

Receiver Design for Realizing On-Demand WiFi Wake-up using WLAN Signals

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Abstract—In this paper, we design a simple, low-cost, and low-power wake-up receiver which can be used for an IEEE 802.11-compliant device to remotely wake up the other devices by utilizing its own wireless LAN (WLAN) signals. A typical usage scenario of such a wake-up receiver is energy management of WiFi device: a device equipped with the wake-up receiver turns WiFi interface off when there is no communication demand, which is powered-on only when the wake-up receiver detects a wake-up signal transmitted by the other WiFi device. The employed wake-up mechanism utilizes the length of 802.11 data frame generated by a WiFi transmitter to differentiate the information conveyed to the wake-up receiver. The wake-up receiver is designed to reliably detect the length of transmitted data frame only with simple envelope detection and limited signal processing. We develop a prototype of the wake-up receiver and investigate the detection performance of the envelope of 802.11 signals. Based on the obtained experimental results, we select appropriate parameters employed by the wake-up receiver to improve the detection performance. Our numerical results show that the proposed wake-up receiver achieves much larger detection range than the off-the-shelf, commercial receiver having the similar functionality.

I. INTRODUCTION

Reducing the energy wastefully consumed by radio devices has become a new challenge for wireless researchers/engineers after the successful deployment of broadband and spectrally-efficient radio access networks. Wireless local area network (WLAN), also known as WiFi, is a representative example, which has shown tremendous growth in its worldwide popularization over the last decade as a means to provide its users with ubiquitous access to the Internet.

One of the most common methods to reduce energy consumption of a WiFi device is to transit WiFi interface into a sleep state during its idle period where there is no communication demand. For instance, a power saving (PS) mode is defined in IEEE 802.11[1], where WiFi stations (STAs), such as laptop PC and smartphone, transit their interfaces into a sleep mode and periodically wake up to check demands on communications from its associated access point (AP). However, it is difficult to adapt the wake-up schedule to the unpredictable traffic pattern, which inherently causes communications latency and wake-up without actual communications demands. Therefore, the use of an extremely low-power secondary radio has been proposed to realize *on-demand*, remote wake-up of WiFi interface[2][3][4][5][6][7]. The secondary radio is in charge of wake-up signaling by which a device

sends a wake-up command to the other sleeping device. The sleeping node turns WiFi interface on only when the wake-up command is detected through its secondary radio. By employing a secondary radio which consumes much smaller amount of energy than WiFi, we can significantly reduce the amount of energy wastefully consumed during idle periods while keeping small latency to start communications between WiFi devices.

There have been different approaches on how to incorporate secondary, wake-up radio into WiFi devices. Some works introduce completely independent radio of WiFi into both sender and receiver (e.g., ZigBee in [3] and Bluetooth in [4]) while the others exploit WiFi device at the sender side to generate wake-up signals. A mechanism called wake-on-wlan has been introduced in [8] where a low-power sensor mote (802.15.4) is installed into a WiFi receiver. The sensor mote operates at 2.4 GHz and is used to monitor the communications activities over WLAN channels and to detect energy of WLAN signals, which triggers the wake-up of WiFi interface. This wake-up scheme does not require additional transmitter of wake-up signal, however, it suffers from large probability of false wake-up since the sensor mote uses only energy level in ISM band to trigger the wake-up. In order to solve this problem, a novel approach called ESENSE has been proposed in [9]. With ESENSE, 802.11 device embeds information into frame length (length of energy burst) which is detected through energy sensing by an 802.15.4 hardware attached to WiFi receiver. This enables 802.11 device to send specific identification (e.g., wake-up ID) to the other sleeping device which is equipped with a secondary 802.15.4 device. We have also proposed in [10] a mechanism for WiFi STA to send wake-up ID to a sleeping access point (AP) which is equipped with a secondary wake-up receiver. The proposed approach does not require each STA to install extra hardware to generate wake-up signals while many idle APs can be transited into sleep mode, which can reduce significant amount of wasteful energy consumed by widely-spread WiFi APs[11][12][13].

The communications exploiting the length of 802.11 data frames proposed in [9] and [10] require a receiver to reliably detect the length of each transmitted frame. In [9], the use of a commodity 802.15.4 hardware containing CC2420 chip platform[14] was proposed as a possible receiver. However, in [9], there is no investigation on communication range achieved through energy sensing based on CC2420-based platform. The

wake-up range in on-demand WiFi wake-up is required to be comparable to that of WiFi data communications. If CC2420-based platform does not offer sufficient communication range, more elaborated, yet simple receiver is desired. On the other hand, in [10], only simulation results were provided and there was no investigation on receiver design and its practical feasibility.

The main contributions of this paper are twofold. First, we investigate communication range achieved through energy sensing with CC2420-based platform proposed in [9]. With experiments, we show that such an off-the-shelf device, which is not specifically designed for detecting frame length, is not sufficient to achieve wake-up range required in on-demand WiFi wake-up. Second, based on the above observation, we design and develop a simple, low-cost, and low-power receiver dedicated to detecting the length of 802.11 frame. The receiver operates with a simple envelope detection and limited signal processing. With the developed receiver, we evaluate the basic performance for the wake-up receiver to detect 802.11 frame length. We investigate the impact of employed parameters on the accuracy of frame length detection. We evaluate detection range of the designed wake-up receiver, and show that our proposed wake-up receiver achieves much larger detection range than CC2420-based platform and has a potential to offer sufficient wake-up range for on-demand WiFi wake-up.

II. SYSTEM MODEL AND PROBLEM DEFINITION

A. Basic idea of wake-up signal transmissions

The scenario considered in this paper is shown in Fig. 1. Here, a WiFi device equipped with a wake-up receiver is in a sleeping mode where WiFi interface is completely turned off in order to save energy. The other active WiFi device, which attempts to communicate with the sleeping device through WiFi interface, sends a wake-up ID corresponding to the sleeping WiFi device. Our target is to transfer information on wake-up ID from the active WiFi device to the wake-up receiver. The wake-up receiver should be a low-cost and low-power device which can only employ simple detection/demodulation scheme and is not capable of decoding contents of WLAN data frame. The use of frame length to convey information from WiFi device to a simple device, which has a functionality to detect the length of energy burst, was proposed in [9]. We have also proposed a mechanism for 802.11 STA to send information to a simple on-off-keying (OOK) receiver in [10]. The basic idea is to embed wake-up ID into the length of data frame transmitted by 802.11 module. We prepare a mapping between a bit sequence and the length of WLAN frame as shown in the example in Fig. 1. The active WiFi device transmits frames so that the bit sequence represented by a sequence of frames corresponds to the wake-up ID of the sleeping device. The broadcast data are transmitted, therefore, STA does not have to wait for the reception of ACK frames. How to avoid the interruption by the surrounding nodes into the sequence of wake-up frames is out of the scope of this paper (interested

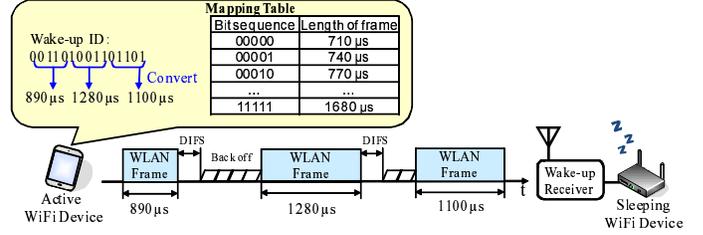


Fig. 1. System model and basic idea for conveying information through WLAN frame length.

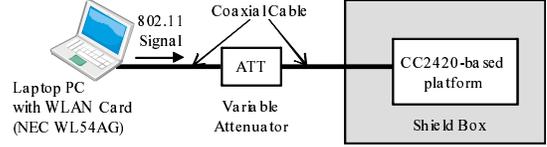


Fig. 2. Experimental setup for evaluating detection performance of CC2420-based platform.

readers may refer to [9] and [10] for some mechanisms to mitigate the adverse effect of such an interruption).

B. Problem Definition: Limitations of CC2420-based platform

In order to realize information transfer using the length of 802.11 data frame, the receiver needs to detect the length of received frame. In [9], the authors suggested using outputs from clear channel assessment (CCA) pin of 802.15.4 receiver, which is the observed channel occupancy, in order to detect the length of energy burst. A simple, low-cost, and low-power platform based on CC2420 chip was proposed as a receiver[14], and the feasibility was validated through experiments. However, there was no investigation on possible communication range achieved by the proposed platform. Therefore, here, we investigate the detection performance of CC2420-based platform with different received power.

Fig. 2 shows a setup used for evaluating the detection performance of CC2420-based platform. WLAN data frames are generated and transmitted by a laptop PC with a WLAN card (NEC WL54AG). The CC2420-based platform is put inside a shield box and connected with the WLAN card using a coaxial cable. The received signal level is controlled by adjusting a variable attenuator attached to the coaxial cable. The transmission power of 802.11 is fixed to be 5 dBm. Note that we use cables and shield box just to finely tune the received signal level at the receiver. From WLAN card, UDP packets are transmitted with IEEE 802.11b employing WLAN data rate of 1 Mbps. We test the detection performance of two different frame length: 800 μs (UDP payload of 12 bytes) and 1000 μs (UDP payload of 37 bytes). For each length, 10000 frames are transmitted, and we measure for each frame the number of outputs from CCA pin of CC2420.

Figs. 3 and 4 show the probability of occurrence of number of outputs from CCA pin of CC2420 with different received power levels for 800 μs frame and 1000 μs frame, respectively. From Fig. 4, we can see that the number of outputs from CCA pin is 33 with the highest probability when the received power is the largest, i.e., -61.56 dBm. The time measurement

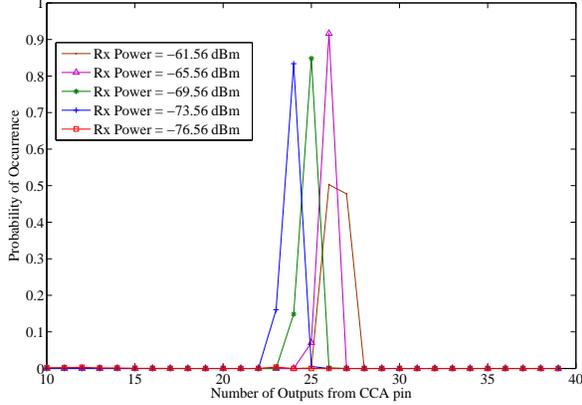


Fig. 3. Probability of occurrence of each output from CCA pin (transmitted frame length = 800 μ s).

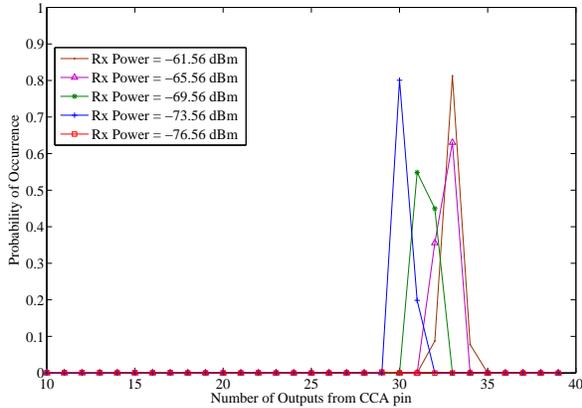


Fig. 4. Probability of occurrence of each output from CCA pin (transmitted frame length = 1000 μ s).

granularity of CC2420-based platform is 30.5 μ s[9], therefore, 33 outputs correspond to the measured frame length of 1006.5 μ s. The other numbers of outputs like 32 and 34 are also observed with this received power level. However, if we allow the margin of error to be a maximum of 2 outputs, i.e., 61 μ s, CC2420-based platform can reliably identify the length of transmitted frame, i.e., 1000 μ s for this large level of received power, which is a similar result to [9]. However, looking at results with smaller received power, we notice the following limitations of CC2420-based platform:

- For both length, outputs from CCA pin are observed with very little probability for the received power level below -76.56 dBm. The CC2420 is designed for receiving 802.15.4 signal which has the bandwidth of 5 MHz while the energy of 802.11 frame is spread over 20 MHz. Therefore, only 25% WLAN (5 MHz/20 MHz) signal energy passes the CC2420 filter. This directly reduces sensitivity level of CC2420 by 6 dBm. In addition, using a 5 MHz filter to receive the 20 MHz WLAN signal changes the envelope of WLAN frames, which degrades the performance of frame length detec-

tion. This makes it difficult for CC2420-based platform to reliably detect the frame length for the received power level below -76.56 dBm. Considering that the sensitivity level required in data communications by IEEE 802.11b is -90dBm@1Mbps[9], the wake-up range (range within which the transmission of wake-up ID is possible) achieved by CC2420-based platform is much smaller than data communication range of IEEE 802.11b. This causes an active WiFi device to fail to wake-up a sleeping WiFi device which can otherwise achieve WiFi communications with sufficiently high data rate.

- For both frame length, as the received power level becomes smaller, less number of outputs from CCA pin is observed with higher probability. This is due to the moving average employed by CC2420 for obtaining an average RSSI which is used to decide the output from CCA pin[14]. When the received power is small, it takes some period for the average RSSI to exceed the threshold to declare the busy channel, which results in less number of outputs from CCA pin. Reducing fluctuations of received signal level with moving average could be useful to improve the detection performance, however, it is hard to modify and optimize its parameter as it is implemented inside a chip. One way to enable the identification of each frame length with this limitation is to allow larger margin of errors for the observed outputs. For instance, if we consider that 29–35 outputs from CCA pin correspond to 1000 μ s, the receiver can differentiate 1000 μ s frame from 800 μ s frame until the received power of -73.56 dBm since 29 outputs are not observed when 800 μ s frame is transmitted. However, such a large margin limits the number of frames used for conveying the information (the size of alphabet set with the terminology given in [9]).

The above results show the limitations of CC2420-based platform to be used for detecting the length of 802.11 data frame. This is not surprising since CC2420 has been developed for data communications following 802.15.4 standard, and the receiver circuit and its parameters are optimized not for detecting 802.11 frame length but for supporting 802.15.4 communications under dynamic environment even with large fluctuations of received signal level. However, this clearly motivates us to design a wake-up receiver dedicated to detecting 802.11 frame length, which can achieve sufficiently large wake-up range for on-demand WiFi wake-up.

III. WAKE-UP RECEIVER DESIGN FOR DETECTING 802.11 FRAME LENGTH

In this section, we design a wake-up receiver dedicated to detecting the length of 802.11 data frame. The receiver should be simple and low-cost, and operate with extremely low-power consumption. Therefore, we employ OOK with non-coherent detection as a basic detection scheme as often employed in wake-up receiver designed in sensor networks[15]. We add a simple function to calculate frame length from

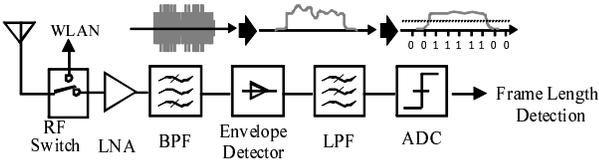


Fig. 5. A configuration of the developed wake-up receiver.

results of detection and signal processing to enhance the detection accuracy.

The block diagram of the developed wake-up receiver is shown in Fig. 5. The RF switch is attached for the wake-up receiver to share antenna with WiFi interface. With low noise amplifier (LNA: NEC uPC8178TB, 11 dB gain) and band pass filter (BPF: a self-developed Chebyshev filter with 20 MHz bandwidth), the receiver passes 802.11 signals only in a specific channel¹ to the envelope detector (Linear Technology LTC5534). The samples output from the envelope detector are smoothed with low pass filter (LPF) whose outputs are then passed to analog to digital convertor (ADC). The impact of LPF can be similar to moving average of CC2420-based platform, however, here, we have room to optimize its parameter for frame length detection, which will be discussed in detail in the following subsection. The outputs of ADC are the results of OOK bit detection at each sampled instance, which are used to estimate the length of transmitted data frame. In this work, we fix the bit detection interval to be 10 μ s.

The detection of 802.11 signal is basically carried out through the envelope detector and ADC. Each sampled value of signal envelope is compared with a predefined threshold: if the value is larger than the threshold, a bit "1" is detected, otherwise, "0". While the probability to erroneously detect 1 without actual transmissions of 802.11 signals ($p(1|0)$) depends on the noise level and predefined threshold, the probability to miss the transmitted signals ($p(0|1)$) is largely influenced by the received signal strength as well as signal waveform. The signal waveform depends on the modulation schemes employed by IEEE 802.11 standards, which are categorized into two types: single carrier modulation and multi carrier modulation. While 802.11b adopts a former type, which is direct sequence spread spectrum with complementary code keying (DSSS/CCK), the other standards offering higher rates such as 802.11a/g use the latter one, orthogonal frequency division multiplexing (OFDM). The OFDM is known to have large peak-to-average power ratio (PAPR) than that of single carrier modulation [16], which means that the level of OFDM signal fluctuates largely. In our preliminary experiment, we have investigated the impact of signal waveform on bit detection performance and confirmed that 802.11b signal with DSSS/CCK offers better bit detection performance than 802.11g employing OFDM. Therefore, in our wake-up mechanism, we utilize 802.11b for a WiFi device to create a wake-up signal².

¹We keep the detailed design of wake-up protocol, including how to select a channel to transmit wake-up signals, outside the scope of this paper.

²Note that IEEE 802.11b is supported by most of the currently-available WLAN chips to maintain backward-compatibility.

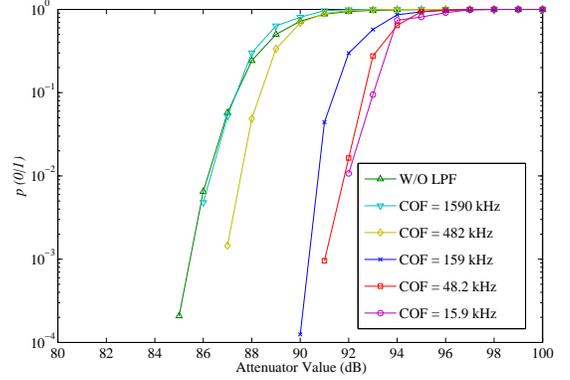


Fig. 6. The impact of cut-off-frequency (COF) of LPF on bit error probability, $p(0|1)$.

A. Impact of LPF on bit detection performance

In our developed wake-up receiver, in order to reduce the fluctuation of envelope and to make the signal waveform smoother, we introduce LPF between the envelope detector and ADC as shown in Fig. 5.

As LPF, we use a very simple RC filter³. Here, we investigate the impact of cut-off-frequency (COF) of LPF on bit detection performance. The experimental setup is similar to Fig. 2 except that CC2420-based platform is replaced with our developed wake-up receiver. We vary COF of LPF by tuning the values of its resistance and capacitance. Fig. 6 shows $p(0|1)$ against attenuator value (dB) for different values of COF set in LPF. The detection threshold is adjusted so that we have approximately $p(1|0) = 10^{-3}$ for all the attenuator values. This figure shows a significant improvement on $p(0|1)$ as the value of COF becomes smaller. If we compare the result employing COF of 159 kHz with that without LPF, we have around 5 dB gain at $p(0|1) = 10^{-3}$, and around 6 dB gain for COF of 48.2 kHz. This gain is brought by the reduction of fluctuations within the sampled signal. Furthermore, thanks to LPF, noise level is also reduced and the detection threshold can be set to a lower value to keep $p(1|0) = 10^{-3}$. This also contributes to the improvement on $p(0|1)$ which should be decreased as the detection threshold becomes smaller.

B. Impact of LPF on the observed frame length

Although the introduction of LPF improves the bit detection performance, it has a side-effect that the observed frame length becomes different from the one that is actually transmitted. This is due to slower rise and decay caused by LPF for the head and tail of frame envelope, respectively, as shown in Fig. 7. The frame length is estimated to be longer than the actual one when the received power is relatively larger than the detection threshold. An example is shown in Fig. 8 (a). Here, l is the length of frame that is actually transmitted by WiFi device. In Fig. 8 (a), while the envelope rises above

³More sophisticated LPF may be used, but all the discussions given in this section can be applied to any kind of LPF.

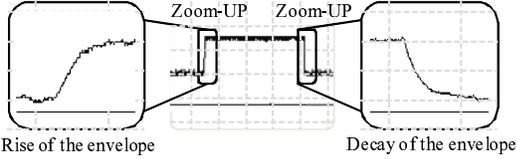


Fig. 7. A snapshot of signal waveform when LPF is applied.

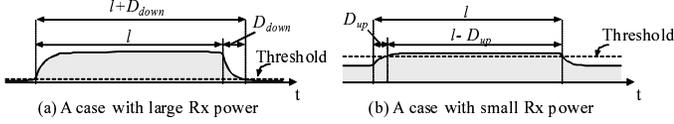


Fig. 8. The impact of LPF on the estimated frame length: (a) A case with large Rx power (b) A case with small Rx power.

the threshold fast enough, the tail of the observed frame is extended due to the large delay for the envelope to decay below the detection threshold (let us define this delay as D_{down}). On the other hand, when the received power is relatively small in comparison to the detection threshold (Fig. 8 (b)), the delay for the envelope to reach the threshold (D_{up}) can make the observed frame length shorter than the actual value.

Among the above problems, the extension of the observed frame length can cause a fatal problem on the estimation on frame length. As a wake-up signal, multiple frames may be transmitted sequentially as shown in Fig. 1. In order to reliably estimate a frame length, inter-frame space (i.e., at least one "0" between two succeeding frames) must be detected besides the correct detections of all bits of "1" constituting a single frame. The shortest inter-frame space can be observed when WiFi device picks up a back-off counter of 0, which results in DIFS between two succeeding frames. If D_{down} caused by the introduction of LPF is large enough to mask DIFS, it becomes impossible for the wake-up receiver to detect a space between two succeeding frames. In fact, considering that WiFi device and the wake-up receiver are not synchronized, we have to keep space of at least sampling interval, which is $10 \mu\text{s}$ in this study, between succeeding frames. Since DIFS is $50 \mu\text{s}$, D_{down} must be less than $40 \mu\text{s}$. Table I shows D_{down} for different COF measured by our prototype. For each value of COF, we conduct 10 measurements, and show minimum, maximum, and average values of D_{down} . The received power is set to be -10.2 dBm which is almost the same value as the maximum received signal power assumed in IEEE 802.11 standard [1], i.e., -10 dBm^4 . From this table, we can see that smaller values of COF make D_{down} larger, and COF of 15.9 kHz and 48.2 kHz have D_{down} larger than $40 \mu\text{s}$ for all the minimum, maximum, and average values. Therefore, these values of COF are not applicable though they have better bit detection performance. On the other hand, the average values for COF of 482 kHz and 1590 kHz are less

⁴This value is extremely large. Considering the transmission power of 802.11 module and well-known propagation model like two-ray path loss model, the distance between transmitter and receiver to have such a large received power is far less than one meter, which in fact does not require remote wake-up of WiFi device.

TABLE I
MEASUREMENT RESULTS OF MINIMUM, MAXIMUM, AND AVERAGE D_{down} FOR DIFFERENT COFs.

COF	minimum (μs)	maximum (μs)	average (μs)
15.9 kHz	149.6	192.2	168.98
48.2 kHz	70.2	83.4	77.5
159 kHz	35.8	57.4	47.24
482 kHz	4.2	85.8	12.76
1590 kHz	3	3.8	3.3

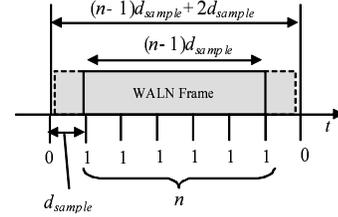


Fig. 9. The impact of asynchronous bit detection on estimated frame length.

than $40 \mu\text{s}$, however, bit error probabilities for these COF are high as seen in Fig. 6. The COF of 159 kHz has the maximum and average D_{down} larger than $40 \mu\text{s}$, however, its average value is close to $40 \mu\text{s}$. Furthermore, considering that random back-off with contention window (CW) is applied, the minimum separation of $40 \mu\text{s}$ between succeeding frames occurs with low probability. Therefore, COF of 159 kHz can be a good candidate considering the trade-off between bit error performance and space detection, and is used for evaluating the detection performance of the developed wake-up receiver in the next subsection.

C. Detection Performance of developed wake-up receiver

Here, we investigate detection range of the developed wake-up receiver. We examine frame length detection error rate (probability that the frame length is not detected correctly) for three different frame length, $720 \mu\text{s}$, $800 \mu\text{s}$, and $1000 \mu\text{s}$. We allow the margin of error of $\pm 30 \mu\text{s}$ for frame length detection. For instance, for $720 \mu\text{s}$, if the continuous detection of "1" is observed for 69–75 times, we consider that $720 \mu\text{s}$ frame is transmitted by WLAN card (Recall that the bit detection interval of the developed wake-up receiver is $10 \mu\text{s}$). Note that this resolution is the same as the one used in [9], therefore, we can define the same alphabet size considered in [9]. This margin is used for accommodating the impact of LPF on the observed frame length as discussed in the previous subsection. Furthermore, since WiFi device sending a wake-up signal and wake-up receiver are not synchronized with each other, there can be a maximum error of $2 \times d_{sample}$ if the frame length is estimated from the number of succeeding detections of "1", where d_{sample} is the sampling interval (see Fig. 9). The error margin is used to alleviate the adverse effect of such an asynchronous transmission.

Fig. 10 shows the frame length detection error rate against received signal power for three different frame length. In this experiment, 10000 frames of each length are transmitted. From this figure, we can first see that the detection error rate is

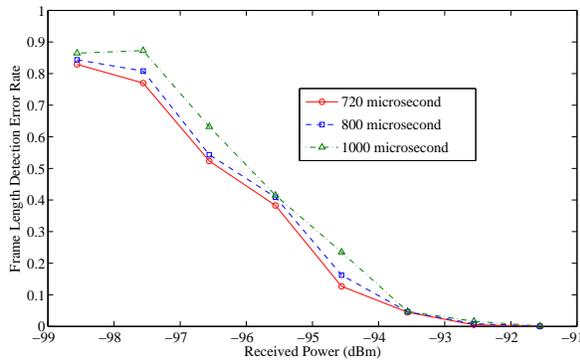


Fig. 10. Frame Length Detection Error Rate against Received Power for the developed wake-up receiver.

lower for shorter frame length. This is because we need more number of correct detections of "1" for correctly detecting longer frame. The detection error rate is deteriorated as the received power becomes smaller, however, the figure shows that the correct detection of frame length is possible with high probability even with the received power below -90 dBm. This means that within data communication range of 802.11b (sensitivity level of -90 dBm), our developed wake-up receiver can reliably detect the length of 802.11 frame transmitted by the active WiFi device. Therefore, successful wake-up of sleeping WiFi device is possible with high probability whenever data communications with sufficiently high data rate are possible. Thus, our developed wake-up receiver can meet the requirement to be employed for on-demand WiFi wake-up.

D. Discussions on power consumption

We have also measured power consumption of our developed wake-up receiver and found out that its power consumption is approximately 30 mW. Considering that CC2420-based platform has the power consumption of 60 mW[9], we can say that our wake-up receiver operates with low power consumption. However, its value is still higher than the other wake-up receivers developed in the research field of sensor network, which operates less than 1 mW. Note that these wake-up receivers for sensor network have the optimized circuit configuration to reduce their power consumption. Our developed wake-up receiver is still a prototype and has much room to reduce its power consumption by optimizing circuit configuration and choosing appropriate components, which is kept for our future work.

IV. CONCLUSIONS

In this paper, we have designed a simple, low-cost, and low-power wake-up receiver dedicated to detecting 802.11 frame length. This type of receiver can be applied to reduce wasteful energy consumed by WiFi devices without installing specialized hardware to transmit wake-up signals. We have experimentally investigated the detection performance of the developed receiver which is capable of making only simple

envelope detection and limited signal processing. We have tuned parameters of the developed wake-up receiver based on the measurement results. Our numerical results have shown that our proposed wake-up receiver can achieve larger detection range than the commodity CC2420 receiver which has functionality to detect the length of energy burst and previously proposed as a receiver in the similar setting.

Our future work includes the investigation of detection performance in a practical wireless environment, and the design of wake-up protocols to validate the system-level feasibility of our wake-up approach.

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