Optimization of Frame Length Modulation-Based Wake-Up Control for Green WLANs

Suhua Tang, *Member, IEEE*, Hiroyuki Yomo, *Member, IEEE*, and Yoshio Takeuchi

***Abstract*—In this paper, green wireless local area networks (WLANs), where idle access points (APs) are put into sleep and activated upon the request of mobile nodes, are realized by exploiting WLAN signals to convey wake-up messages. Specifically, wake-up messages, sent by nodes, are modulated onto frame lengths (physical transmission time) of successive WLAN signals and detected by non-WLAN low-cost receivers equipped at APs. This method, however, is susceptible to serious 1) false negative events due to low signal quality or collisions with background WLAN frames and 2) false positive events where background WLAN frames happen to have the same frame lengths as those of wake-up messages. In the proposed scheme, WLAN frames forming a wake-up message are transmitted in a burst and interpreted as an equivalent message. On this basis, false probability is reduced from two aspects: 1) Modulation constellations of frame lengths are optimized to maximize the Hamming distance between equivalent messages, and 2) preamble frame and envelope smoothing are used to mitigate false events. In addition to theoretical analysis and simulation, a prototype test bed is built and experimented on. Extensive evaluations confirm that the proposed scheme helps to greatly improve the reliability of wake-up control compared with state-of-the-art methods.**

***Index Terms*—Burst transmission, frame length modulation, green wireless local area networks (WLANs), wake-up receiver (WuRx).**

I. Background and Related Work

Wireless local area networks (WLANs) [1] are widely deployed to provide ubiquitous access to the Internet. Access points (APs) of WLANs, although frequently being idle, are power hungry in their idle state [2]. With the trend of green communications, it is necessary to reduce the power consumption of idle APs to realize green WLANs [3].

Power saving [4] in WLANs depends on the idle patterns. 1) In the micro timescale, a WLAN module is idle in the interpacket interval. Packets can be aggregated and transmitted in a burst at a high rate to enable a longer idle period for sleeping [5]. Practically, only the WLAN module can be put to sleep. The power consumption of a WLAN module is mainly due to its high clock frequency, which may be dropped in the idle state and reverted back to receive or transmit packets [6]. 2) In the macro timescale, APs are frequently idle for long periods, e.g., not used in late night. Then, the whole system of APs (about 10 W), including the WLAN module (about 1 W), can be put into sleep [3], which effectively reduces power consumption. However, it is necessary to activate an AP from its sleep state on demand when new nodes arrive. This is usually realized by asynchronous wake-up [7]: Each AP is equipped with a wake-up receiver (WuRx); the main system of an AP, except its WuRx, is turned off in its idle state and activated again when its WuRx receives a wake-up request.

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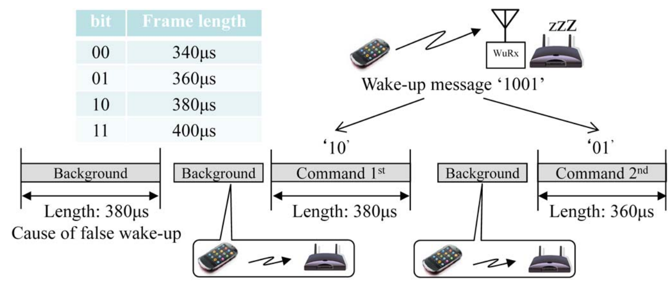

Fig. 1. Information transmission via frame length modulation.

In this paper, we leverage the wake-up control to reduce the power consumption of APs due to the macro-time scale idleness. A wake-up message is sent from a node requesting a communication service and detected by a WuRx equipped at an AP. The wake-up function usually requires a dedicated transmitter (additional hardware) [7] to send a wake-up message, which increases the installation cost at nodes such as smartphones and tablets. Therefore, it is desirable to transmit wake-up messages without adding extra hardware to each node. This is possible if each node transmits wake-up messages via its own WLAN module. As shown in Fig. 1, the frame length property (physical transmission time) of WLAN signals can be modulated to convey wake-up messages. Transmission of a WLAN frame is a continuous radiation of energy, and its length is measured by periodically sampling the channel. Using "1" for a busy channel and "0" for an idle channel, the length of a WLAN frame can be detected by counting the number of consecutive "1's", either via a ZigBee device [8]–[10] or a low-cost WuRx [11]. Then, frame lengths can be demodulated to original wake-up messages. As shown in Fig. 1, nodes sending wake-up messages share the same channel with colocated nodes contending to send WLAN traffic. To avoid ambiguity, in the following, frames exchanged between WLAN modules where information is carried in their payload are called *background*

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frames, and length-modulated WLAN frames carrying wake-up messages to non-WLAN receivers are called *command frames*.

The aforementioned wake-up policy, however, is susceptible to serious: 1) false negative events due to low signal quality or collisions with background WLAN frames and 2) false positive events where background WLAN frames happen to have the same frame lengths as those of wake-up messages. We have exploited burst transmission in our previous work [12] to reduce false negative probability (*FNP*, i.e., the probability that a wake-up message is not correctly received by the target WuRx). In this paper, we further study 1) how to reduce *FNP* by optimizing the constellations of frame lengths (mapping between bits and frame lengths in Fig. 1) and leveraging envelope smoothing and 2) how to reduce false positive probability (*FPP*, i.e., the probability that a wake-up message is falsely generated due to the presence of other wake-up messages or background frames) via a preamble frame and burst transmission.

A. Related Work and Research Problem

Wake-up schemes for WLANs can be classified into two categories according to the implementation of transceivers: 1) Using a WLAN module to transmit and an additional ZigBee module to detect the wake-up signal [8]–[10]. However, the power consumption of a ZigBee device, being around 50 mW, is still relatively high. Furthermore, the bandwidth of a ZigBee module is less than that of a WLAN signal, which degrades the performance of frame length detection [13]. In addition, it is hard to optimize the receiver operation of wake-up control because the configurability of the off-the-shelf ZigBee modules is limited. 2) Using an optimized low-power transceiver [4], [7], [14], [15]. This, however, requires a dedicated device to transmit wake-up messages, which increases the cost of deployment. This paper combines 1) and 2) using a WLAN module to transmit and an optimized WuRx to detect wake-up signals.

Simply using frame lengths of WLAN signals to convey wake-up messages, however, has the following problems.

i) Mixed transmissions of command frames and background frames, as shown in Fig. 1. One solution is to detect wake-up messages via state transition [11], each state representing a target frame length. In our previous work [12], we solve this problem by transmitting command frames of a wake-up message in a burst way, preventing background frames from interfering.

ii) Frame synchronization errors. Errors in the envelope of a command frame may cause it to be detected as two frames or more. Then, a WuRx will detect a different number of frame lengths from that of a wake-up message. This problem, called frame synchronization error, is solved in [12] by treating the whole waveform of command frames transmitted in a burst as an *equivalent message* and comparing the equivalent message with a received signal via direct correlation (called *DirCorr* in this paper).

iii) Poor performance at low signal-to-noise ratio (SNR). This can be improved by enlarging the Hamming distance between wake-up messages. BCH codes [16] are used in [17] to encode wake-up messages before frame length modulation.

iv) Frame collisions. A collision occurs when a command frame is simultaneously transmitted with a background frame.

v) False positive events. A false positive event occurs when a sequence of frames, either background frames only or mixed with command frames of a wake-up message, is falsely interpreted as another wake-up message. Bimodal frame length distribution is exploited in [8] to mitigate this problem. Frame lengths, whose appearing frequencies within a WLAN trace of background frames are less than a threshold, are selected as a modulation constellation for command frames. Even this way, a background frame matches the length of a command frame with a nonzero probability (see Fig. 1), which leads to false positive events. In addition, multiple command frames of a wake-up message are separately transmitted. The mixed transmission of command frames and background frames increases *FPP*.

Among these problems, 1) and 2) are well solved. As for 3), previous schemes [8], [11] use the same set of frame lengths for all command frames, which limits the capability of distinguishing different wake-up messages, 4) has not been touched in previous work yet, and 5) is the largest problem of frame length modulation.

B. Work in This Paper

We extend our previous work [12], solving the aforementioned problems and further improving the reliability of wake-up control. The new contribution is threefold.

- The Hamming distance between wake-up messages under frame length modulation, not addressed in previous works [8], [11], is studied in this paper. On this basis, optimal modulation constellations of frame lengths are suggested, which maximize the Hamming distance between wake-up messages.
- Envelope smoothing is exploited in message detection to decrease *FNP* under low SNR. A preamble frame is used to reduce *FNP* caused by frame collisions and mitigate *FPP*. These methods, although simple, are effective in improving system reliability, and their performance is theoretically analyzed.
- A prototype test bed is built using an off-the-shelf WLAN card as a transmitter and a newly developed WuRx as a receiver. Experiments are conducted in the presence of moderate background WLAN communications, which confirm that the proposed scheme runs in real environments.

Theoretical analysis, simulation evaluations, and test bed experiments all confirm that the proposed scheme effectively improves the reliability of delivering wake-up messages via WLAN frame lengths and decreases the power consumption of APs. *FPP* caused by background frames and the error floor of *FNP* due to frame collisions are made negligibly small compared with previous schemes [8], [11]. In addition, *FNP*

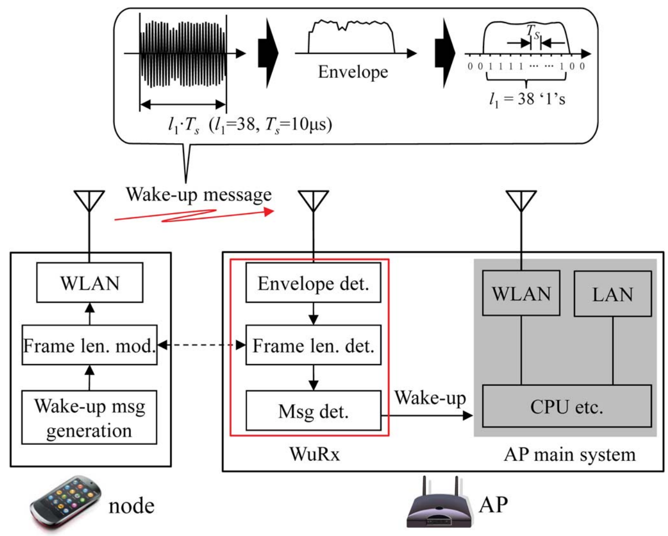

Fig. 2. System model of using WLAN signals for the wake-up control of APs. A wake-up message is modulated onto frame lengths of consecutive WLAN signals and detected by low-cost wake-up receivers.

at low SNR is effectively reduced by envelope smoothing. The proposed scheme is not limited to the wake-up control of APs. It helps to turn smartphones and tablets equipped with WLAN modules into universal remote controllers, if only target appliances are equipped with suitable WuRx.

The rest of this paper is organized as follows. Section II proposes a new scheme to improve the reliability of wake-up control from different aspects. Section III gives theoretical analysis of *FPP* in the presence of background communications and *FNP* due to collisions and random bit errors. Numerical results of theoretical computation, simulation evaluations, and test bed experiments, including *FPP*, *FNP*, and power consumption, are presented in Section IV. Finally, Section V concludes this paper.

II. Proposed Scheme

Here, the system model is presented in Section II-A. Then, we propose a new wake-up scheme, i.e., direct correlation with Optimal modulation Constellation and envelope Smoothing (*DirCorr(OCS)*), to enhance the basic frame length modulation [8] from three aspects: 1) enlarging the Hamming distance between wake-up messages by refining the modulation constellation. In Section II-B, the Hamming distance between two wake-up messages is deduced, and the search space of optimal solutions is reduced via some observations; 2) further improving system reliability in Section II-C, reducing the effect of random, isolated bit errors in envelope detection, and exploiting a preamble frame to synchronize the burst transmission and mitigate the effect of collisions. The coexistence with co-located WLANs is also discussed in Section II-D.

A. System Model

The system model of wake-up control for WLAN APs is shown in Fig. 2. An AP is equipped with a low-power WuRx. An AP in its idle state turns off all components (WLAN module, LAN module, CPU, etc.), except that its WuRx is kept awake. A node, initiating a new data flow, first sends a wake-up message (computed from the service set identifier of a target AP) to activate the AP.

TABLE I
Notations for the Analysis of Frame Length Modulation

Not.	Meaning
T_s	Sampling period
m_n	Number of bits carried in the length of n^{th} command frame
d_n	Common difference in n^{th} set of frame lengths (unit T_s)
$i_{j,n}$	n^{th} word of wake-up message i_j, m_n bits
l_0	Minimal frame length used in modulation (unit T_s)
$l_{j,n}$	n^{th} frame length of wake-up message i_j, $l_{j,n} = l_0 + i_{j,n} \cdot d_n$
σ	Length of IFS under burst transmission, $IFS = \sigma \cdot T_s$

The channel conveying a wake-up message from a WLAN module to a non-WLAN WuRx is different from a conventional channel. Here, a wake-up message is modulated onto frame lengths (physical transmission time) of WLAN signals. The generated command frames are sent via a WLAN module, and their lengths are detected by a WuRx. As shown in Fig. 2, the pulse shaping function of frame length modulation corresponds to a rectangle (the envelope of a WLAN signal).

In the following, we explain the transmitter and receiver, respectively. Some frequently used symbols are listed in Table I.

Transmitter Side: Each wake-up message has I bits. The jth wake-up message i_j is divided into N words $i_{j,n}, n = 1, \ldots, N$, each with m_n bits and $\sum_n m_n = I$. For example, $I = 8$ bits "10010011" are divided into four groups, and $i_{j,1} = 4$ corresponds to bits "100" in Fig. 3(a). To facilitate the system design, we assume that: 1) The unit of frame length is T_s (the sampling period); and 2) a continuous range of frame length starting from l_0 is available. Then, the nth word $i_{j,n}$ is mapped to a frame length $l_{j,n} = l_0 + i_{j,n} \cdot d_n$ using the constellation

$$const_n = \{l_k | l_k = l_0 + k \cdot d_n, k = 0, 1, \ldots, 2^{m_n} - 1\} \quad (1)$$

which is determined by parameters m_n,d_n. As a comparison, the same mapping (modulation constellation) is used to decide all command frames of a wake-up message in [8] and [11].

The constructed command frames of a wake-up message have a broadcast medium access control address. They are successively transmitted in a burst with a fixed interframe space (IFS) [1] (with a length σ) on the channel that the target WuRx monitors. Each command frame carries a nonzero duration field to set network allocation vector (NAV) at nearby WLAN modules to prevent background frames from interfering.

Transmissions of a wake-up message also depend on several other parameters, as follows.

- Frame type. In our previous work [12], we found that envelopes of orthogonal frequency-division multiplexing (OFDM) frames greatly change due to the peak-to-average power ratio problem, which leads to a large *FNP* even at high SNR. Therefore, in this paper, we use the non-OFDM, 802.11b frames (available in 802.11 g/n for backward compatibility) as command frames, which have almost constant envelopes.

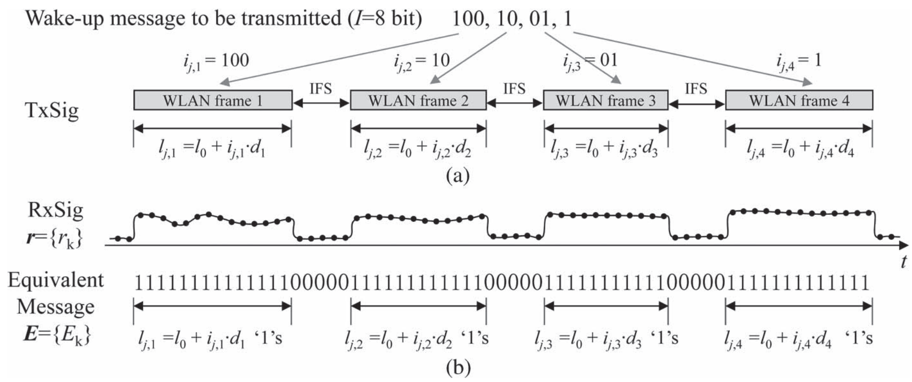

Fig. 3. Communication model of transmitting wake-up messages via WLAN signals. (Transmitter side) A wake-up message is modulated onto lengths of successive WLAN frames, each using a different set of frame lengths. (Receiver side) The waveform of successive transmissions is re-interpreted as an equivalent message and detected by direct correlation. (a) Transmitting wake-up message i_j via frame length modulation. (b) Detecting i_j via correlation between received signal and equivalent message.

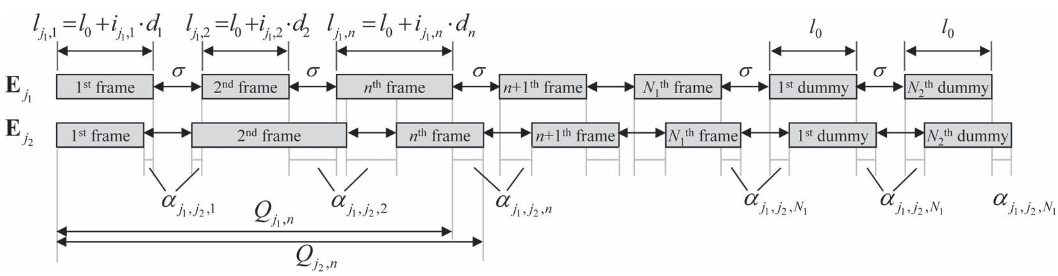

Fig. 4. Analysis of the Hamming distance between equivalent messages.

- T_s. T_s is set to 10 μs[1] based on some initial experiments.
- IFS. As will be explained later, the performance of distinguishing wake-up messages is limited by the length of an IFS. On the other hand, an off-the-shelf WLAN module cannot accurately generate a predefined IFS greater than the distributed coordination function IFS (DIFS). Hence, an IFS is set to a DIFS (50 μs; $\sigma = 5$).
- l_0. The set of frame lengths that can be used as a modulation constellation depends on the distribution of background frames [8]. We investigated the frame length traces released by CRAWDAD [18] and selected a continuous range of frame lengths starting from $l_0 = 34$ (corresponding to $L_0 = l_0 \cdot T_s = 340$ μs).

Receiver Side: The envelope of consecutive command frames,[2] including IFSs, is detected and sampled to a sequence of bits $\boldsymbol{r} = \{r_k\}$ at a sampling period T_s by using a 1-bit A/D converter. A frame length l corresponds to a sequence of l "1's," and an IFS corresponds to a sequence of σ "0's". Command frames of a wake-up message, transmitted in a burst, have well-defined timing relationship (adjacent frames have a fixed IFS). Therefore, the waveform of a wake-up message, sampled at T_s, can be re-interpreted as an *equivalent message* $\boldsymbol{E} = \{E_k\}$. For example, the wake-up message i_j in Fig. 3(a) has an equivalent message $\boldsymbol{E}$ shown in Fig. 3(b). It is natural to compute the direct correlation (*DirCorr*) between $\boldsymbol{E}$ and the received signal $\boldsymbol{r}$ to perform message detection. Hereafter, equivalent messages are used instead of wake-up messages. In comparison, first demodulating frame lengths and then detecting wake-up messages via correlation are called indirect correlation (*IndCorr*).

B. Optimal Constellations of Frame Lengths

Parameters of $const_n$ (m_n, d_n) in (1) are optimized to maximize the Hamming distance between equivalent messages.

1) Minimal Hamming Distance Between Equivalent Messages: The Hamming distance between two equivalent messages $\boldsymbol{E}_{j_1}$ and $\boldsymbol{E}_{j_2}$ is computed by using the model shown in Fig. 4. Each wake-up message is composed of $N_1 > 0$ information frames (frame lengths carry wake-up information) and $N_2 \geq 0$ dummy frames with a fixed frame length (dummy frame will be discussed later). The sth $(s = 1, \ldots, N_1)$ frame length is equal to $l_0 + i_{j,s}d_s$. The total lengths of the first n command frames of $\boldsymbol{E}_{j_1}$ and $\boldsymbol{E}_{j_2}$, including their IFSs, are computed as

$$Q_{j,n} = (n-1)\sigma + \sum_{s=1}^{n}(l_0 + i_{j,s}d_s)$$
$$0 \leq i_{j,s} \leq 2^{m_s} - 1, \quad j = j_1, j_2. \quad (2)$$

A nonzero difference between $Q_{j_1,n}$ and $Q_{j_2,n}$ contributes to a Hamming distance between $\boldsymbol{E}_{j_1}$ and $\boldsymbol{E}_{j_2}$ at the end of the nth frame. When $|Q_{j_1,n} - Q_{j_2,n}|$ is greater than σ, the Hamming

[1]The resolution of frame length at 802.11b 11 Mb/s is 8/11 μs (symbol length). Under this resolution, frame lengths being integral times of $T_s = 10$ μs can be well approximated.

[2]Both frame lengths and IFS length are integral times of T_s.

distance is limited by σ (e.g., the IFS between the second and third frames in Fig. 4) and is computed as

$$\alpha_{j_1,j_2,n} = \min\left(|Q_{j_1,n} - Q_{j_2,n}|, \sigma\right) = \min\left(\left|\sum_{s=1}^{n} k_{j_1,j_2,s} d_s\right|, \sigma\right)$$
$$k_{j_1,j_2,s} = i_{j_1,s} - i_{j_2,s} \in \{-(2^{m_s}-1), \ldots, 2^{m_s}-1\}. \quad (3)$$

Because the IFS between the nth and the $n+1$th frame is fixed, there is also a difference of $\alpha_{j_1,j_2,n}$ at the beginning of the $n+1$th frame, as shown in Fig. 4. As dummy frames have a fixed length, $\alpha_{j_1,j_2,n}$ $(n \geq N_1)$ is equal to α_{j_1,j_2,N_1}. Then, the overall Hamming distance between $\boldsymbol{E}_{j_1}$ and $\boldsymbol{E}_{j_2}$ is equal to

$$D_{j_1,j_2} = \sum_{s=1}^{N_1} 2\alpha_{j_1,j_2,s} + (2N_2 - 1)\alpha_{j_1,j_2,N_1}. \quad (4)$$

It is composed of two parts, i.e., contribution due to N_1 information frames and contribution due to N_2 dummy frames.

The minimal Hamming distance between all pairs of equivalent messages

$$D_{\min} = \min_{j_1,j_2,\sum_s |k_{j_1,j_2,s}| \neq 0} D_{j_1,j_2} \quad (5)$$

depends on $2N_1 + 1$ parameters $m_1, m_2, \ldots, m_{N_1}, d_1, d_2, \ldots, d_{N_1}, N_2$, where the former $2N_1$ parameters determine modulation constellations $const_n,\ n = 1, \ldots, N_1$. These parameters will be found by maximizing $D_{\min}$.

A larger Hamming distance can be obtained at the cost of more transmission time, and a tradeoff is necessary between the Hamming distance and transmission time. The average time taken to transmit $N = N_1 + N_2$ command frames of a wake-up message is equal to

$$t = (N_1 + N_2)(\sigma + l_0)T_s + \sum_{s=1}^{N_1} \left((2^{m_s} - 1) \cdot d_s T_s / 2\right). \quad (6)$$

The average time taken by *DirCorr(BCH)* [12], where the same set of frame lengths is used for all command frames, is regarded as the target time t_{target}. Then, under the constraint that the average transmission time is no more than t_{target}, we maximize the Hamming distance to find the optimal parameters, as follows:

$$\{m_1, \ldots, m_{N_1}, d_1, \ldots, d_{N_1}, N_2\} = \arg\max_{m_s, d_s, N_2} D_{\min}$$
$$\text{s.t.} \quad \sum_{s=1}^{N_1} m_s = I,\ t \leq t_{\text{target}}. \quad (7)$$

2) Observation of the Hamming Distance: The space of parameters in (7) is too large to perform an exhaustive search. To reduce the search space, we investigate the properties of frame length modulation under burst transmission and find several design rules, which are discussed and summarized in Fig. 5. In the investigation, we consider two wake-up messages $i_j, j = 1, 2$.

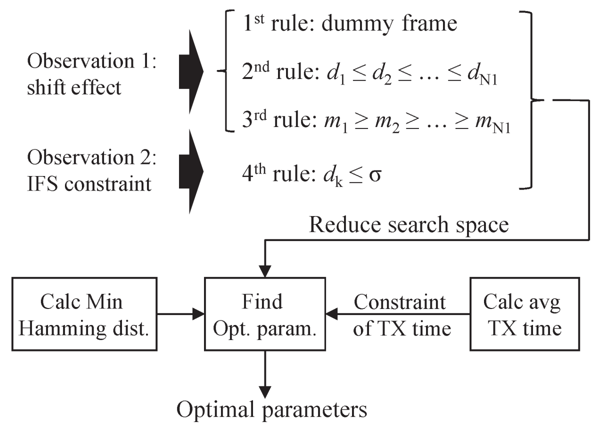

Fig. 5. Flowchart to find optimal parameters of frame length modulation.

Observation 1—Shift Effect: When the difference between i_1 and i_2 is only one bit, e.g., $i_{1,k} = i_{2,k}$ for $k \neq n$ and $|i_{1,n} - i_{2,n}| = 1$, this leads to a length difference $|l_{1,n} - l_{2,n}| = d_n$ or a Hamming distance d_n between the two equivalent messages at the nth command frame. Fig. 6(a) shows an example where $n = 2,\ l_{2,n} - l_{1,n} = d_n = 1$. In this case, the difference in equivalent messages is not limited to the nth frame. Frames following the nth frame are shifted right,[3] generating a Hamming distance d_n at both ends of each subsequent frame. As a result, the Hamming distance generated is actually equal to

$$(2 \cdot (N - n) + 1) \cdot d_n. \quad (8)$$

The Hamming distance contributed by each word depends on its position n: The larger n is, the smaller its contribution. To increase the Hamming distance, we divide N command frames into two parts, i.e., the first N_1 command frames carry information bits, whereas the subsequent N_2 command frames are dummy (A dummy frame has the shortest length l_0). Accordingly, *the first rule* is to constrain n to be no more than N_1 so that $N - n$ is no less than N_2.

The part of distance expression in (8), i.e., $2 \cdot (N - n) + 1$, decreases at a larger n. Accordingly, to make the whole distance large enough, *the second rule* is to adjust the other part in (8), i.e., d_n, using a large d_n for a large n; in other words, $d_1 \leq d_2 \cdots \leq d_{N_1}$.

To improve the modulation efficiency, the numbers of bits in information words should be adjusted to d_n. Then, *the third rule* is that more bits should be modulated by a modulation constellation with a smaller d_n. Therefore, the numbers of bits of the N_1 information words should satisfy $m_1 \geq m_2 \cdots \geq m_{N_1}$ and $m_{N_1+1} = \cdots = m_N = 0$ for dummy frames.

Observation 2—IFS Constraint: $|l_{1,n} - l_{2,n}|$ may get greater than σ, the number of bits due to an IFS. In this case, actually, only the IFS part contributes to the Hamming distance. For example, in Fig. 6(b), $n = 2$, $l_{2,n} - l_{1,n} = 6 > \sigma = 5$, but the Hamming distance at the second frame is limited by σ. Then, *the fourth rule* is $d_k \leq \sigma,\ k = 1, \ldots, N_1$.

3) Optimal Solutions: By exploiting these design rules, the search space of (7) is greatly reduced, and the optimal solution

[3] This is due to the effect of a fixed IFS between adjacent frames.

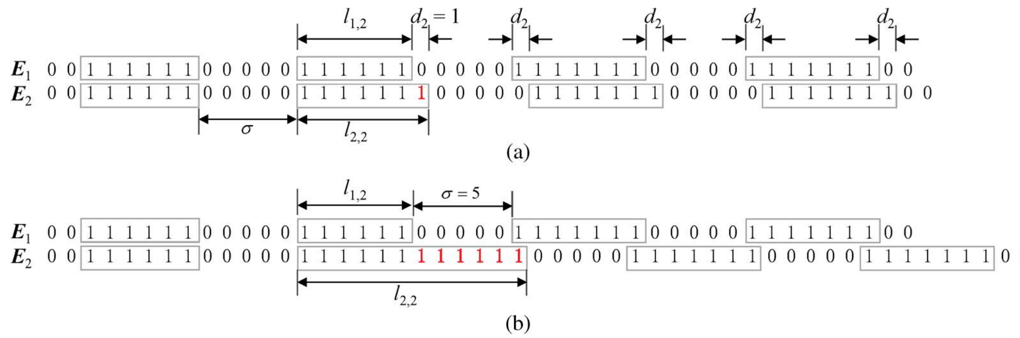

Fig. 6. Observation of the Hamming distance between equivalent messages under frame length modulation. (a) Observation 1: shift effect. (b) Observation 2: IFS constraint.

TABLE II
MINIMAL HAMMING DISTANCE BETWEEN EQUIVALENT MESSAGES UNDER DIFFERENT CONFIGURATIONS

	$N_1 = 4$	$N_1 = 5$	$N_1 = 6$	$N_1 = 7$	$N_1 = 8$
$N_2 = 0$	5	5	5	5	5
$N_2 = 1$	**10**	**10**	**10**	**10**	2
$N_2 = 2$	**10**	**10**	8	2	
$N_2 = 3$	8	6	2		

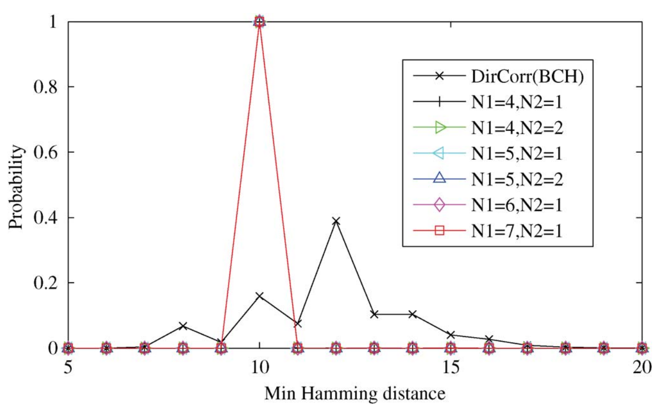

Fig. 7. Distribution of the Hamming distances between equivalent messages under frame length modulation and burst transmission.

can be easily found. The minimal Hamming distances of solutions $(I = 16)$ are shown in Table II, with N_1 and N_2 as parameters. An empty cell means that the average time of a solution is greater than t_{target}. There are six optimal solutions with the same minimal Hamming distance being 10.

Fig. 7 shows the distribution of the Hamming distances between equivalent messages, achieved by the six potential optimal solutions of *DirCorr(OCS)* in addition to the *DirCorr(BCH)* scheme. In *DirCorr(BCH)*, BCH(31,16) codewords are used in frame length modulation. The minimal Hamming distance is equal to 7, although most Hamming distances are larger. On the other hand, in the six solutions of *DirCorr(OCS)*, the minimal Hamming distance reaches 10.

Equivalent messages of the six solutions have different distributions of transmission times, as shown in Fig. 8. With $N_1 = 7$ and $N_2 = 1$, the transmission times are most concentrative. This one is selected from the six solutions because its longest transmission time is the shortest, which reduces the maximal transmission delay.

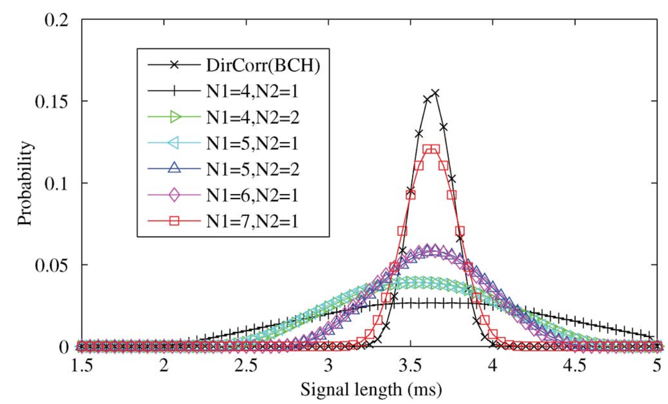

Fig. 8. Distribution of the total time taken to transmit all command frames of a wake-up message.

C. Further Improving Reliability

A wake-up message is modulated onto frame lengths, where adjacent command frames are separated by an IFS. A command frame with length l has l consecutive "1's" and an IFS spans σ "0's." Any patterns of mixed "1's" and "0's" such as "101" and "010" in an equivalent message are erroneous. The number of bits in an equivalent message is much greater than that in an original wake-up message, as shown in Fig. 3. Therefore, in the message detection, the chance that the number of random bit errors goes beyond the error protection capability is large for equivalent messages, which degrades system reliability.

We design reliable filters to remove random bit errors in the envelope of command frames because these error patterns are dominant in an equivalent message. Heuristically, a single "0" between multiple "1's" (e.g., "11011") indicates a high probability of a single bit error from "1" to "0" in a command frame and a much lower probability of multiple "0's" to "1's" in an IFS. The following equation:

$$r_k \leftarrow r_k | (r_{k-2} \& r_{k-1} \& \widetilde{r}_k \& r_{k+1} \& r_{k+2}) \quad (9)$$

gives a simple example of bit filtering, where $\sim$, &, and $|$ are the bitwise NOT, AND, and OR, respectively. This bit filter removes the error pattern of "11011" and has little effect on the IFS. A more advanced filter can do better at an increased cost.

In addition, a preamble frame, with a length l_{pre}, is added to the front of command frames to realize frame synchronization. l_{pre} does not appear in the modulation constellations of frame

TABLE III
COMPARISON OF FOUR SCHEMES USING FRAME LENGTH MODULATION

Schemes	Transmission	Detection
IndCorr	BCH(31,16), same const.	Env Sm.+Len Det.+Corr.
DirCorr(BCH)	BCH(31,16), same const.	Direct corr.
DirCorr(OC)	I=16bits, opt. const.	Direct corr.
DirCorr(OCS)	I=16bits, opt. const., pream.	Env Sm.+Direct corr.

lengths. A preamble frame marks the start of a burst transmission and helps mitigate both *FPP* (as discussed in Section III-A) and *FNP* (as discussed in Section III-B).

D. Coexistence With Colocated WLANs

The same WLAN protocol is used to transmit wake-up messages, which is compatible with background WLAN communications. According to Fig. 8, a wake-up message is less than 4 ms at the selected parameters. Together with its preamble frame, the total length is no more than 5.6 ms (when using a preamble $l_{\rm pre} = 156$, as discussed in Section IV-B) and is on the same order as a burst transmission of background WLAN frames. On a channel where the channel busy ratio is about 25% due to background WLAN frames [18], transmitting wake-up messages once per second only increases the channel busy ratio by an amount of 0.56%. In a real application, wake-up messages are transmitted much less often. Therefore, transmissions of wake-up messages have no noticeable influence on the performance of colocated WLANs.

III. PERFORMANCE ANALYSIS

We give a theoretical analysis of *FNP* and *FPP* of four wake-up schemes based on frame length modulation, which are briefly summarized in Table III and compared in terms of transmission and detection. 1) Transmission. In *IndCorr* [8], [11] and *DirCorr(BCH)* [12], a wake-up message with $I = 16$ bits is converted to a BCH(31, 16) codeword and then modulated onto $N = 8$ frame lengths using the same constellation of frame lengths for all command frames. The $I = 16$ bits are directly modulated onto $N = 8$ frame lengths using the optimized constellations of frame lengths in *DirCorr (OC)* and *DirCorr(OCS)*. A preamble frame is used in *DirCorr(OCS)* but not in the other schemes. Burst transmission is used in all schemes except *IndCorr*. 2) Detection. The received signal is demodulated into a wake-up message and correlated with an assigned wake-up message in *IndCorr* and detected via direct correlation between received signals and equivalent messages in the other three schemes. Envelope smoothing is applied in *IndCorr* and *DirCorr(OCS)* but not in the other two schemes.

A. Analysis of FPP

A false wake-up event may be triggered due to the presence of background frames or other wake-up messages. Assume frame length l of background frames follows a distribution $p_{bg}(l)$. In the following, we analyze *FPP* caused by mixed transmissions of background frames and command frames. In the analysis, bit errors due to low SNR are not considered.

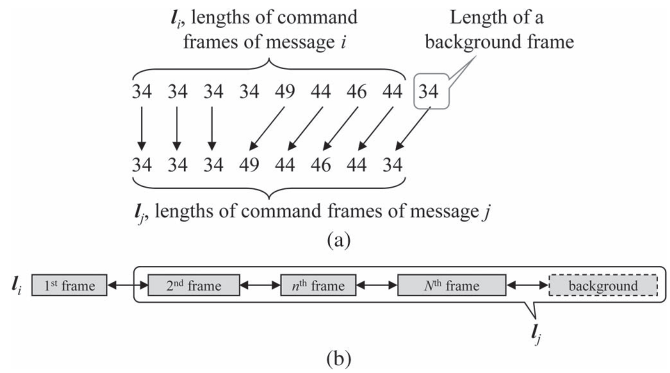

Fig. 9. Partial similarity between wake-up messages and false positive events due to background frames. (a) Without burst transmission. (b) With burst transmission.

1) FPP Without Burst Transmission: Without burst transmission in *IndCorr*, each command frame of message i with frame lengths $\boldsymbol{l}_i = \{l_{i,k}, k = 1, \ldots, N\}$ is separately transmitted. The sequence of frame lengths detected at a WuRx will be $P_0, l_{i,1}, P_1, l_{i,2}, \ldots, P_{N-1}, l_{i,N}, P_N$. The number of background frames in each position P_i is a random variable n_i. Up to C background frames are allowed to appear in each position P_k, where C is a parameter used to consider the effect of channel sharing [11]. Therefore, $n_i \le C$ for all command frames is regarded as a successful reception of the wake-up message. When one node contends to send a wake-up message and the other B nodes contend to send background frames in the saturation state, the probability that a frame is from a specific node is equal to $1/(B+1)$. Then, n_i follows a distribution $p(n_i) = (1 - 1/(B+1))^{n_i} \cdot 1/(B+1)$.

Partial similarity between messages i and j and the presence of background frames greatly affect *FPP*. Assume that messages i and j share $N-k$ frame lengths $\boldsymbol{l}_{i,j}^{N-k}$ in order, and the rest of k frame lengths in $\boldsymbol{l}_j$ are $\boldsymbol{l}_{i,j}^{k} = \boldsymbol{l}_j \setminus \boldsymbol{l}_{i,j}^{N-k}$, located in S of the $N+1$ positions P_k, each with k_s, $s = 1, \ldots S$ target frame lengths in $\boldsymbol{l}_{i,j}^{k}$. Fig. 9(a) shows an example where $\boldsymbol{l}_{i,j}^{N-k} = \{34, 34, 34, 49, 44, 46, 44\}$, and $\boldsymbol{l}_{i,j}^{k} = \{34\}$ is in P_N $(S = 1; k_1 = 1)$. When k_s is equal to 1 and the target frame length is equal to l_s, the probability that there is at least one background frame with a length l_s is equal to

$$p(l=l_s) = \sum_{n_i=1}^{C} p(n_i) \cdot [1-(1-p_{bg}(l_s))^{n_i}] \approx B \cdot p_{bg}(l_s). \quad (10)$$

When all k_s are equal to 1 and $\boldsymbol{l}_{i,j}^{k}$ are produced by background frames in specified positions, the FPP of message j caused by message i can be computed as

$$FPP_{i\to j}^{\rm NoBurst}(k) = \prod_{l_s \in \boldsymbol{l}_{i,j}^{k}} p(l = l_s) \approx B^k \cdot \prod_{l \in \boldsymbol{l}_{i,j}^{k}} p_{bg}(l). \quad (11)$$

A similar analysis can be conducted for $k_s \ge 2$. Generally, this FPP is on the order of $B^k \cdot p_{bg}(l)^k$ ($k = 1$ for most messages). This analysis applies to schemes [8]–[10] that use frame length modulation for wake-up control.

2) FPP With Burst Transmission: Background frames will not appear between consecutive command frames when burst transmission is used. However, due to the possible duplicate frame lengths in a wake-up message, the second to ninth frame lengths of $\boldsymbol{l}_i\|\{34\}$ in Fig. 9(a) can be still regarded as $\boldsymbol{l}_j$ without skipping a frame. In the following, we analyze this false positive pattern: Message j shares $N-k$ frame lengths with message i; part of message i and k background frames following message i lead to the false message j, as shown in Fig. 9(b).

In the saturation state, each node contends to transmit a frame via carrier sense multiple access. The transmission probability per node per slot [19]τ can be estimated from the total number of nodes $(B+1)$ in the network. A background frame, following message i, may be either from the node that just sent the wake-up message or from any of the other B neighboring nodes. The probability that a background frame is transmitted immediately after the IFS is equal to $p_B = 1-(1-\tau)^{B+1} \approx (B+1)\cdot\tau$. The *FPP* of message j

$$FPP_{i\to j}^{\text{Burst}}(k) = (p_B)^k \cdot \prod_{l\in \boldsymbol{l}_{i,j}^k} p_{bg}(l) \tag{12}$$

is composed of two parts: The first term is the probability that k background frames are successively transmitted IFS apart after message i, and the second term is the probability that they happen to have the same frame lengths as the rest k frames of message j. This FPP is on the order of $(B\tau\cdot p_{bg}(l))^k$ ($k=1$ for many messages).

3) FPP With Burst Transmission and a Preamble Frame: False positive events in times of burst transmission happen because a WuRx does not know where a wake-up message starts. In the proposed scheme, a leading preamble frame with a length l_{pre} is used to mark the start of a burst transmission. l_{pre} does not appear in modulation constellations of frame lengths. It helps remove false positive events due to partial similarity between wake-up messages. Then, message j is falsely triggered when $N+1$ consecutive background frames are transmitted in a burst (with a probability $(p_B)^N$) and have the same lengths as the preamble and N command frames of message j. The *FPP*

$$FPP_j^{\text{BurstPream}} = (p_B)^N \prod_{l\in\{l_{\text{pre}}\}\bigcup \boldsymbol{l}_j} p_{bg}(l) \tag{13}$$

is on the order of $(B\tau)^N \cdot p_{bg}(l)^{N+1}$, which is much less than $p_{bg}(l)^1$ of previous schemes.

B. Analysis of FNP

Simultaneous transmission of multiple frames leads to a collision in WLANs. When a collision occurs, the payloads of all frames in the transmission are corrupted. After this collision, nodes, sending unicast background frames and failing to receive ACKs, will double their contention window and enter a random backoff period. On the other hand, command frames are broadcast without requiring ACKs. If the first command frame is longer than colliding background frames, its sender will sense an idle channel after the collision and continue its burst transmission. Other nodes detecting the transmission of subsequent command frames will not transmit their background frames. In addition, a wake-up message is carried in the lengths of command frames and not the payload. Therefore, if the length of the first command frame is greater than that of the colliding background frames, the frame length can be still correctly detected. *In this sense, wake-up communications via frame lengths are very robust to frame collisions*.

Let the length of the first frame of a burst transmission be l_{first}. It is equal to l_{pre}, which is the length of the preamble frame in *DirCorr(OCS)* and belongs to the frame length set $const_1$ in other schemes. A false negative event occurs 1) when a collision occurs at the first frame and the length of a colliding background frame is greater than l_{first} or 2) if too many bit errors occur at low SNR. Let the collision probability be γ and the false probability due to low SNR be FNP_{SNR}. Then, *FNP* under all cases is

$$FNP_{\text{all}} = \gamma\cdot p_{bg}(l>l_{\text{first}}) + (1-\gamma\cdot p_{bg}(l>l_{\text{first}}))\cdot FNP_{\text{SNR}}. \tag{14}$$

γ depends on the volume of background traffic and the number of contending nodes. According to simulations, γ is equal to 0.0016 when the channel busy ratio is 27.86%, i.e., a medium traffic condition.[4] $p_{bg}(l>l_{\text{first}})$ is decided by l_{first} and the distribution of background frame lengths. The first term in (14) leads to an error floor at high SNR and can be greatly reduced by using a large l_{pre} in the proposed scheme.

Detailed analysis of FNP_{SNR} for a specific message is presented in the Appendix. Because equivalent messages have different lengths and different minimal Hamming distances, average *FNP* should be computed over all messages.

A large l_{pre} helps reduce the error floor due to collisions but increases *FNP* at low SNR (because the envelope of a preamble frame may be also erroneous). Fortunately, random bit errors can be effectively mitigated by envelope smoothing. Therefore, in our design, l_{pre} is set to a large value, mainly to reduce the effect of collisions.

IV. Numerical Results

Here, we present the theoretical and simulation results of different schemes. Then, on this basis, we analyze total power consumption. Finally, we show some experimental results obtained by using a prototype test bed.

A. Theoretical Result of FPP

FPP depends on the distribution of background frame lengths and the number of nodes contending to transmit frames. We exploited the trace data of WLAN frame lengths released by CRAWDAD [18]. The distribution of frame length $L\mu s$ is aggregated to discrete bins as $p_{bg}(l) = prob(|L-l\cdot T_s| < T_s/2)$ and shown on the top of Fig. 10. There are 11 nodes: one contending to send wake-up message and the others contending to send background frames in the saturation scenario. The per-node per-slot transmit probability is $\tau = 0.05974$ computed according to [19]. On this basis, *FPP* is computed for

[4] Background frames are generated by six nodes. Packet arrival intervals are independent and identically distributed exponential random variables.

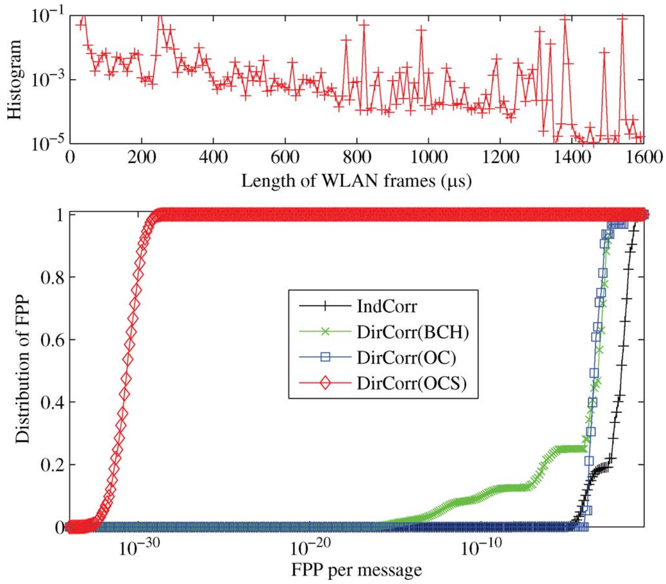

Fig. 10. Cumulative distribution functions of per-message *FPP* under different schemes using the distribution of WLAN frame lengths.

each wake-up message using (11) for *IndCorr*, (12) for *DirCorr(BCH)* and *DirCorr(OC)*, and (13) for *DirCorr(OCS)*. Then, with the *FPP*s of all wake-up messages, their cumulative distribution function is computed for each scheme and shown at the bottom of Fig. 10. The horizontal axis is *FPP* (x) and the vertical axis is the percentage of wake-up messages whose *FPP*s are no more than x. *DirCorr(BCH)* and *DirCorr(OC)* reduce *FPP* slightly compared with *IndCorr* by using burst transmission. Further exploiting a preamble frame in *DirCorr(OCS)* helps reduce *FPP* to be negligibly small, as analyzed in Section III-A.

B. Theoretical and Simulation Results of FNP

We evaluated the proposed scheme by simulation using the following setting: White Gaussian noise with a power value of −91 dBm/20 MHz (i.e., the typical value used in network simulator QualNet [20]) is added to WLAN signals; wake-up messages are detected after the envelope detection. All (65536) valid wake-up messages are evaluated. Background WLAN frames are generated according to the WLAN frame length traces released by CRAWDAD [18] and have a similar channel busy ratio. The simulation is run with 20 different seeds. From these simulation results, collision probability γ, FNP_{SNR}, and bit error rate are obtained. Then, *FNP* of simulation results is obtained by (14), and *FNP* of theoretical results is computed by using (17)–(21) in the Appendix.

FNP results, averaged over all wake-up messages, are shown in Fig. 11, where theoretical and simulation results are plotted in dotted and solid lines, respectively. As for theoretical results, Fig. 11 reveals the following points: 1) The average performance of *DirCorr(OC)* is similar to that of *DirCorr(BCH)*, although this average hides the weak codes of *DirCorr(BCH)* (refer to Fig. 7); 2) *DirCorr(OCS)* can effectively reduce *FNP* at low SNR compared with *DirCorr(OC)* by applying envelope smoothing to filter out random bit errors. At $\mathrm{FNP} = 10^{-3}$,

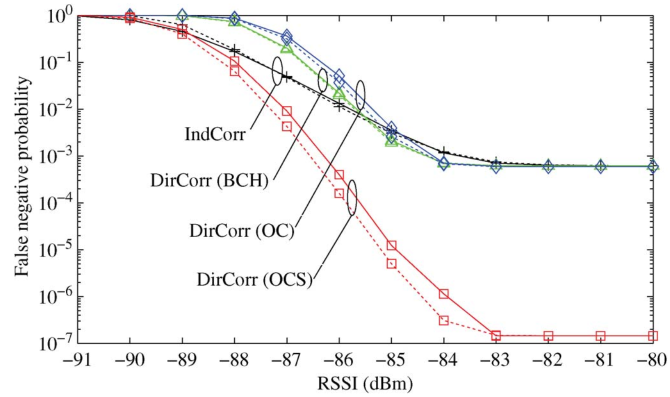

Fig. 11. Average *FNP* of different schemes. Dotted lines are theoretical results, and solid lines are simulation results.

DirCorr(OCS) has an SNR gain of about 2.0 dB compared with *DirCorr(OC)*. *IndCorr*, after applying envelope smoothing, also performs better than *DirCorr(BCH)* and *DirCorr(OC)* at low SNR; 3) *DirCorr(BCH)*, *DirCorr(OC)*, and *DirCorr(OCS)* have sharper *FNP* curves compared with *IndCorr*, which confirms the order analysis of *FNP* in the Appendix; 4) there is an error floor at high SNR due to frame collisions in WLANs. Without a preamble frame, the average probability of $p_{bg}(l > l_{\mathrm{first}})$ is equal to 0.388 in *IndCorr* and *DirCorr(BCH)* and 0.369 in *DirCorr(OC)*. In comparison, $p_{bg}(l > l_{\mathrm{pre}})$ is equal to 9.1×10^{-5} when using a preamble frame with a length $l_{\mathrm{pre}} = 156$ in *DirCorr(OCS)*, and the error floor is greatly reduced.

All simulation results match the theoretical results relatively well in Fig. 11. As for *DirCorr(OCS)*, the small gap between the simulation and theoretical lower bound exists because simple envelope smoothing cannot remove all random bit errors.

C. Analysis of Power Consumption

In the wake-up control of APs, the power consumption may be due to the transmission (and retransmissions under a nonzero *FNP*) of a wake-up message at a node, the reception at a WuRx when its colocated AP sleeps, and a power waste at an AP when the AP is falsely activated under a nonzero *FPP*.

The measured power consumption of our WuRx is around $P_{\mathrm{WuRx}} = 10$ mW and can be further reduced by leveraging integrated circuit design. This is much less than the power consumption of a ZigBee module used for frame length detection [8]–[10], which is around 50 mW. Assume that the power consumption of a node (a smartphone with its WLAN module as a transmitter) is $P_N = 0.9$ W [21] and that of an AP is $P_{\mathrm{AP}} = 10$ W [3]. An AP works with a duty ratio O_{AP}, and its WuRx works in the rest $1 - O_{\mathrm{AP}}$ when the AP is in sleep. Each false wake-up takes a time T_{AP} during which an AP, powered on by wake-up control, boots its OS and shuts down again after it somehow detects this false event. The booting time of off-the-shelf commercial APs (Aterm WR8370N) is about $T_{\mathrm{AP}} = 20$ s according to our measurement. The average transmission time of a wake-up message without a preamble frame is $T_{N,\mathrm{NoPre}} = 3.6$ ms according to Fig. 8, and $T_{N,\mathrm{WithPre}} = 5.2$ ms when a preamble frame is used. The error floor of *FNP* without or with a preamble frame is equal to

TABLE IV
PARAMETERS AND TOTAL POWER CONSUMPTION OF A NODE AND AN AP

	No Preamble	With Preamble
Node power consumption	$0.9\text{watt}\cdot 3.6\cdot 10^{-3}\text{s}$	$0.9\text{watt}\cdot 5.2\cdot 10^{-3}\text{s}$
Error floor of *FNP*	$5.9\cdot 10^{-4}$	$1.45\cdot 10^{-7}$
AP power waste	10watt·20s	10watt·20s
Average *FPP*	$1.7\cdot 10^{-3}$	$9.8\cdot 10^{-31}$
Total power consumption	0.34watt	$4.7\cdot 10^{-3}$watt

TABLE V
TOTAL POWER CONSUMPTION OF AN AP UNDER THE WAKE-UP CONTROL

	$O_{AP}=0.5$	$O_{AP}=0.3$	$O_{AP}=0.1$
No Preamble	5.18watt	3.25watt	1.32watt
With Preamble	5.01watt	3.01watt	1.01watt

$FNP_{\text{NoPre}}=5.9\cdot 10^{-4}$ and $FNP_{\text{WithPre}}=1.45\cdot 10^{-7}$, respectively. *FPP* in Fig. 10 changes with wake-up messages, and the average is $FPP_{\text{NoPre}}=1.7\cdot 10^{-3}$ without a preamble frame and $FPP_{\text{WithPre}}=9.8\cdot 10^{-31}$ with a preamble frame.

When wake-up messages are sent once per second, the total power consumed by a node (transmissions and retransmissions) and an AP (false wake-up only, power consumption due to the AP on duty and its WuRx is neglected) is computed as

$$P_{\text{Total},m}=\frac{P_N\cdot T_{N,m}+P_{\text{AP}}\cdot T_{\text{AP}}\cdot FPP_m}{1-FNP_m}$$
$$m=\text{NoPre},\text{WithPre}. \tag{15}$$

All the parameters and total power consumption are summarized in Table IV. The power consumed with a preamble frame is much less than that without a preamble frame. A more careful look at Table IV reveals that power consumption without a preamble frame is mainly due to the false wake-up at the AP, but with a preamble frame, more power is consumed by the node in the transmission. In a scenario where a false wake-up leads to much more power waste at an AP than the power used for a transmission at a node, using a preamble frame helps to effectively lower the total power consumption.

The power consumption of an AP under wake-up control, including the power of its WuRx (waiting for wake-up request), is computed as

$$P_{\text{AP}}^{Wu}=P_{\text{AP}}\cdot O_{\text{AP}}+[P_{\text{WuRx}}+P_{\text{AP}}\cdot T_{\text{AP}}\cdot FPP_m]\cdot(1-O_{\text{AP}}) \tag{16}$$

and summarized in Table V under different duty ratios. Compared with the default power $P_{\text{AP}}=10$ W without wake-up control, using a WuRx effectively reduces the power consumption of an AP. The effect of a preamble frame is especially obvious when the duty ratio of an AP decreases.

D. Test Bed Experimental Results

We also evaluated the proposed scheme with a prototype test bed using the experiment configuration shown in Fig. 12.

Transmitter Side: The transmitter part is a note PC equipped with a WLAN card. The note PC is a ThinkPad with a Linux system. Its MadWiFi device driver for WLAN cards is modified to enable burst transmission. More specifically, 1) a small queue is created to collect all command frames of a message generated by the application program, and then, all command frames are sent to the WLAN card at once; 2) each command frame is broadcast and carries nonzero duration to set NAV at nearby nodes to protect subsequent command frames; and 3) the backoff between successive transmissions of command frames is disabled so that IFS is fixed. Wake-up messages are transmitted using either the fixed or optimized modulation constellations of frame lengths.

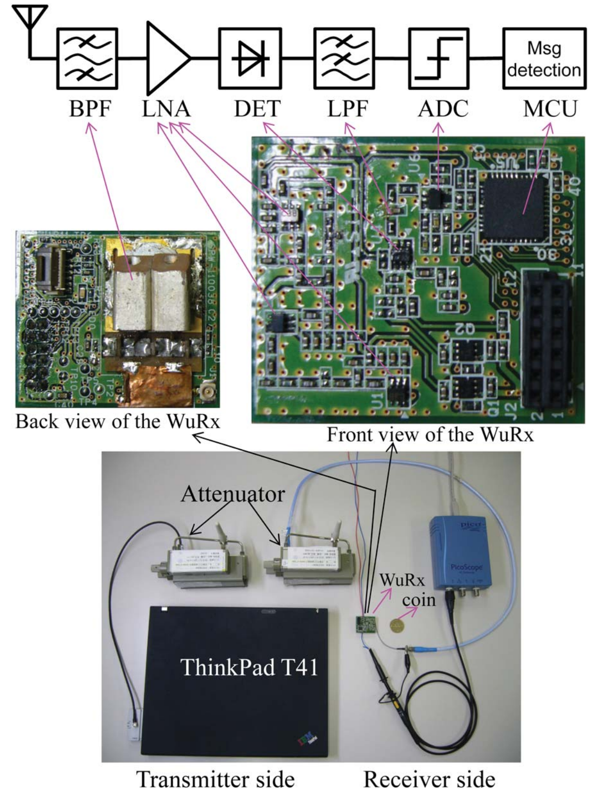

Fig. 12. Test bed experiment configuration.

Receiver Side: At the receiver part, a signal passes an attenuator and is detected by a WuRx. The WuRx performs bandpass filtering (BPF), low noise amplification (LNA), envelope detection (DET), and low-pass filtering (LPF). Its size is comparable to a coin, as shown in the experiment setup at the bottom of Fig. 12. Its structure is shown at the top of Fig. 12, and interested readers may refer to [13] for more details. In our experiment, the signal envelope after LPF is sampled by a software oscilloscope so that each signal can be decoded by different schemes.

Background WLAN Traffic: Six note PCs, colocated with the node transmitting wake-up messages, are used to transmit background frames. Each PC simulates one of the six trace files of WLAN frame lengths released by CRAWDAD [18]. These traces were recorded in different environments, e.g., a cafe room and a library. Frame lengths are accurately generated by adjusting packet sizes and transmission rates. Packet arrival intervals are a best effort approximation because of the limitation in the response of the Linux OS. Altogether, the channel busy ratio is about 25% due to these background frames.

In the experiment, the WuRx is set in a room. Six PCs generating background WLAN traffic and the node transmitting

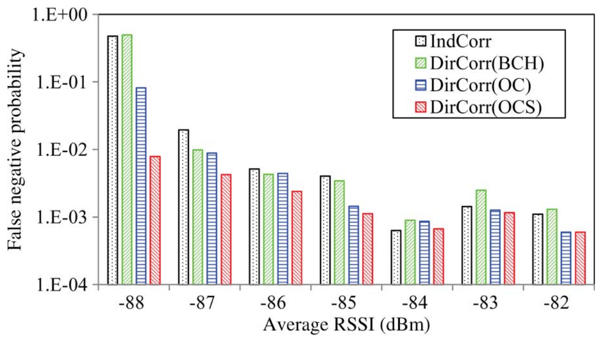

Fig. 13. FNP in a test bed experiment.

wake-up messages are placed in the corridor outside the room. There is no line-of-sight path between the transmitter and the WuRx.

FNP results under different received signal strength indicators (RSSIs) are shown in Fig. 13. *FNP* is computed as the ratio of the number of erroneous messages to the totally transmitted 30 000 messages. Because there is no line-of-sight path, average RSSI is estimated from signal strength. Hidden terminal problem may also occur. The burst transmission of command frames of a wake-up message will fail when signals from hidden terminals cause an IFS, expected to be idle by setting NAV, to become busy. Therefore, the experimental results are not as perfect as the theoretical analysis. However, these results confirm that under most cases, particularly at the low RSSI range, *DirCorr(OCS)* achieves a much lower *FNP* than other schemes.

V. Conclusion

We have suggested using frame lengths of WLAN signals to convey wake-up messages from WLAN transmitters to low-cost WuRx for the wake-up control of APs. The proposed scheme improves system reliability in two ways: 1) increasing the Hamming distance between wake-up messages and 2) reducing false events by using a preamble frame and applying envelope smoothing. As for the former, nonuniform optimal modulation constellations of frame lengths are found, and theoretical analysis results are given for the latter. Simulation results of *FNP* match theoretical analysis relatively well, and the analysis of power consumption on the basis of *FPP* and *FNP* is promising. The effect and feasibility of the proposed scheme are also evaluated by a prototype test bed. The proposed scheme helps reduce the power consumption of WLAN APs and can be applied for other remote control as well.

Appendix A
Analysis of False Negative Probability at Low Signal-to-Noise Ratio

Consider an equivalent message j with a length Q_j and a minimal Hamming distance d_j^i with other equivalent messages, where i is the name of a detection scheme. In the analysis, an IFS corresponds to $\sigma = 5$ "0's." Altogether, $N' = N + 1$ frame lengths (one preamble frame and N command frames with $Q'_j = Q_j + \sigma + l_{\text{pre}}$ bits) in *DirCorr(OCS)* and N frame lengths in other schemes will be detected.

FNP_{SNR} of IndCorr: IndCorr relies on direct detection of frame lengths, and command frames are separated by IFSs under burst transmission. The envelope smoothing scheme is also applied to *IndCorr* in order to make a practical comparison. In this implementation, $k \le \sigma$ consecutive "0's" are regarded as an IFS. There are two cases of frame synchronization errors in *IndCorr*. 1) Division of a command frame to multiple ones. Due to fading in envelopes of command frames, some envelope samples inside a command frame may be decided to be "0's." When a burst of k or more consecutive bit errors occur in the envelope of a command frame, the frame is divided into two and the number of detected frames is increased. 2) Merging of adjacent frames. When the number of consecutive "0's" in an IFS period is less than k, two frames are merged as one and the number of detected frames is decreased. The probability of case 1) is described by (17) and that of case 2) is expressed by (18), both as a function of k, where $p_{0|1}$ and $p_{1|0}$ are the error rates of detecting "1" and "0," respectively. Equation (18) can be explained as follows: one of the $N - 1$ IFSs (with $\sigma = 5$ bits) cannot be correctly detected if a) all 5 "0" are detected as "1" when $k = 1$; b) two bit errors cause the error pattern "01010" when $k = 2$; and c) one bit error causes the error pattern "00100" when $k = 3, 4$

$$P_{j,\text{SyncErr}}^{\text{IndCorr}}(1 \to 0) = O\left(Q_j \cdot p_{0|1}^k\right) \tag{17}$$

$$P_{j,\text{SyncErr}}^{\text{IndCorr}}(0 \to 1) = \begin{cases} O\left(N \cdot p_{1|0}^5\right), & k = 1 \\ O\left(N \cdot p_{1|0}^2\right), & k = 2 \\ O(N \cdot p_{1|0}), & k = 3, 4. \end{cases} \tag{18}$$

By minimizing $P_{j,\text{SyncErr}}^{\text{IndCorr}}(1 \to 0) + P_{j,\text{SyncErr}}^{\text{IndCorr}}(0 \to 1)$, a tradeoff can be made between the two synchronization errors and the optimal k is found to be 2. When $p_{0|1} \approx p_{1|0} \approx p$, the order of synchronization error probability is $O(p^2)$.

Without synchronization errors, a false negative event occurs in *IndCorr* when there are more than K_j^{BCH} bit errors in the detected message, where $d_j^{\text{BCH}} = 7$ and $K_j^{\text{BCH}} = \lfloor (d_j^{\text{BCH}} - 1)/2 \rfloor = 3$ are the same for all BCH(31, 16) codewords. It is approximate that out of the $2N$ frame edges, more than K_j^{BCH} are erroneous, each with 1-bit error. This is a binomial distribution $\mathcal{B}(2N, p)$ [22] with $p = p_{0|1} + p_{1|0}$. The error probability is

$$P_{j,\text{Sync}}^{\text{IndCorr}}\left(d > K_j^{\text{BCH}}\right) \approx \sum_{n=K_j^{\text{BCH}}+1}^{2N} f(n; 2N, p)$$

$$f(n; N, p) = C_N^n p^n (1-p)^{N-n} \tag{19}$$

by using the binomial distribution function f, and its order is $O(p^4)$. *FNP* of *IndCorr* is the sum of probabilities in ((17)–(19)) and is dominated by synchronization errors.

FNP_{SNR} of DirCorr(BCH) and DirCorr(OC): The analysis of *FNP* under direct correction of equivalent messages is similar for *DirCorr(BCH)* and *DirCorr(OC)*. An equivalent message j cannot be correctly received if out of the Q_j bits more than K_j (decided by the minimal Hamming distance) bits are erroneous. Among the $n > K_j$ bit errors, n_1 are "0" → "1"

in $N-1$ IFSs, and the other n_2 are "1" $\rightarrow$ "0" in the envelope of command frames. Accordingly, the *FNP* is computed as

$$FNP_j^{\mathrm{DirCorr}}(Q_j, K_j) = \sum_{n=K_j+1}^{Q_j} \sum_{n_1+n_2=n} f\left(n_1; \sigma(N-1), p_{1|0}\right) \cdot f\left(n_2; Q_j - \sigma(N-1), p_{0|1}\right). \quad (20)$$

Here, K_j depends on each message. The minimum of K_j is equal to $K_j^{\mathrm{BCH}} = 3$ in the *DirCorr(BCH)* scheme (with a minimal Hamming distance 7) and $K_j^{\mathrm{OC}} = 4$ in the *DirCorr(OC)* scheme (with a minimal Hamming distance 10).

FNP_{SNR} *of DirCorr(OCS):* Out of the Q'_j bits in an equivalent message, the number of more than K_j^{OC} erroneous bits can be reduced to be no more than K_j^{OC} by envelope smoothing and lead to a correct reception. The $n > K_j^{\mathrm{OC}}$ erroneous bits consist of two parts: n_1 in N IFSs and n_2 in the envelope of command frames. Some of the n_2 bit errors in command frames can be removed by envelope smoothing, and there are two main cases. 1) Each of n_2 erroneous bit "0's" in the frame envelopes is separately located in one of $Q'_j - \sigma N - n_2 - 1$ spaces between $Q'_j - \sigma N - n_2$ correct "1's," with $C_{Q'_j - \sigma N - n_2 - 1}^{n_2}$ possible patterns. In this case, each erroneous "0" is surrounded by "1's." For the simplicity of analysis, we assume that all these error patterns can be removed, i.e., the number of erroneous bits remaining in command frames is $n'_2 = 0$ after envelope smoothing. 2) Except an erroneous block with a length $n'_2 \geq 2$, the other $n_2 - n'_2$ erroneous bits are isolated and removed by envelope smoothing. These $n_2 - n'_2 + 1$ groups of erroneous "0's" have $n_2 - n'_2 + 1$ possible relative positions, and each can be further located in one of $Q'_j - \sigma N - n_2 - 1$ spaces between $Q'_j - \sigma N - n_2$ correct "1's," altogether $(n_2 - n'_2 + 1) \cdot C_{Q'_j - \sigma N - n_2 - 1}^{n_2 - n'_2 + 1}$ possible patterns. In these scenarios, a wake-up message is still correctly detected with a probability

$$P_{j,\mathrm{Smooth}}^{\mathrm{DirCorr(OCS)}} \approx \sum_{n=K_j^{\mathrm{OC}}+1}^{Q'_j} \sum_{\substack{n_1+n_2=n \\ n_1+n'_2 \leq K_j^{\mathrm{OC}}}} f(n_1; \sigma N, p_{1|0}) \cdot \sum_{n'_2} R\left(n'_2\right) p_{0|1}^{n_2} (1-p_{0|1})^{Q'_j - \sigma N - n_2}$$

$$\begin{cases} R\left(n'_2\right) = C_{Q'_j - \sigma N - n_2 - 1}^{n_2}, & n'_2 = 0 \\ R\left(n'_2\right) = (n_2 - n'_2 + 1) \cdot C_{Q'_j - \sigma N - n_2 - 1}^{n_2 - n'_2 + 1}, & n'_2 \geq 2 \end{cases} \quad (21)$$

if the number of erroneous bits after envelope smoothing, i.e., $n_1 + n'_2$, is no more than K_j^{OC}. For an equivalent message j, its *FNP* by *DirCorr(OCS)* is the difference between $FNP_j^{\mathrm{DirCorr(OC)}}(Q'_j, K_j^{\mathrm{OC}})$ and $P_{j,\mathrm{Smooth}}^{\mathrm{DirCorr(OCS)}}$. Because some occasional erroneous patterns cannot be removed by simple envelope smoothing, this analysis roughly determines a lower bound of *FNP* of *DirCorr(OCS)*.

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