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# Enhanced power saving mode for low-latency communication in multi-hop 802.11 networks

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ABSTRACT

The Future Internet of Things (IoT) will connect billions of battery-powered radio-enabled devices. Some of them may need to communicate with each other and with Internet gateways (border routers) over multi-hop links. While most IoT scenarios assume that for this purpose devices use energy-efficient IEEE 802.15.4 radios, there are use cases where IEEE 802.11 is preferred despite its potentially higher energy consumption. We extend the IEEE 802.11 power saving mode (PSM), which allows WLAN devices to enter a low-power doze state to save energy, with a traffic announcement scheme that facilitates multi-hop communication. The scheme propagates traffic announcements along multi-hop paths to ensure that all intermediate nodes remain awake to receive and forward the pending data frames with minimum latency. Our simulation results show that the proposed Multi-Hop PSM (MH-PSM) improves both end-to-end delay and doze time compared to the standard PSM; therefore, it may optimize WLAN to meet the networking requirements of IoT devices. MH-PSM is practical and software-implementable since it does not require changes to the parts of the IEEE 802.11 medium access control that are typically implemented on-chip. We implemented MH-PSM as a part of a WLAN driver for Contiki OS, which is an operating system for resource-constrained IoT devices, and we demonstrated its efficiency experimentally.



## 1. Introduction

Nowadays almost every desktop computer, laptop, tablet, and smartphone is connected to the Internet. The emergence of the Internet of Things (IoT) will provide global IP connectivity to a broader variety of devices, such as entertainment electronics, wearable sport gadgets, home appliances, and industrial sensors. Some of these devices are portable, battery-powered, and need to connect wirelessly to surrounding devices and Internet gateways. The wireless communication may significantly contribute to their overall battery consumption, especially in the case of constrained embedded devices. Therefore, minimizing the energy consumption of wireless interfaces and networking protocols is one of the prerequisites for the IoT (see Fig. 1).

Different wireless standards have been proposed for IoT. Zigbee, which is based on the IEEE 802.15.4 standard [1], is often referred to as a wireless technology of choice for home and building automation, smart metering, and IoT in general because of its simplicity and energy-efficiency. *Z*-Wave [2] is another technology that targets similar applications and environments with emphasis on home automation. Both Zigbee and *Z*-Wave provide meshing capabilities, which are required by many IoT applications. Although it does not support meshing, Bluetooth Low Energy (BLE) is also a candidate technology for IoT. The advantages of BLE are the low energy consumption

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**Fig. 1.** Application scenario in which smart radio-enabled toys communicate with decorative lightning (©Disney).

and the common presence in smartphone radio stacks. These technologies, however, do not cover the entire spectrum of IoT devices and applications. Wi-Fi, which is based on IEEE 802.11 standard [3], dominates the consumer electronics segment: Any IoT device that needs to connect to smartphones, tablets, TVs, set-top boxes, game consoles, and toys would benefit from Wi-Fi connectivity. Also, some sensors that operate at high sampling rates, such as those used in seismic monitoring and imaging, may generate large amounts of data that cannot be transmitted using ZigBee due to its limited throughput, but can easily be transmitted by Wi-Fi. The economy of scale and the possibility of reuse of the existing Wi-Fi infrastructure offer key cost savings and facilitate faster deployment with Wi-Fi than with competing technologies. Furtheremore, Wi-Fi has the advantage of native compatibility with IP, which is the key enabler for IoT: IP eliminates the need for expensive gateway solutions to connect IoT devices to the Internet. The feasibility of connecting battery powered sensors to the IoT using commercially available Wi-Fi chips has been demonstrated in [4]. In [5], the authors share their experiences of using off-shelf Wi-Fi modules to connect *things* to the Web of Things.

One of the key challenges for the use of Wi-Fi in IoT objects is its energy consumption, which is relatively high compared to ZigBee. An always-on Wi-Fi interface may quickly drain the battery of a device. Long battery recharge/replacement cycles are preferred for cost and convenience reasons. For example, a survey has shown that 51% of electronic toy consumers are concerned about the battery replacement costs [6]. There have been some notable improvements in hardware and many low-power Wi-Fi chips with energy-efficient radio transceivers have appeared on the market. The 802.11 MAC protocol, however, is inherently energy-hungry. One of the major sources of unnecessary energy consumption in 802.11 MAC is idle listening, which consumes energy even when there is no traffic in the network – the radio must perform idle listening continuously in order to detect arriving packets. The energy consumption of idle listening in 802.11 is comparable to that of packet transmission and reception [7]. To alleviate the problem, the 802.11 standard [3] specifies a Power-Saving Mode (PSM) that allows an idle 802.11 station to transition to a low-power doze state by switching off its radio transceiver. The role of 802.11 PSM is similar to that of Radio Duty Cycling (RDC) in 802.15.4. There are some notable differences: RDC typically operates below MAC, directly on top of the 802.15.4 PHY layer. It may include information from the MAC layer, in which case MAC and RDC are cross-optimized as in [8], but it can also be isolated from MAC. With RDC, a radio can be switched on and then rapidly switched off after a few milliseconds if no activity is detected on the channel. The 802.11 PSM is part of the MAC layer management entity. The intervals in which PSM alternates between doze and awake states are typically measured in tens and hundreds of milliseconds: All 802.11 stations wake up synchronously at the beginning of a beacon interval, listen for traffic announcements from other stations that have data packets destined to them, and announce their own data packets (if any) destined to other stations. If a station does not receive any traffic announcements and it does not have any buffered packets that need to be transmitted in the current beacon interval, it returns to the doze state.

The IEEE 802.11 standard specifies the details of PSM for the infrastructure/BSS mode (Basic Service Set with an access point) and the ad hoc/IBSS mode (Independent Basic Service Set without an access point). Since it has been originally designed for single-hop communication in the infrastructure mode (from the access point to a station and vice versa), the PSM performs poorly in the ad hoc mode, especially in multi-hop networks [9–11]. When a data frame is forwarded over multiple hops, the PSM may significantly increase the delivery delay because only the next-hop station is notified about the pending frame via traffic announcements, while the stations on subsequent hops may remain in the doze state. Therefore, in each beacon interval the frame is forwarded over a single hop and has to be buffered before being forwarded further. Depending on the number of hops, the end-to-end delay may be long enough to affect time-sensitive applications. Another problem of PSM is that a station is occasionally forced to stay awake even though it has no frames to transmit or receive. The reason to stay awake is to respond to probe requests of devices that are actively scanning the medium when attempting to discover and join networks. For example, if there are two stations in an 802.11 ad hoc network, at least one of them would have to remain awake at any time, which limits the sleep time to at most 50%. Hence, the 802.11 PSM is not suitable for low-energy low-latency multi-hop communication, which is a common requirement for the IoT.

In this paper, we address the problem of increased frame delays due to PSM in multi-hop ad hoc networks. We propose a mechanism that wakes up downstream stations so that data frames can be forwarded over multiple hops in a single beacon interval. This is achieved by instructing each station along the path to forward the traffic announcement to its downstream neighbor. The proposed mechanism significantly reduces the end-to-end delay, especially for bursty traffic where intermediate