responsible for initializing, maintaining, and controlling the network. In a star network, devices must directly connect to the coordinator. For tree and mesh networks, devices can communicate with each other in a multihop fashion. The network backbone is formed by one ZigBee coordinator and multiple ZigBee routers (which must be 802.15.4 FFDs). RFDs can only join the network as end devices by associating with the ZigBee coordinator or ZigBee routers. In a tree network, the coordinator and routers can announce beacons. However, in a mesh network, regular beacons are not allowed. Beacons in superframe structure are an important mechanism to support power management. Therefore, the tree topology is preferred, especially when energy saving is a desirable feature.

The ZigBee coordinator defines the superframe structure of a network by controlling two parameters: *beacon order* (BO) and *superframe order* (SO), which decide the lengths of a superframe and its active portion, respectively. For a beacon-enabled network, the setting of BO and SO should satisfy the relationship $0 \leqslant SO \leqslant BO \leqslant 14$. (A non-beacon-enabled network should set $BO = SO = 15$ to indicate that superframes do not exist.) In a beacon-enabled star network, a device only needs to be active for $2^{-(BO-SO)}$ portion of the time. Changing the value of $(BO - SO)$ allows us to adjust the on-duty time of devices. However, for a beacon-enabled tree network, routers have to choose different times to start their active portions to avoid collision. Once the value of $(BO - SO)$ is decided, each router can choose from 2^{BO-SO} *slots* as its active portion.

In the revised version of IEEE 802.15.4 [10], a router needs to select one active portion as its outgoing active portions, and based on the active portion selected by its parent, it also selects the same active portion as its incoming active portions (refer to Fig. 2(a)). In an outgoing/incoming active portions, a router is expected to transmit/receive a beacon to/from its child routers/parent router. When choosing a slot, neighboring routers' active portions (i.e., outgoing active portion) should be shifted away from each other to avoid interference. However, the specification does not clearly define how to choose the locations of routers' active portions.

2.2. The proposed superframe structure for two-way communications

In this work, we modify the original superframe structure of IEEE 802.15.4 to support two-way commnunications. According to the original definition of IEEE 802.15.4, each router should wake up in two slots (outgoing and incoming active portions) per superframe. In this work, we propose that each router can broadcast two beacons and wake up in four slots per superframe. These four slots are denoted as *TbUp*, *TbDn*, *RbUp*, and *RbDn*, as shown in Fig. 2(b). In TbUp/TbDn slots, a node will transmit beacons to its children for receiving upstream/transmitting downstream data from/to them. In RbUp/RbDn slots, a node will receive beacons from its parent for transmitting upstream/receiving downstream data to/from its parent. To support such extensions, we can use the *reserved field* in the beacon frame to announce the positions of these extra slots. This design is backward compatible with the original specification.