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A cross-interface design for energy-efficient and delay-bounded multi-hop communications in IoT

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ABSTRACT

The future Internet of Things (IoT) will enable Internet connectivity for a vast amount of battery-powered devices, which usually need to wirelessly communicate with each other or to some remote gateways through multi-hop communications. Although ZigBee has become a widely used communication technology in IoT, Wi-Fi, on the other hand, has its unique advantages such as high throughput and native IP compatibility, despite its potentially higher energy consumption. With the development of IoT, more and more IoT devices are equipped with multiple radio interfaces, such as both Wi-Fi and ZigBee. Inspired by this, we propose a cross-interface power saving management (CPSM) scheme, which leverages the existing low-power ZigBee interfaces to wake up the high-power Wi-Fi interfaces on demand towards enabling multi-hop communications in IoT. The objective is to minimize the network energy consumption while satisfying certain end-to-end delay requirements. The results of extensive simulations and prototype-based experiments have demonstrated that the energy consumption of our proposed CPSM is 79.2% and 68.9% lower than those of the IEEE 802.11's standard power saving scheme and a state-of-the-art scheme in moderate traffic scenarios, respectively.

1. Introduction

1.1. Motivation

With the emergence of the Internet of Things (IoT), a wide variety of devices, such as entertainment electronics, health appliances, wearable gadgets and industrial sensors, are connected to the Internet. Many of them are embedded devices that are portable and powered by batteries, and need to wirelessly communicate with each other or some remote IoT gateways. Due to the short communication range of IoT devices, the communications between two IoT devices may involve multi-hop data delivery accomplished by multiple devices.

To realize this, many wireless technologies can be employed. On one hand, the IEEE 802.15.4 standard (or ZigBee) has been proposed and widely used for home and building automation, smart metering and IoT in general, due to its low-cost and low-power features. On the other hand, the IEEE 802.11 standard (or Wi-Fi) dominates the present-day consumer electronics fields because of its high data rate and long communication range. Any IoT device that connects to smartphones, tablets, digital cameras, TVs and PCs would benefit from Wi-Fi connectivity for reliability and high throughput. In addition, Wi-Fi has the advantage of native compatibility with IP, which is the key for IoT communications [1]. Nevertheless, due to its energy-hungry nature, Wi-Fi is often not recommended for short range multi-hop communications in IoT, though the feasibility of connecting battery-powered sensors to the IoT using off-the-shelf Wi-Fi chips has been demonstrated [2,3].

1.2. Problems in existing solutions

To improve the energy efficiency of Wi-Fi based multi-hop networks, the IEEE 802.11 standard specifies a power saving management (PSM) for the ad hoc mode or the distributed coordination function (DCF). With the PSM, as illustrated in Fig. 1, all nodes are synchronized with each other through exchanging beacon frames every certain time interval (called beacon interval or BI). One BI consists of an ATIM (Ad-hoc Traffic Indication Message) window in which each node first contends to broadcast a beacon frame for time synchronization and then stays awake for announcing possible data transmission to its neighbor nodes by sending ATIM frames (called *ATIM handshake*), and a data transmission window for conducting the actual data transmission announced in the ATIM

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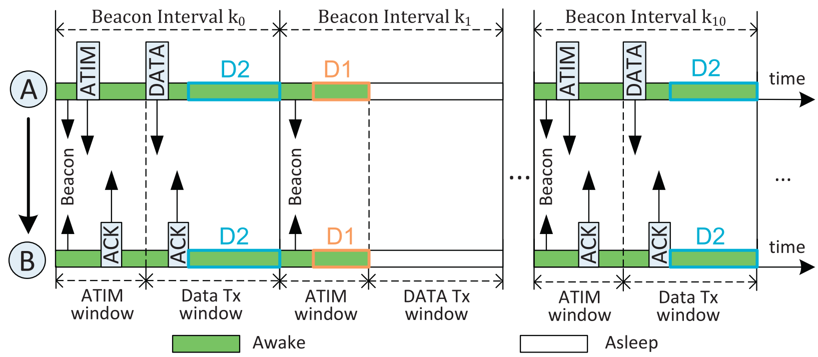

Fig. 1. An example of the standard PSM. Node *A* transmits data packets to node *B* with the inter-packet arrival time of 2 s (i.e., 0.5 pkt/s). The length of BI is 200 ms. On average, one useful BI (e.g., Beacon Interval k_0) is followed by 9 useless BIs (e.g., Beacon Interval k_1 to k_9), yielding an energy efficiency of 10%.

window. If no data packet is announced in ATIM window, the node sleeps for power saving; otherwise, it stays awake during the entire data transmission window for packet delivery, so the data packets that arrive after the ATIM window can be sent immediately in the current BI.

Although PSM can greatly reduce power consumption, its energy efficiency varies greatly under different traffic patterns due to two major drawbacks: **(D1)** low utilization of ATIM window and **(D2)** inefficient use of data transmission window, as illustrated in Fig. 1. Suppose the length of BI and ATIM window are 200 ms and 40 ms [4], respectively. The inter-packet arrival time between node *A* and *B* is about 2 s. To deliver one packet, **(D1)** both node A and B conduct 9 unnecessary wakeups followed by one useful wakeup and **(D2)** the activated data transmission window only delivers one packet. In this scenario, the energy efficiency (e.g., the number of the useful wakeups during which a node has a data packet to transmit divided by the total number of wakeups) is merely 10%. This is because of the fact that a node does not know the packet arrival time and thereby needs to wake up periodically (with relatively short interval to ensure low delay) even if there is no incoming traffic. Moreover, to achieve better throughput, both sender and receiver nodes need to keep awake during the data transmission window even if there is only one packet to deliver.

To improve energy efficiency of PSM, lots of protocols [4–13] have been proposed. The basic idea is to use some heuristics to adjust the behaviors of PSM (e.g., the length of BI, the length of ATIM/data transmission window, the content of MAC frames, etc.) according to current traffic. However, due to the unpredictability of traffic in practice, high energy efficiency is hard to be achieved, especially when traffic varies irregularly. Besides, they require inconsistent modification to the 802.11 standard.

Another major problem of PSM is the large wakeup latency, which could be as long as one BI (e.g., typically 300–500 ms [14] to reduce wakeup frequency and thus energy consumption), and such delay makes it unsuitable for time-sensitive IoT applications such as device monitoring, environmental surveillance, localization and tracking, and intrusion detection. To lower end-to-end delay, there exist several approaches, such as shortening the length of BI, switching to the constantly active mode (CAM) when there is incoming data traffic [14], and modifying ATIM handshake to allow a data packet to travel multiple hops in a single BI [1]. Nevertheless, these methods cannot eliminate the energy waste caused by unnecessary wakeups.

In a nutshell, low energy and low delay cannot be achieved simultaneously for multi-hop communications. The fundamental reason is that a Wi-Fi radio must perform high-power idle listening (comparable to transmission and reception [15]) continuously in order to prepare for unpredictable incoming traffic, which renders a dilemma that *more (less) frequent wakeup of Wi-Fi interface results in shorter (longer) delay but higher (lower) energy consumption*. This dilemma has driven recent research on developing dedicated wakeup receiver [16–21] and leveraging co-located ZigBee or Bluetooth interface [22–25] to assist Wi-Fi transmission. Unfortunately, most of existing schemes focus on centralized, single-hop WLANs, and cannot be directly borrowed for the good of decentralized, multi-hop data delivery in IoT, where the unreliability on control message delivery becomes a more significant obstacle for the coordination with Wi-Fi transmission.

1.3. Proposed research

To address the above issues, we propose a cross-interface power saving management (CPSM), which leverages the co-located ZigBee and Wi-Fi interfaces to minimize energy consumption with satisfying certain end-to-end delay requirements for multi-hop communications in IoT. The design of CPSM follows the basic paradigm of leveraging the control flow managed by the low-power ZigBee radios to dynamically schedule the high-power Wi-Fi radios for delivering data flows generated by IoT devices, as illustrated in Fig. 2.

To maximize the economic gains of reusing the existing Wi-Fi infrastructures for IoT communications, we build CPSM on top of the standard 802.11 PSM and demand no changes to the underlying MAC layer; hence, it is able to communicate with the devices or the gateways supporting the standard 802.11 MAC. To overcome PSM's two major drawbacks (i.e., **D1** and **D2**), CPSM adopts the following two ideas: (i) utilizing the low-power ZigBee interface to dynamically activate the high-power Wi-Fi interface to perform ATIM handshake only when there exists incoming data traffic, and (ii) deferring the wakeup of Wi-Fi interface as long as possible so as to allow more data packets to be buffered and then delivered within a single data transmission window. In this way, wakeup overheads (i.e., Wi-Fi's transmission/reception of ATIM/ATIM-ACK frames and idle listening during ATIM/data transmission window) could be minimized, which can particularly entitle our system to employ a short BI (e.g., 100 ms as used in our simulations and experiments) to satisfy more constrained end-to-end delay requirements without incurring much energy consumption.

To evaluate the performance of CPSM in large-scale networks, extensive simulations have been conducted. The results show that CPSM can effectively reduce network energy consumption in a wide range of scenarios and achieve a level of energy consumption that is close to a lower bound derived from the theoretical analysis. Besides, as a proof of concept, a prototype system is built on top of a testbed of 9 laptops equipped with both Wi-Fi and ZigBee interfaces. The results have demonstrated that the energy consumption of our proposed CPSM is 79.2% and 68.9% lower than those of the standard PSM and a state-of-the-art scheme in moderate traffic scenarios, respectively.