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Zigbee-Assisted Power Saving Management for Mobile Devices

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ABSTRACT:

WiFi transmission can consume much energy on energy-constrained mobile devices. To improve energy efficiency, the Power Saving Management (PSM) has been standardized and applied. The standard PSM, however, may not deliver satisfactory energy efficiency in many cases as the wakeup strategy adopted by it cannot adapt dynamically to traffic pattern changes. Motivated by the fact that it has been more and more popular for a mobile device to have both WiFi and other low-power wireless interfaces such as Bluetooth and ZigBee, we propose a ZigBee-assisted Power Saving Management (ZPSM) scheme, leveraging the ZigBee interface to wake up WiFi interface on demand to improve energy efficiency without violating delay requirements. The simulation results have shown that ZPSM can save energy significantly without violating delay requirements in various scenarios.

Index Terms:

WiFi, ZigBee, power saving management, energy efficiency, delay bound..

1. INTRODUCTION:

Meanwhile, mobile devices are increasingly equipped with multiple network interfaces [2], [3]. It has been common for a mobile device (e.g., smart phone, PDA and laptop) to have both WiFi and Bluetooth interfaces. As the ZigBee technology becomes more and more mature, embedded ZigBee interfaces have emerged and the size is becoming smaller and smaller. It will not be surprising to see the ZigBee interface commonly embedded in mobile devices together with WiFi interface in near future [4]–[6].

With the ZigBee interface, mobile devices can communicate with various electrical and electronic appliances to realize smart home entertainment and control, home awareness, mobile services, commercial building and smart industrial plants [7]. Motivated by this trend, we propose a ZigBee-assisted power saving management (ZPSM) for WiFi devices, aiming to deliver energy efficiency with bounded delay. The key idea is to use the low-power ZigBee radio to dynamically wake up asleep high-power WiFi radio for packet transmission between the AP and clients. Unlike the standard PSM, ZPSM system presents a wakeup strategy which is adapted to both packet arrival rate and delay requirements in order to maximize energy efficiency. Moreover, ZPSM is built atop the standard PSM, and thereby, requires no change to the WiFi standard.

To evaluate the performance of ZPSM in a large-scale network, a detailed ns2-based simulator is built and extensive simulations have been conducted. The results show that our proposed system can significantly reduce power consumption in a wide range of scenarios, compared to the standard PSM, and achieve a level of performance approaching an optimal value derived from our theoretical analysis. In the following, Section II presents preliminaries, followed by theoretical analysis in Section III. Section IV elaborates the proposed design of ZPSM. The results of comprehensive simulation are reported in Section V. Section VI summarizes related work, and finally Section VII concludes the paper.

2. METHODOLOGY:

A. Power Management for WiFi Devices WiFi devices usually support two power modes: the power saving mode (PSM) in which the radio periodically wakes up to receive data packets so as to reduce the duration for idle listening and thereby energy consumption, and the constantly awake mode (CAM) in which data packets can be received promptly at the cost of high power consumption. In the PSM, the AP broadcasts beacon frames every beacon interval (BI); each client wakes up every certain number of BIs, called listening interval (LI), to check whether it has data packets buffered at the AP. The AP indicates the presence of buffered packets by setting the Traffic Indication Map (TIM) fields in the beacon frame. If a client finds the corresponding TIM field is set, it sends a Power Save Polling (PS-POLL) frame to retrieve buffered packets from the AP. Besides, the AP uses MORE bit in the data packet to indicate if more packets are buffered, helping the client to decide when to go to sleep. Parameter LI is configurable, and its setting directly influences the performance.

B. A Realistic Concern: Interference To utilize the coexistence of WiFi and ZigBee interfaces, a realistic concern is how severely they can interfere with each other, as both ZigBee and WiFi interfaces may work on the same frequency band (e.g., 2.4 GHz). Experiments [8], [9] have shown that WiFi communication can interfere with ZigBee communication severely if their working channels overlap. However, if their channels do not overlap, the interference becomes insignificant. To verify the validity of the above observation when WiFi and ZigBee interfaces are co-located in the same mobile station, we further conducted experiments. The experimental results indicate that, concurrent transmissions launched by co-located WiFi and ZigBee interfaces only result in small packet loss ratio (< 5%) on the ZigBee communication if the channels used by them do not overlap.

C. System Model In our proposed system, each of the AP and clients has a ZigBee (IEEE 802.15.4) and a WiFi (IEEE 802.11) interfaces. The WiFi interface is for data transmission while the ZigBee interface is for power management. The WiFi and ZigBee interfaces of the AP are always awake, while the WiFi and ZigBee interfaces of clients are awake intermittently for energy conservation. In addition, each client can run in either the standard PSM (SPSM) or the ZigBee-assisted PSM (ZPSM). Particularly, when a client is out of the ZigBee range (but still in the WiFi range) of the AP, it defaults to SPSM. Each client i has a desired delay bound for downlink packet transmission. Specifically, the percentage of packets received with a delay lower than the desired delay bound di among all incoming packets should be at least δi (called delay-meet ratio), where $0 < \delta i < 1$. This is called delay requirements. Here, the delay is defined as the time elapsed from the arrival of a packet at the AP to the receipt of the packet at the destination client. For compatibility with SPSM, ZPSM clients are only allowed to retrieve packets after receiving a beacon frame as specified in the SPSM. Hence, in the worst case, a packet may have a delay up to two BIs (i.e., one BI delay for the AP to wait for client to wake up and one BI delay for the client to be served by the AP). Thus, for each ZPSM client, the delay bound should be at least two BIs; otherwise, it defaults to SPSM. As with the SPSM, we assume all clients are synchronized with the AP. In addition, due to the unreliable link quality of ZigBee channel, ZigBee transmission may fail; as the ZigBee interface at a client may be used for other purposes, packets transmitted by the ZigBee interface at the AP may fail to reach the client occasionally.

We use the link quality pi to represent the probability that a packet sent by the AP through its ZigBee interface arrives at client i successfully. Note that the value of pi may vary over time. The AP is static while the clients can be mobile. We assume that the mobility of clients is relatively low. For example, the mobile WiFi devices may be carried by people who stay in conference rooms, libraries, cafe shops, stadiums, etc., where it is typical that a client is static, or moves for a while and then pauses for a while and so on and so forth, following the well-known random waypoint model. D. Design Objectives • Energy Efficiency: Through minimizing unnecessary wakeup and idle listening, our design should decrease the overall power consumption (including both WiFi and ZigBee power consumption) of clients in various scenarios. • Bounded Delay:

Our system should be able to satisfy the delay requirements for each client. • Compatibility: Due to the popularity and diversity of the WiFi devices, our system should not demand changes to the IEEE 802.11 standards. The system should be built atop the standard PSM and thereby transparent to the underlying standard PSM. E. Wakeup Strategies To successfully transmit a data packet from the AP to a client, the WiFi interface of the client should be turned on. This can be achieved by using the following two wakeup strategies.

I.3. IMPLEMENTATION:

To provide a theoretical foundation, this section develops an optimization problem step by step to formulate the design challenge in our proposed system. The analysis results can be used as a guide to design a practical scheme and as a reference to evaluate the practical design. A. Problem Definition The problem to be solved in our proposed system is how to schedule the regular and on-demand wakeups for each client so as to minimize the overall energy consumption (including both WiFi and ZigBee) of all clients while satisfying their delay requirements. For simplicity, we only consider the behaviors of ZPSM clients when the system is in steady stateB. Assumptions The following assumptions are made to simplify the analysis, though the practical design to be presented in the following section is not restricted by these assumptions. • Uplink data traffic (i.e., data traffic from clients to the AP) and the data traffic to/from CAM clients are not considered. • Downlink data packets for each client arrive at the AP following the Poisson process [3], [10], [11]. • Ideal WiFi channel conditions, meaning no packet loss, are assumed. The packet delay due to contention can be either negligible or constant.

• The size of all data packets is the same. • The system is not saturated and no packet is dropped due to overflow of the queue. Thus, the buffered packets for clients will be eventually transmitted. • xi , yi R +. C. Delay Analysis We first analyze the relation among m (i.e., the number of wakeup slots contained in a WI), xi (i.e., the number of successful on-demand wakeups of client i during one LI) and yi (i.e., the number of BIs contained in one LI of client i) that should be satisfied in order to meet the delay requirements. Consider the packet transmission between the AP and a ZPSM client i during a LI. Without loss of generality, the period is assumed to be from time instant 0 to yiB. Let λi denote the average arrival rate of packets targeted at client i. Then, the number of packets whose delay bound can be guaranteed through regular wakeup is (di − B)λi , because all packets arriving between time yiB −(di −B) and yiB can be transmitted during the BI following the next regular wakeup (i.e., between time yiB and yiB + B) with a delay less than di . Thus, the number of packets that need on-demand wakeup during a BI is yiBλi − (di − B)λi = (yiB − di + B)λi . As the ZigBee transmission may fail, on-demand wakeup cannot be always guaranteed. To deal with this, we assume that, once the AP sets the corresponding bit in wakeup frame, it keeps that bit set until the AP receives a PS-POLL (indicating the client wakes up and retrieves packets) from that client, which can be modelled as Geometric distribution. Then, for a client i with link quality pi , the success probability of any on-demand wakeup, denoted by θi , can be computed as θi = 1 − (1 − pi) di−B mW . (1) This is because any packet arriving di −B time before an ondemand wakeup can be transmitted during the BI following that wakeup with a delay less than di . Therefore, the delay requirements of client i can be defined as δi ≤ (yiB − di + B)θi + (di − B) yiB ≤ 1. (2) From Eq. (2), we can solve yi and get yi ≥ di − B B (3) and (δi − θi)yi ≤ (1 − θi)(di − B) B . (4) For Eq. (4), there exist the following two cases. • Case I: if δi ≤ θi , the inequality always holds regardless the value of yi . This indicates that the delay requirements can be satisfied through only on-demand wakeup. Since the IEEE 802.11 standard only specifies 2 bytes to represent the LI parameter, yi ≤ Ymax = 216 − 1, where Ymax denotes the maximum LI.

Combining it with Eq. (3), we have di − B B ≤ yi ≤ Ymax. (5) • Case II: if δi > θi , then di − B B ≤ yi ≤ (1 − θi)(di − B) B(δi − θi) , (6) which indicates that on-demand wakeup alone cannot satisfy the delay requirements without using regular wakeup. In addition, the expected time interval between two ondemand wakeups of client i, denoted by τi , consists of two parts. One is the expected time of the first packet arrival after one on-demand wakeup, which is 1/λi . The other is the expected time between the first packet arrival and the next on-demand wakeup of client, which can be computed as follows.If the client is woken up before the deadline (with the probability of θi), the client has to wait for at most di before its wakeup; otherwise (with the probability of 1 − θi), based on the memoryless property of Geometric distribution, the waiting time can be computed as di + mW/pi , where 1/pi is the expected number of attempts to wake up the client after deadline.

Hence, τi = 1/λi + [θidi + (1 − θi)(di + mW/pi)] , (7) For any LI, it holds that yiB − (di − B) ≤ τixi ≤ yiB − B. (8) D. Energy Consumption Analysis 1) WiFi Energy Consumption: For a given BI j, suppose there are nj clients woken up to retrieve packets. Then, nj can be computed as P iZ xi+1 yi . The overall energy consumption of all clients consists of three parts, which are computed as follows. • nj • E0: the total energy consumed by all clients for receiving beacon frames and sending PS-POLLs, where E0 is the energy for receiving a beacon frame and sending a PS-POLL.

Specifically, let TB and TP OLL denote the durations for receiving a beacon frame and sending a PS-POLL, respectively. Then, E0 = TB • Prx + TP OLL • Ptx + SIF S • Pidle, where Ptx, Prx and Pidle are the rates of energy consumption (in Watt) for WiFi interface to transmit, receive and stay idle listening, respectively. • lj • ED: the total energy consumed by all clients for receiving data packets from the AP, where ED is the energy consumption for receiving a data packet and lj is the total number of packets to be retrieved during BI j. Specifi- cally, let TD and TACK denote the durations for receiving a data packet and sending an ACK, respectively. Then, ED = TD • Prx + TACK • Ptx + (DIF S + SIF S)Pidle. • Let Eidle denote the energy consumed by a client for idly listening while other client is retrieving one data packet. Then, Eidle = (TD + TACK + DIF S + SIF S)Pidle.

As elaborated in Section III of [12], the total energy consumed by all clients for idly listening data transmission of other clients is computed as nj • EP OLL + (nj −1)lj • Eidle/2, where EP OLL = TP OLL • Pidle. Hence, the overall WiFi energy consumption, denoted by Ewif i, for BI j, is given by Ewif i = (E0 + EP OLL + Eidlelj 2)nj + (ED − Eidle 2)lj , (9) where lj = B • P iZ λi , which is constant. 2) ZigBee Energy Consumption: In addition to WiFi energy consumption, each client also consumes energy for receiving ZigBee wakeup frames. To save energy, once a client receives a wakeup frame, it can completely turn off its ZigBee radio until it has retrieved the data packets from its AP. After the completion of packet transmission, it wakes up for a short duration at the beginning of each wakeup slot to sense the channel. If the channel is idle, indicating no wakeup frame is to be received, then the ZigBee radio goes to sleep.

Note that, as to be presented in the following section, m may change over time as the packet rate and ZigBee link quality may vary over time. Thus, clients do not have exact knowledge of m used by the AP for broadcasting wakeup frame and thereby need to sense the channel for possible incoming wakeup frames. For any given LI, the expected number of wakeup frames received by client i within a BI is xi/pi yi and thereby the corresponding number of channel sensing is m • xi/pi yi . Hence, the overall ZigBee energy consumption in a BI, denoted by Ezigbee, can be computed as Ezigbee = Ewakeup • X iZ xi piyi + Esense • X iZ mxi piyi , (10) where Ewakeup and Esense denote the energy consumed for receiving and sensing a ZigBee wakeup frame, respectively. 3) Summary: Minimizing the overall energy consumption (i.e., Ewif i + Ezigbee) is equivalent to minimizing Eoverall = E0 + EP OLL + EidleB Pn i=1 λi 2 • X iZ xi + 1 yi + (Ewakeup + m • Esense) • X iZ xi piyi , (11) where xi , yi i Z and m are unknown. E. Optimization Problem Combining the above analysis, we can get an optimization problem formulated as follows. Here, Ω = {m} {(xi , yi) | i Z} represents wakeup schedule for the system. Objective: Find Ω to minimize Eoverall s.t., if δi > θi, yi ≤ (1 − θi)(di − B) B(δi − θi) , i Z (12) yiB − (di − B) ≤ τixi ≤ yiB − B, i Z (13) 0 ≤ xi ≤ yi − 1, i Z (14) di − B B ≤ yi ≤ Ymax, i Z (15) 1 ≤ m ≤ max di − B W iZ (16) Obviously, this problem is non-linear and hard to be solved. However, a numerical method can be adopted to solve the problem after we transform the problem. Specifically, we first transform the above problem to an equivalent problem by letting x 0 i = xi/yi and y 0 i = 1/yi . Then, based on the observation that m can be any integer within the range of {1, 2, • • • , max b di−B W c iZ }, which is a small set in practice, we can solve the transformed problem for all possible m efficiently and get the solution that yields the smallest objective value as the optimal solution to the original problem.

4. DISCUSSION:

From on the above analysis, we can see that appropriate scheduling of regular and on-demand wakeups is the key to minimize energy consumption while satisfy delay requirements. To achieve this, we present a practical scheme that dynamically adjusts the regular and on-demand wakeups of WiFi interfaces.B. Wakeup Framework An optimal solution to the scheduling problem defined in Section III-E consists of three parts: m for the AP, yi and xi for all clients. m and yi explicitly determine the periodic wakeup behaviors of the AP's ZigBee interface and the clients' WiFi interfaces, respectively. Thus, they together constitutes the wakeup framework of ZPSM. Besides, xi characterizes the behavior of on-demand wakeup for each client, which can be changed frequently to adapt to dynamic traffic and link quality. This is called wakeup dynamics, which will be presented in the next subsection. In the proposed system, the AP periodically solves the optimization problem with inputs λi and pi , which are measured online. The resulting optimal solution is used to determines the values of m and yi for each client i. To reduce computational overhead, the wakeup framework dose not change over frequently and the updated interval is pre-determined (e.g., 10 s in this paper).

Moreover, since our system directly adopts the configurations (i.e., m and yi) from optimal solution and the delay requirements given by Eq. (2) only depends on m and yi , the delay requirements can be satisfied under our proposed wakeup framework. C. Wakeup Dynamics The wakeup framework only defines the time points at which the AP is allowed to wake up clients on demand. In this subsection, we present the scheme to determine when each client should wake up to minimize energy consumption. 1) Insights: Consider any k consecutive BIs in our ZPSM system. The total number of incoming packets during k BIs, denoted by L, can be computed as kB • P iZ λi . Let n be a random variable representing the total number of wakeups of all clients during these k BIs, nj be the total number of awake clients and lj be the total number of data packets transmitted at the j th BI (j = 1, • • • , k). Then, by Eq. (9), the total WiFi energy consumption E of these BIs can be computed as E = Xk j=1 (E0 + EP OLL + Eidlelj 2)nj + (ED − Eidle 2)lj . (17)

5. RELATED WORK :

Numerous work has been conducted to improve WiFi energy efficiency in mobile devices, especially for web browsing applications. For example, authors in [1], [15] proposed to minimize the energy consumption with bounded slowdown. To reduce the congestion at the AP and thus improve the performance of the standard PSM, an opportunistic PSM is proposed in [16] to allow one download at any time. One common shortcoming of these schemes lies in that, their savings largely depend on the accuracy in predicting client network usage patterns, because they are not able to wake up asleep clients at will without the assistance of additional interfaces. Thus, their performance is limited. Research has also been conducted to investigate co-located interfaces to assist WiFi transmission. One of the first work that brought forth the idea is CoolSpots [17], which proposed some basic policies to enable a mobile device to automatically switch between multiple radio interfaces such as WiFi and Bluetooth, in order to increase battery lifetime. Blue-Fi [2] uses the co-located Bluetooth to predict the availability of the WiFi connectivity, which allows the device to intelligently turn the WiFi interface on only when there is WiFi connectivity available. Another Bluetooth assisted protocol has been proposed in [3] to reduce power consumption of WLAN by using Bluetooth to form a cluster, called Bluetooth Personal Area Network (PAN). The cluster head acts as a gateway between the PAN and the WLAN, enabling clients to access the AP via low-power Bluetooth.

Different from these schemes, our system uses ZigBee interface, which has a much longer communication range. Thus, it can provide better communication capability under the mobile environment. Because of using different hardware and methodologies, the accomplishment is also different. Recently, ZiFi [4] was proposed to utilize ZigBee radios to identify the existence of WiFi networks through WiFi beacons. WiZi-Cloud protocols [6] were proposed to use WiFi and ZigBee radios on mobile phones and APs to achieve ubiquitous connectivity, high energy efficiency, real time intradevice/inter-AP handover. Besides infrastructure WLAN, a ZWiFi system was proposed in [5] to leverage the ZigBee interface to improve throughput and energy efficiency in IEEE 802.11 ad hoc network. Unlike these approaches, our work leverages the ZigBee interface to improve energy efficiency while ensuring delay requirements in infrastructure WLAN.

6. Concluding Remarks :

In this paper, we proposed a ZigBee-assisted PSM system to improve energy efficiency in WiFi communication. Simulation results have shown significant improvement on energy efficiency, compared to the standard PSM system.

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