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SmartWAZ: Design and Implementation of a Smart WiFi Access System Assisted by Zigbee

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ABSTRACT Recently, WiFi networks have witnessed an unprecedented deployment, and WiFi APs are ubiquitous around the world. On one hand, the WiFi clients have to actively discover new WiFi access points (APs), and try to access to them, even though most of the APs are privately owned, which wastes the precious energy of mobile devices due to excessive listening and scanning operations of WiFi network interface cards. On the other hand, many wireless technologies coexist in overlapping channels (e.g., 2.4 GHz ISM bands). It provides a new opportunity of cross-technology communication (CTC) that utilizes these overlapping frequencies to share information among different technologies. This paper deeply investigates the application of wireless CTC into smart and energy-effective WiFi access with the assistance of low-power radio. Specifically, we design a smart WiFi access system assisted by Zigbee, SmartWAZ, for mobile terminals with both WiFi and Zigbee interfaces. The most prominent feature of this system is that the different WiFi beacon periods are intentionally used to distinguish publicly accessible and privately owned WiFi APs. Then, the folding algorithm is applied by the Zigbee module in clients to detect the specific WiFi beacon period used by public APs, and then the WiFi interface will be waked only when a public WiFi AP is detected. From the system design viewpoint, we investigate the influence of the beacon period of the sender (i.e., WiFi AP) and the judgment threshold of the mobile client on a false positive and false negative, and provide the basic rule to appropriately set those system parameters. Compared to the traditional WiFi access methods, the SmartWAZ significantly saves the energy consumption of continuous WiFi scanning; compared to other low-power radio assisted WiFi access systems, SmartWAZ avoids waking WiFi interface when private WiFi APs appear. The experiment results show that the SmartWAZ averagely consumes only 36% of the energy of traditional WiFi access schemes and achieves reliable detection with an error rate of less than 1%.

INDEX TERMS Smart WiFi access, Zigbee, cross-technology communication.

I. INTRODUCTION

A. RESEARCH BACKGROUND

Under the emerging paradigm of Internet of Things (IoT), we have witnessed the explosive growth of wireless technologies in diversity (e.g., WiFi, Zigbee, and Bluetooth, etc.) as well as in density, to enrich different domains of our daily lives. For example, it is expected to see 20 billion Internet-connected things by 2020 [1].

With the rapid deployment of IoT applications, many wireless technologies coexist in overlapping channels (e.g., 2.4GHz ISM band, Industrial Scientific Medical band). The impact of this wireless coexistence has two opposite aspects. On one hand, it causes cross-technology interference (CTI) and inefficiency in spectrum utilization, due to incompatible PHY/MAC standards, which becomes one of the fundamental causes of network performance degradation [2]–[6]. On the other hand, it provides new opportunities: cross-technology communication utilizes these overlapping frequencies to share information among different technologies. To this end, researchers have recently proposed cross technology communication (CTC) technique which enables direct connection between heterogeneities, and is regarded as one of key techniques to explore the full capacity of heterogeneous wireless technologies.

Basically, existing CTC schemes can be categorized into the packet-level CTC and the PHY-layer CTC [7]. The packet-level CTC uses the information of packet level

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information, like the packet duration, beacon interval, data traffic pattern, and energy amplitude, etc. to convey messages across technologies. While, the key idea in PHY-layer CTC is to emulate signal by manipulating the payload of a packet, and makes a wireless transmitter (e.g., WiFi or Bluetooth, etc.) generate a receiver (e.g., Zigbee, etc.) compliant packet.

Both categories have their disadvantage. Due to the coarse-grained packet-level information, packet-level CTC throughputs are restricted to a few tens of bps; PHY-layer CTCs are commonly transmitter-side techniques requiring a high-end transmitter (with a high degree of freedom in signal manipulation) to emulate the receiver signal closely. (e.g., from WiFi to Zigbee). To fill in the gap, [7] presents XBee, a receiver-side CTC, where the key innovation lies in the unique mechanism of cross-technology decoding that interprets a Zigbee frame by carefully observing the bit patterns obtained at the BLE receiver. FreeBee belongs to the category of packet-level CTC scheme [8], which modulates symbol messages by shifting the timings of periodic beacon frames already mandatory for diverse wireless standards.

Enabling direct communication between wireless technologies immediately brings significant benefits including, but not limited to, cross-technology interference mitigation and context-aware smart operation.

Reference [9] presents ECC (explicit channel coordination technique) that uniquely enables explicit channel coordination among heterogeneities via CTC. This ECC via message exchange among heterogeneities provides the potential to fundamentally resolve CTI and bring performance breakthrough in spectrum sharing.

CTC not only alleviates the issue of interference, but also serves as a fundamental building block for collaborative applications via cross-technology cooperation, because the standards for individual technologies are specialized and hence possess strengths in different areas that are, often the weaknesses of the others. For instance, two such networks, WiFi (IEEE 802.11 WLAN) and Zigbee (IEEE 802.15.4 WPAN), that operate in the 2.4 GHz license-exempt band have received considerable attention. WiFi is designed for Internet access, video streaming, etc., whereas Zigbee targets low duty-cycle monitoring and control applications such as healthcare and home/industrial automation. They are expected to run simultaneously in close proximity.

While WiFi has access to a virtually unlimited amount of information via the Internet, it consumes a considerable amount of power, and causes battery problems in mobile devices. Conversely, the Zigbee network often operates as a standalone and has limited information, but is extremely energy efficient. Thus, both networks can be enhanced via mutual supplementation, demonstrating the positive side of coexistence [10]. For example, CTC brings cost-efficient smart home by enabling WiFi-equipped devices (e.g., smart phones) to directly interact with Zigbee-embedded smart appliances.

B. RESEARCH MOTIVATION AND CONTRIBUTION

Recently, WiFi networks have witnessed an unprecedented deployment, and WiFi APs are ubiquitous around the world. WiFi-enabled devices (e.g., laptops, PDAs, and smartphones, etc.) must actively discover new WiFi access points (APs) once they leave the coverage of current network. However, this approach wastes the precious energy of mobile devices due to excessive listening and scanning operations of WiFi network interface cards (NICs). A system called ZiFi is developed by [11], which utilized Zigbee radios to identify the existence of WiFi networks through inferring the signatures generated by WiFi beacons, and only waked up WiFi NIC on mobile terminals once the WiFi AP was detected. But, the weakpoint lies in that: commonly, WiFi APs are densely deployed, and worse, most of APs are privately owned (i.e., they can't be publicly accessible). Therefore, in the case of private AP, waking up NIC and scanning operations are meaningless, and just waste mobile terminals' power.

Targeting at the issue above, we design and implement SmartWAZ, a smart WiFi access system assisted by Zigbee, for mobile terminals with both WiFi and Zigbee interfaces. The most prominent feature of this system is that, different WiFi beacon periods are used to distinguish public and private WiFi APs. A mobile device uses its Zigbee radio to detect the existence of WiFi APs with the designated beacon period (corresponding to the publicly accessible APs) in a purely passive manner, and then WiFi NICs on mobile terminals are waked up, only when public APs are available.

Specifically, we deeply investigate the influence of system parameters on the detection accuracy (i.e., false negation and false positive), including the beacon period of the sender (i.e., WiFi AP) and the judgment threshold of the mobile client, and provide the basic rule to appropriately set those parameters.

SmartWAZ can work for two different scenarios: mobile terminals have both built-in Zigbee and WiFi interfaces, and these devices can connect a WiFi node with an external Zigbee node. The advantages of SmartWAZ are twofold. First, from the viewpoint of system deployment, SmartWAZ is easy-to-deploy and cost-effective: save the expense for a dedicated controller or a costly gateway hardware (it is also the main reason why SmartWAZ adopts the simple packet-level CTC technique); from the viewpoint of mobile clients, it can work on off-the-shelf commodity mobile devices without any customized hardware and software, and greatly save the power of mobile terminals.

The rest of the paper is organized as follows. Section 2 briefly reviews the existing work of smart CTC applications (especially for smart WiFi access) and discusses the shortcomings of these schemes. In Section 3, we describe the SmartWAZ system framework, and investigate how to appropriately determine the fundamental system parameters in SmartWAZ. Section 4 verifies the SmartWAZ performance through real system implementation and deployment. Finally, we briefly summarize our work.

II. RELATED WORKS

There exist much overlapping between IEEE 802.11 (i.e., WiFi) and IEEE 802.15.4 (i.e., Zigbee) channels: in particular, only 4 among total 16 channels of 802.15.4 are orthogonal with the channels of 802.11. Moreover, most commercially available 802.15.4 radios have programmable channel center frequencies within the 2.4 GHz band, and a received signal strength indication (RSSI) register is typically provided by commodity 802.15.4 radios. Thus, it is feasible for 802.15.4 radios to sense the existence of 802.11 transmissions.

Esense was designed by [12] to allow Zigbee and WiFi radios to communicate with each other through sensing and interpreting energy profiles. Specifically, Esense embedded the WiFi to Zigbee CTC message within multiple dedicated WiFi packets via specific packet durations. The packet duration can be distinguished from background noises at the receiver side. However, Esense required WiFi APs to transmit special codes not defined in 802.11 standard to communicate with the Zigbee radio on WiFi clients. HoWiES [13] extended the work of Esense [12] by using a specific coding scheme, to create a communication channel, in which an AP can convey thousands of messages to Zigbee radios.

For saving energy, recent studies have utilized a low-power secondary radio to wake up the WiFi interface only when APs are present, since a WiFi interface consumes 669.9mW when it is awake, but it drops to only 10mW once it starts to sleep. Zigbee, in contrast, requires only 75mW, even when active. Among the works in this category, ZiFi [11] suggests attaching a low-power Zigbee radio to the device (e.g., with a Zigbee SD card inserted in a smart phone) to wake up the WiFi NIC whenever it detects the existence of any WiFi AP. ZiFi completely relies on the Zigbee interface on WiFi clients to detect the existence of WiFi APs and requires no modification to WLAN infrastructure. Moreover, ZiFi detects WiFi signal by passively sensing its energy, which ensures a similar detection range as WiFi interface.

Given that most of APs nowadays are private, blindly waking up the WiFi, without knowing whether an AP is accessible or not, leads to the significant energy waste. FreeBee [14] addressed this issue by allowing APs to broadcast binary information to indicate the accessibility (e.g., 0/1 for open/private APs, respectively). The key concept of FreeBee is to modulate symbol messages by shifting the timing of periodic beacon frames already mandatory for wireless standards without incurring extra traffic. However, the operation of frequently shifting time of periodic beacon needs the dedicated hardware (e.g., universal software radio peripheral transceivers) or modifies the lower-layer driver. In other words, the current APs have to be specially customized to enable this scheme, which makes the scalability and practicability limited.

In brief, the above solutions suffer from the following issue: assume a "cooperative" setting where substantial software and/or hardware modifications to existing network infrastructures have to be made, which hinders their wide deployment. To address this issue, we design and implement a practical and easy-to-deploy Zigbee assisted smart WiFi access system, SmartWAZ. SmartWAZ simply uses different beacon periods to distinguish the privately owned APs (i.e., using the default WiFi beacon period) and publicly accessible APs (utilizing the designated WiFi beacon period different from the default), and effectively detects the designated beacon period through software based folding algorithm. Considering the fact that different beacon period can be directly and simply set on almost all off-the-shelf commercially available APs, SmartWAZ neither needs customized hardware, nor affects WiFi communications, therefore can be deployed easily and widely.

Note that that this paper focuses on the smart and effective access technology through exploiting the heterogeneous wireless radios. The efficient and convenient communication services through utilizing heterogeneous networks can be found at [15]–[17].

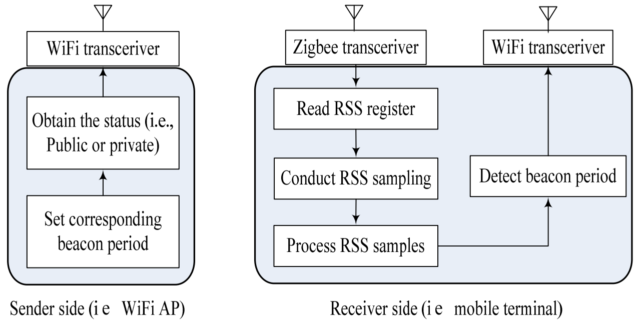

FIGURE 1. The system framework of SmartWAZ.

III. SYSTEM MODEL AND DESIGN PRINCIPLE

A. SmartWAZ SYSTEM FRAMEWORK

The principle behind packet based CTC is that wireless devices, despite of the technologies they use, are available and mandatory to sense the energy of the channel (i.e., RSSI) in order to access the channel and communicate with each other. Although devices using different technologies cannot decode each other's information due to incompatible physical layer, they are all able to identify the existence of each other through channel energy sensing. Specifically, SmartWAZ utilizes the RSS indicator available on Zigbee-compliant radio, to capture WiFi interference signatures, and detects whether the designated beacon period that corresponds to the publicly accessible WiFi APs, exists or not.

SmartWAZ senses 802.11 transmissions by sampling the RSSI register of 802.15.4 radio, and searches for periodic beacon signals in the RSSI samples. Periodic beacon broadcasting is mandatory in 802.11 infrastructure networks. The typical length of beacon frame ranges from 80 to 200 bytes depending on the amount of management information (e.g., the supported rates and security settings) it carries [11].

Fig. 1 shows the system architecture of SmartWAZ, which is explicitly composed of receiver side (i.e., mobile client), and sender side (i.e., WiFi AP). On sender side, according to

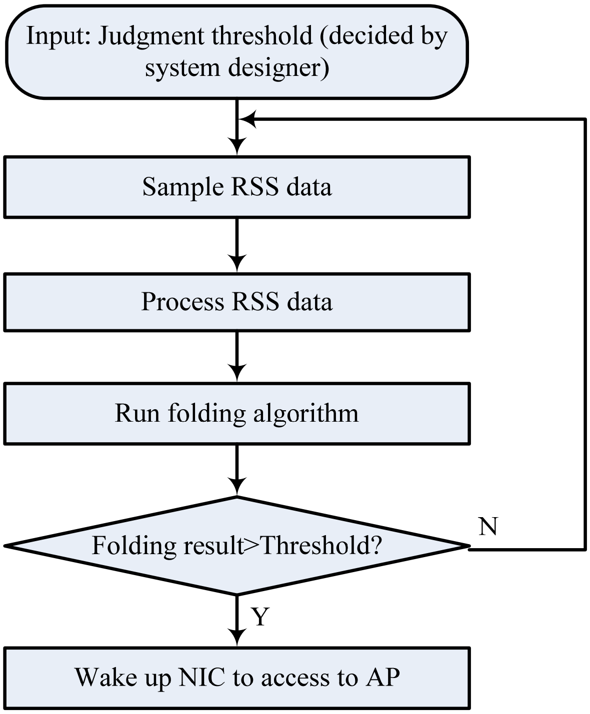

FIGURE 2. The work flowchart in receiver side.

the accessibility property (i.e., publicly accessible or privately owned), WiFi APs correspondingly set their beacon period. Considering the fact that, commonly, there exist much more private APs than public APs, to minimize the adjustment to the off-the-shelf APs, only public APs are customized to use the designated beacon period P different from the default, while the beacon period of private APs remains as default (e.g., 100ms). Properly determining the beacon period P depends on multiple conflicting factors, including (the sender's overhead, the response time of receivers, and detection accuracy, etc.), which will be deeply investigated in the following subsections.

On receiver side, similar as ZiFi [11], mobile terminals have both built-in Zigbee and WiFi interfaces, or alternatively, these devices can connect a WiFi node with an external Zigbee node. The built-in RSSI register of Zigbee radio is sampled at a specific frequency. Then, the RSS samples are shaped to mitigate the bad effect of noise and the data frames on the WiFi beacon detection. The shaped RSS samples are then used to detect whether the designated period P exists or not. Finally, if the WiFi beacon period P is detected, the radio controller turns on the WiFi NIC of the mobile terminal to access to the public WiFi AP.

In this paper, using comprehensive experiments, we investigate how to appropriately determine the key factors in SmartWAZ system, including the beacon period at the sender side and the judgment threshold at the receiver side, through experimentally measuring their positive and negative influences on the performance metrics of beacon period detection, i.e., false positive (FP) and false negative (FN).

B. DESIGN OF RECEIVER SIDE

As shown in Fig. 2, the following components are included in the receiver side: RSS sampling and processing, detection of beacon period P through folding, and properly setting the judgment threshold value according to the tradeoff of performance metrics.

① RSS sampling and processing

At receiver side, each mobile terminal samples the RSSI register of Zigbee radio every T*us* for total D*us*. T and D are respectively referred to as RSS sampling period and sampling window size. The sampling period should be short enough to capture the transmission of 802.11 beacon frames. However, a short sampling period may lead to high overhead for resource-constrained Zigbee module.

According to IEEE 802.15.4 specification [18], Zigbee samples the channel every 32 us and the value (dBm) is averaged for 8 symbols (128 us), which corresponds to the sampling frequency 7.8KHz. This frequency is enough to capture WiFi beacon frame. Thus, in SmartWAZ system, the sample period is set as 128us.

After enough RSS samples are collected, these RSS values are shaped (i.e., adjusting the power magnitude of them) to mitigate the influence of noisy data on beacon detection. Generally, by noisy data it means the non-beacon signals (including the real noise and WiFi data frame signal) and bad quality beacon signal (i.e., its RSS magnitude is too low to be used correctly). Specifically, the following steps are utilized to alleviate the impact of noisy data on beacon detection.

- The magnitude of an RSS sample is set to zero if it is below −82 dBm, and the magnitudes of all other remaining RSS samples are set to 1 dBm. This step will alleviate the influence of real noise and bad-quality beacon signal, for even if the sample contains this kind of beacons, a low RSS indicates poor signal quality from the AP and low probability of successful client association. Note that, the reason why the threshold −82 dBm is used, comes from the specified WiFi clear channel assessment [19].
- To alleviate the influence of WiFi data frame, the magnitude of S consecutive non-zero samples will be set to zero if $S \notin [s_1, s_2]$. The underlying reason for this processing is that a cluster of such samples can be inferred as WiFi data traffic. We now discuss how to determine s_1 and s_2 based on beacon size and 802.11 transmission rates. The 802.11 beacon frame has a typical size between 80 and 200 bytes. When possible 802.11 transmission rates are considered, the in-air time of a beacon frame is from 256 to 1720us, which leads to the RSS sample count within the range [256/T, 1720/T], where T is the RSS sampling period, set as 128us in our system. Therefore, s_1 and s_2 are approximately equal 2 and 14.

Therefore, if the number of consecutive samples lies outside this range [2], [14], then these samples are inferred as WiFi data frame, and are removed. After the above two steps, the magnitude of RSS samples is either 0 or 1 and the number of consecutive non-zero RSS samples is within [2], [14].

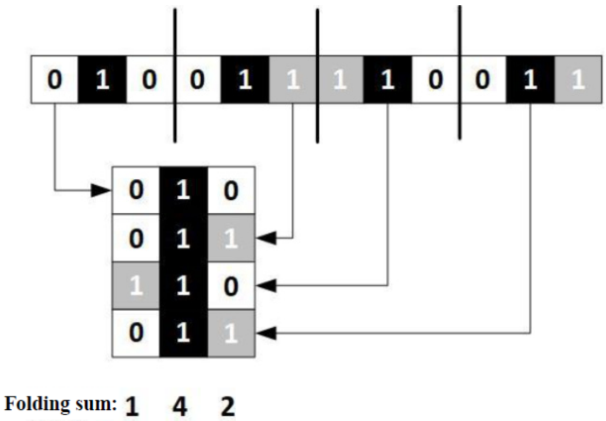

FIGURE 3. Illustration of folding process.

② Detection of beacon period P through folding

Folding was first used to search pulsar in the radio noise received by a large radio telescope [20]. Suppose R represents the time series of N RSS samples and $R(i)$, $i = 1, \ldots N$ is the RSS magnitude in the i-th sampling instance. The objective of folding is to search for a periodic signal with period of P. The series is first divided into smaller sequences with length of P at different starting points (e.g., phases). For each folding operation, the sequences are added together in an element-wise fashion. If the phase of folding happens to align with that of the periodic signal, the magnitude of the sum will be amplified at a period of P while the sum of noise in the series is likely smaller due to their non-periodicity. The sum of folding consists of P elements of R:

$$F_{\mathrm{P}}[i] = \sum_{j=0}^{\lfloor N/P \rfloor - 1} R[i + j \cdot \mathrm{P}] \tag{1}$$

where $F_{\mathrm{P}}[i]$ represents the i-th folding result, and the maximum is referred to as the folding peak of period P. Obviously, the folding operation requires $\lfloor N/\mathrm{P} \rfloor$ number of additions.

Fig. 3 gives a pedagogic example to illustrate the folding process, in which the length of RSSI sequence is 12, and the black marks denote the beacon signals (with period 3), and other signals (non-beacon and/or noise) are represented as grey marks. The folding algorithm is run with period 3, and it is can be observed that the middle column has the maximal sum value, and equals 4 (i.e., 12/3). It implies that this RSSI sequence has signals with period 3.

Note that, in [11], the common multiple folding algorithm is designed to detect the unknown period(s) of beacons, whose value has a wide range. In our system SmartWAZ, the receivers know apriori the designated beacon period used by public APs, and only care whether this specific beacon period exists or not. Thus, we simply adopt the traditional folding algorithm to detect the designated beacon period P.

Ideally, if the maximal value of folding sum equals $\lfloor N/\mathrm{P} \rfloor$, it implies that beacon period P exists. But, considering the complicated radio environment in real applications, several factors will affect the detection accuracy, which are discussed deeply in following subsection.

③ Performance metrics: False Negative and False Positive

On one hand, due to the fact that transmission of WiFi beacon should follow the media access control protocol, e.g., carrier-sense multiple access (CSMA) to detect the absence of other traffic before transmitting on a shared transmission medium, that is, when channel is busy, some WiFi beacon transmission may be delayed/shifted, which may result in the phenomenon that strict beacon periodicity can't occur. Thus, the maximum of folding sum may be less than the expected ideal value $\lfloor N/\mathrm{P} \rfloor$. In other words, using the traditional value $\lfloor N/\mathrm{P} \rfloor$ as judgment threshold, in some cases, might make the really existed beacon period P (i.e., positive) undetected, and mistakenly judged as negative, so-called false negative (FN). Large FN ratio will significantly affect mobile terminal to use public APs, and have negative impact on user experience.

To solve the issue, SmartWAZ simple sets a damping factor $\alpha \in (0, 1)$, and using $\lfloor \alpha \cdot N/\mathrm{P} \rfloor$ as the new judgment threshold. That is, if the maximal sum of folding is not less than $\lfloor \alpha \cdot N/\mathrm{P} \rfloor$, then beacon period P is inferred as existed. Properly setting the damping factor depends on a conflicting design goal: first, lower (or higher) α value can decrease (or increase) the FN, but can increase (or decrease) the false positive (FP) judgment. FP means that the ground truth is that no beacon period P exists, but the algorithm falsely infers P existed (i.e., positive).

On the other hand, the processing on RSS samples can only deal with two simple cases: the weak noise and the length of WiFi data signals less than and larger than a specified range. Other strong noise and WiFi data signals will bring interference in the folding process, and in some worst case, may lead to the folding sum larger than the judgment threshold, while beacon signals with period P are actually absent. Then, SmartWAZ mistakenly infers the existence of beacon period P (so-called FP), and wakes up the WiFi NIC to scan and access to AP, which will waste the mobile terminal power. Even worse, to reduce the FN, we intentionally adopt the damping factor α in inferring the beacon period P, which in turn makes the FP increase.

Similar as [11], Let $f(\mathrm{P}, \alpha)$ denote the probability of detecting a false beacon signal of period P. Obviously, $f(\mathrm{P},\alpha)$ equals the probability that the folding peak is no lower than $\lfloor \alpha \cdot N/\mathrm{P} \rfloor$. Formally, $f(\mathrm{P},\alpha)$ is given as follows.

$$\begin{aligned} f(\mathrm{P},\alpha) &= Prob\left\{\max_{i\in[1,P]} F_{\mathrm{P}}[i] \geq \lfloor \alpha \cdot N/\mathrm{P} \rfloor\right\} \\ &= 1 - \prod_{i\in[1,P]} Prob\left\{F_{\mathrm{P}}[i] < \lfloor \alpha \cdot N/\mathrm{P} \rfloor\right\} \\ &= 1 - \left(Prob\left\{F_{\mathrm{P}}[i] < \lfloor \alpha \cdot N/\mathrm{P} \rfloor\right\}\right)^{\mathrm{P}} \end{aligned} \tag{2}$$

According to Eq. (1), the i-th folding result of period P, $F_{\mathrm{P}}[i]$, is the sum of $\lfloor N/\mathrm{P} \rfloor$ RSS samples. Note that each RSS sample is shaped to the value as either 1 or 0. According to the channel utilization model (that is, the channel is deemed as busy if the RSS sample has a non-zero magnitude), the probability that an RSS sample is 1 (e.g., the channel is busy) is equal to the channel utilization rate U. Therefore, the probability that $F_{\mathrm{P}}[i]$ is smaller than $\lfloor \alpha \cdot N/P \rfloor$ can be computed by the

TABLE 1. The folding peak results of 100 experiments.

# of experiments	# of Folding peak 10	# of Folding peak 9	# of Folding peak 8
100	86	13	1

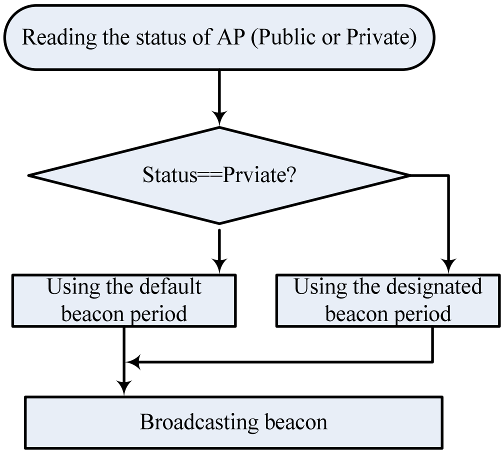

FIGURE 4. The work flowchart in receiver side.

following Eq. (3).

$$Prob\{F_P[i] < \lfloor \alpha \cdot N/\mathrm{P} \rfloor\} = \left(1 - \sum_{k=\lfloor \alpha \cdot N/\mathrm{P} \rfloor}^{\lfloor N/\mathrm{P} \rfloor} \binom{\lfloor N/\mathrm{P} \rfloor}{k} U^k (1-U)^{\lfloor N/\mathrm{P} \rfloor - k}\right)^{\mathrm{P}} \quad (3)$$

In brief, false positive FP, $f(P, \alpha)$ depends on the following parameters: the folding period P, the judgment threshold α, and the sample sequence length N.

The principle to select an appropriate threshold α is to first find out the threshold range that can guarantee a specific FN ratio, and meanwhile the maximal threshold value is chosen to make FP as small as possible. In our work, the appropriate threshold α is set through experiments. In detail, under various channel utilization ratio (i.e., the lowest is 2%, and the highest 28%), we conducted 100 experiments, in which the beacon period is set as 100ms, the sample length N is 1s, that is $N/\mathrm{P} = 10$. The experimental results are following.

Through table 1, we can observe that, when $\alpha = 1$, the FN ratio is 14%; $\alpha = 0.9$, FN ratio 1%; $\alpha = 0.8$, FN ratio zero. Moreover, we find that channel utilization ratio has little impact on FP, but relatively low threshold value will incur high FP, which complies with the theoretical analysis. To balance the performance metrics of FN and FP, in our system, the threshold value α is set as 0.9.

C. DESIGN OF SENDER SIDE

As shown in Fig.4, on sender side, depending on their status (public or private), public WiFi APs will utilize the designated beacon period P different from the default value. Actually, the beacon period is one of important parameters in SmartWAZ design. From sender side, intuitively, it will affect transmission speed and energy consumption. Intuitively, larger beacon period implies lower beacon transmission frequency, which makes the bandwidth used by beacon will decrease (in other words, the data throughput will correspondingly increase), and the energy consumption will reduce, vice versa.

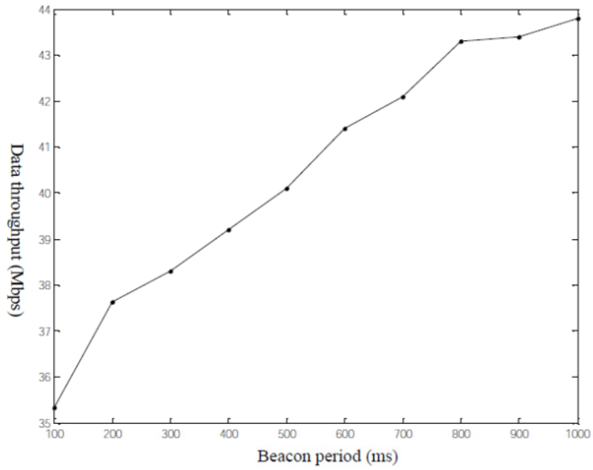

FIGURE 5. Illustration of WiFi AP data throughput varying with beacon period.

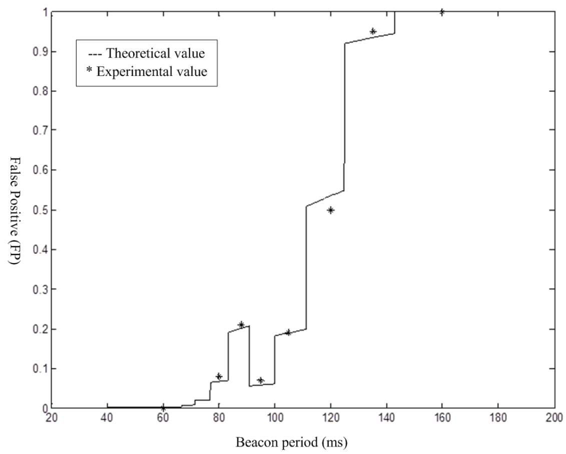

FIGURE 6. Illustration of the impact of beacon period P on FP.

Fig.5 illustrates a typical WiFi AP data throughput varying with beacon period from 100ms to 1000ms. Obviously, the larger beacon period (i.e., the lower beacon transmission frequency) will correspondingly leads to larger WiFi data throughput. Thus, just from the viewpoint of sender side, the larger designated beacon period P brings less negative impact on data throughput. However, from the receiver side, the WiFi beacon period will affect the detection accuracy, i.e., FP and FN. Then, we experimentally examine the impact of beacon period P on the FP and FN.

First, our experiments vary the beacon period P to illustrate its impact on FN. The result shows that FN is little affected by beacon period P.

Fig.6 illustrates the impact of beacon period P on FP under the scenario $U = 28\%$, $\alpha = 0.9$, N = 1s, P = 100ms, in which the solid line is the theoretical value obtained through Eqs (1) and (3), and the star represents the

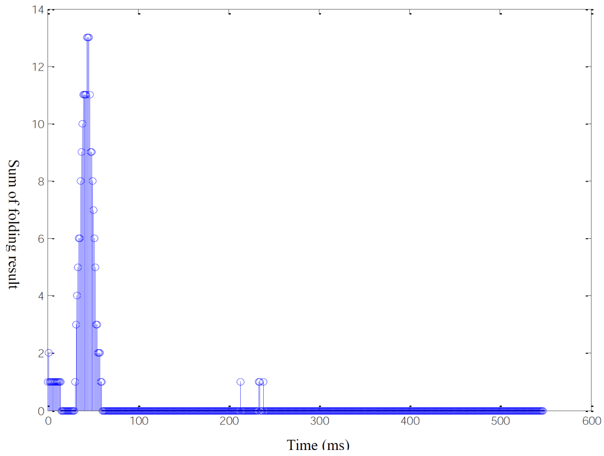

FIGURE 7. Illustration of folding sum (U = 0.03).

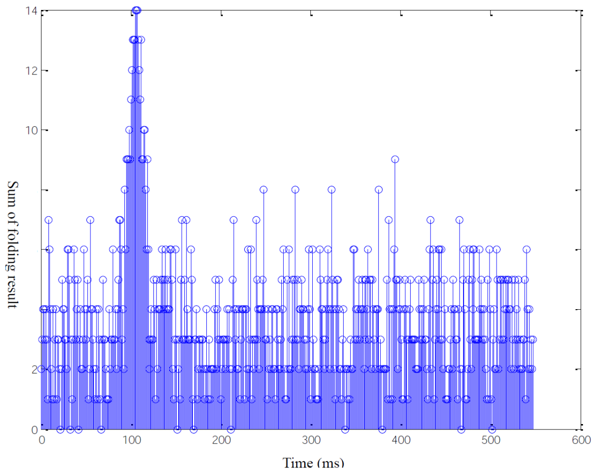

FIGURE 8. Illustration of folding sum (U = 0.26).

experimental values. Note that the larger channel utilization rate is, the larger FP becomes, thus, we set the experimentally maximal U, 28%.

First of all, the experimental result complies with the theoretical analysis. Secondly, we can observe that FP generally becomes larger with the increasing of beacon period P. Specifically, when the beacon period P is less than 72ms, the FP ratio is less than 1%. In that case, SmartWAZ can achieve reliable detection; when P is larger than 140ms, FP ratio approximates to 100%.

In brief, on sender side, data throughput becomes larger with the increasing of beacon period; on the received side, the FP increases quickly with the increasing of beacon period, especially when P is larger than 90ms. To guarantee FP less than 1%, the beacon period P is selected as a detailed value slightly less than 72ms, that is, 70ms is selected in our SmartWAZ system.

IV. SYSTEM IMPLEMENTATION AND PERFORMANCE EVALUATION

We have deployed smartWAZ on real system, and verify its performance.

Fig.7 and Fig.8 respectively illustrate the folding results under two scenarios: low channel utilization (U = 3%) and high channel utilization (U = 26%). Other system parameters are set as the detailed values decided in the previous section: P = 70ms, α = 0.9, N = 1000ms. That is, $\lfloor N/P \rfloor = 14$, $\lfloor \alpha \cdot N/P \rfloor = 12$. As shown in Fig. 7, the folding peak is 13, and in Fig. 8, the folding peak 14, both larger than 12. The results mean that SmartWAZ can make correct detection under both low and high channel utilization scenarios.

To verify the power saving of SmartWAZ, in comparison with the traditional WiFi access technology, using the identical experimental settings in Fig. 7 and Fig. 8, we conduct 500 times the WiFi beacon period detection and access. The results are following: the number of FP is 3, the number of FN is 1, and the average power consumption of traditional WiFi access is 2.4KJ/h, and the average power consumption of SmartWAZ is only 0.86KJ/h.

V. CONCLUSION

Inspired by the wireless cross-technology communication for various context-aware applications, we design and implement, a smart WiFi access system assisted by Zigbee, for mobile terminals with both WiFi and Zigbee interfaces. SmartWAZ utilizes energy sensing through the RSSI of Zigbee radio to detect the existence of the designated WiFi beacon period P used by the publicly accessible AP. From system design viewpoint, we thoroughly investigate how to appropriately determine the main system parameters including judgment threshold and beacon period. The deployment on real WiFi AP and mobile terminals illustrate that SmartWAZ can achieve reliable detection, (i.e., FN and FP both less than 1%), and only averagely consume 36% power of traditional way.

Note that SmartWAZ can be easily extended to other platforms (e.g., some Bluetooth radios that offer the RSS sampling interface) and abundant mobile devices equipped with both low-power and high-power NICs that work in the same open radio spectrum.

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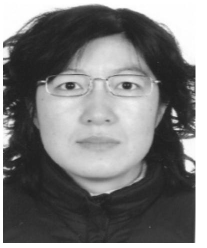

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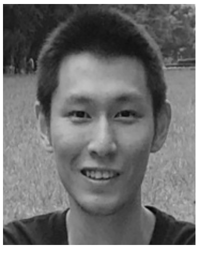

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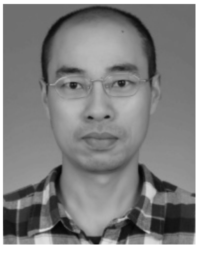

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