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Review Article

A Survey on Spectrum Utilization in Wireless Sensor Networks

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In recent years, the industrial, scientific, and medical (ISM) bands have been intensively shared with unlicensed wireless communications applications such as wireless sensor networks (WSNs). With flourishing popularity of sensor devices and increasing installation of wireless sensor nodes, the cross technology interference (CTI) has become a considerable real-world problem. Because of CTI, wireless devices suffer significant communication dilemma. Moreover, ISM band, as the main communication medium of WSN, should be reasonably utilized in an efficient and effective manner. Extensive approaches have been proposed to explore spectrum utilization in WSN. However, there is no such one, which systematically organizes these works. In this paper, we present a comprehensive survey on spectrum utilization in WSNs. To achieve this goal, We first illustrate the background of WSN and spectrum utilization. Our concern on CTI is then noted. Later we demonstrate the importance of efficient spectrum utilization. Eventually, through classification and summary of recent related works, we provide an essential structure of research in titled field and detailed intellectual merits of published works. Our survey covers more than 80 studies in the scope of spectrum utilization in WSN.

1. Introduction

The industrial, scientific, and medical (ISM) radio bands are spectral bands reserved globally for the usage of spectral resource provided to licensed industrial, scientific, and medical devices. Examples of these devices are microwave ovens and medical diathermy machines. Recently, ISM bands have been intensively shared with unlicensed wireless communications such as WSNs.

Extensive WSN applications have been proposed to utilize shared spectrum of ISM bands. These applications include health care monitoring, environmental sensing, forest fire detection, natural disaster prevention, and battlefield surveillance. To improve the performance of these applications, a great number of studies have been done to explore network protocol design, wireless link property, and energy balancing spectral utilization.

To state the shared situation of ISM bands, Figure 1 shows the channel allocation of Wi-Fi (based on IEEE 802.11) and ZigBee (based on IEEE 802.15.4) in the 2.4 GHz ISM band. We can easily note that channels of both wireless communications are overlapping in the same spectral frequency. However, the powerful radio emissions of licensed ISM devices can cause spectral interference and disturb wireless communication in the same band. More importantly, due to flourishing popularity of sensor devices and wide installation of wireless sensor nodes, the shared ISM bands have become increasingly crowded. Various unlicensed wireless devices can create considerable cross technology interference (CTI) among themselves in located spatial area; an example is shown in Figure 2. Because of CTI, wireless sensor devices suffer significant contention and collision, which introduce unfavorable communication performance, redundant energy consumption, and inefficient spectrum utilization [1, 2]. To address these concerns, it is insufficient to exploit traditional media access control (MAC) because various wireless devices have distinct physical layers, which disallow communications among them. Given consideration for currently large number and scale of wireless networks, it is barely cost-effective to modify existing network infrastructure. Therefore, to achieve friendly coexistence among different wireless devices, researchers have presented several advanced mechanisms such as cross technology sensing, spectral interference avoidance, and multiple-input and multiple-output (MIMO) based solutions. In this paper, we present a comprehensive survey on spectrum utilization in WSN. Through classification and

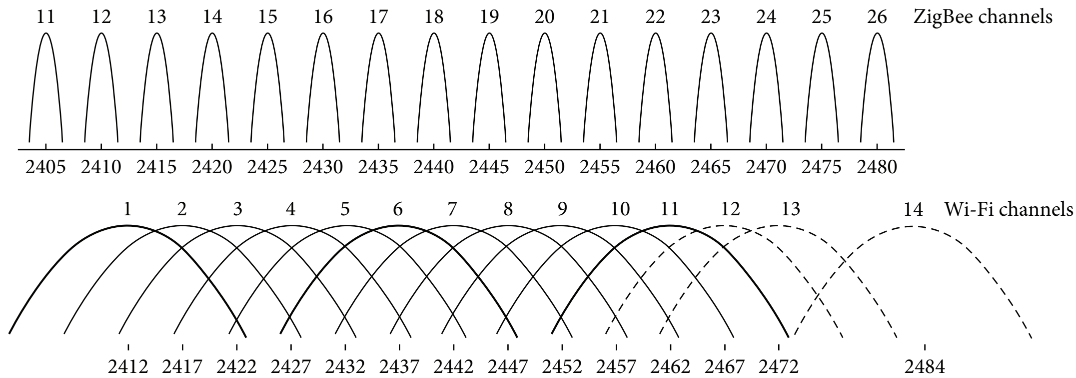

FIGURE 1: Wi-Fi and ZigBee channels in the 2.4 GHz ISM band.

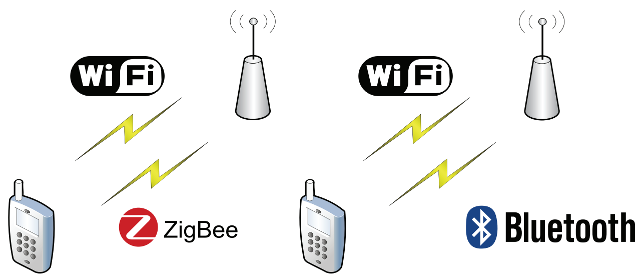

FIGURE 2: Cross technology interference.

summary of recent related works, we provide an essential structure of research in titled field and detailed intellectual merits of published works. To facilitate going through our survey, the major classification and content are presented in Table 1.

The rest of the paper is organized as follows: related studies of WSN are introduced in Section 2; works proposed for combined technology are discussed in Section 3; finally, we conclude our survey in Section 4.

2. Wireless Sensor Network

Wireless sensor network (WSN) is an abstract manifestation of distributively spatial wireless sensors, which are installed to monitor (i) environmental and physical factors, such as temperature, humidity, sound, and luminosity, (ii) personal conditions, such as blood pressure, pulse, and respiratory rate, or (iii) social events, such as traffic and human behavior in a time sensitive manner. Besides that, sensors are enabled to cooperatively transfer their gathered data through the wireless network to a premier point, which can be all kinds of information carriers and executors. Current modern WSNs are bidirectional, which means the sensor activities can also be controlled. Based on different types of monitoring targets and sensor nodes, WSN applications can be classified into several categories, such as habitat observation [3–5], military surveillance [6], road network monitoring [7], health care supervision [8, 9], house security sentry [10, 11], and wireless LAN performance monitoring [12].

With the increasingly extensive placement of wireless sensor nodes, many auxiliary applications have also been developed to provide users better management of WSN. For example, considering the widely large-scale deployment of wireless sensor nodes, the papers [13–18] present methods to perform localization for wireless sensor nodes. Also, because the accuracy of data is critical to WSNs' performance, [19] presents a novel approach to identify nodes with fault reading. On the other hand, there exist a great number of works, which facilitate improving performance of WSN application. For instances, to capture and replay sensing events, [20, 21] provide systems that improve repeatability of experimental testing of WSN. For a common time stamp recorded by wireless sensor nodes, [22] implements an on-demand synchronization method to achieve efficient time synchronization with configurable performance. The paper [23] also proposes a novel WSN time synchronization approach, which leverage beacons broadcasted by Wi-Fi APs to synchronize ZigBee nodes. To achieve target tracking for certain WSN applications like battlefield surveillance, [24, 25] provide real-time design and analysis, which can identify and classify targets in a timely manner. The paper [26] develops a middleware, which helps to accelerate neighbor finding for many existing neighbor discovery schemes in WSN.

However, massive and intense wireless communications sometimes will quickly starve limited spectral resource and reserved energy in sensor nodes and may cause seriously spectral interference, which introduces unnecessarily redundant transmissions. Therefore, in order to achieve efficient wireless communication for enhanced spectrum utilization in WSN applications, researchers have tried to pursue this goal from three major directions: (i) efficient network protocol design described in Section 2.1, (ii) in-depth exploration on wireless link property demonstrated in Section 2.2, and (iii) balanced energy development of WSN noted in Section 2.3.

2.1. Efficient Network Protocol Design for Better Spectrum Utilization. Efficient and reliable network protocol designs can greatly reduce redundant transmissions or make-up retransmissions so as to improve the spectrum utilization. In the rest of this subsection, we will discuss several advanced

Table 1: Classification of references.

WSN	Main target application	Habitat observation, military surveillance,	[3–5, 7]
		Road network monitoring, health care supervision	[8–11]
		House security sentry, wireless LAN performance monitoring	[6, 12]
	Auxiliary application	Sensor node localization, fault reading identification,	[13–16]
		Experimental repeatability improvement,	[17–20]
		On-demand synchronization	[22–25]
	Wireless network protocol	Neighbor finding acceleration	[21, 26]
		Efficient packet broadcasting, flooding and forwarding	[27–30]
		Metric based evaluation methods	[31–34]
	Wireless link property	Wireless link irregularity	[35–37]
		Wireless link asymmetry	[38–41]
		Wireless link correlation	[34, 42–44]
			[45, 46]
	Energy consumption	Adaptive transmission power control, duty cycle scheduling	[47–50]
		Sustainable sensor network, energy sharing concept	[51, 52]
CTI	Cross technology sensing	Energy packet sensing,	[53–56]
		RSS measurement	[57–60]
		CTI identification	[1, 61–63]
	Spectral interference Avoidance	Media access control	[64–67]
		White space leveraging	[68–71]
			[72, 72–74]
		Spectral band management	[75–78]
			[79]
	MIMO based techniques	Exploration on capacity of MIMO,	[80–83]
		Harmony coexistence environment implementation	[84, 85]

network protocol designs and implementations, which aim to better leverage restricted band resource by enabling meaningful spectral usage.

The paper [27] investigates the problem of broadcast radio signals overlapping, which will cause considerable redundancy, contention, and collision and then further result in costly broadcasting. Li et al. first demonstrate how serious the problem is through theoretical analysis and simulations. To reduce redundant rebroadcasts, differentiate timing of rebroadcasts, and alleviate observed problem, authors then present several schemes named probabilistic, counter-based, distance-based, location-based, and cluster-based schemes. Simulation results show that with less number of rebroadcasts and alleviated interference, the system can achieve more efficient broadcast and better spectrum utilization. As the same for broadcast retransmissions reduction, [28] explores the mechanism of multipoint relays to efficiently conduct flooding of broadcast packets in wireless networks. Multipoint relaying is a technique that limits the amount of retransmitters to a relatively small subset of neighbors instead of all neighbors in traditional flooding schemes. This technique provides a sufficient solution to cut down broadcast messages flooding in wireless communication; meanwhile, it can achieve the same purpose of delivery interested message to each node in the network with guaranteed success ratio.

To recover corrupted packets for reliable and efficient transmission, [29] presents a cluster-based forwarding (CBF) method, which is implemented as an augment layer that can be included into existing routing protocol. In CBF, sensor nodes will form a cluster so that any node within one-hop range can take forwarding task. This architecture achieves better spectrum utilization by retransmission reduction. The paper [30] presents the concept of dynamic switch-based forwarding (DSF), which aims to achieve anticipated data delivery ratio and tolerable communication delay. DSF is specifically developed for wireless network systems, which may encounter unreliable communication links and require predetermined traffic schedule. Authors also note that DSF can significantly mitigate end-to-end delay through opportunistic looping, which enables more efficient utilization of spectral resource.

2.2. Explore Wireless Link Property for Efficient Spectrum Utilization. Wireless links of sensor networks are normally considered as numerous, unreliable, and inconstant traffic. Therefore, how to measure, investigate, and exploit wireless link property are considerable challenges for achieving efficient wireless communication in shared ISM band. Several earlier studies [31–33] have proposed quantization and metric based methods to explore wireless link property in terms of various time scopes.

The paper [31] proposes a statistical method to measure temporal properties of low power wireless links in the context of modeling on multihop routing. Authors mention that related studies have analyzed the properties of low power wireless links in real-world settings. Extensive experimental results show that there are significant differences between empirically examined properties and commonly used simulation model. However, most of the proposed works have not explored in depth the temporal properties of wireless communications. Therefore, authors aim to investigate the statistical temporal properties of low power wireless links by researching on some ephemeral phenomenon discovered in low power wireless communications such as lagged correlation of reversed links and successive unchanged path links. Considering combined investigation on these phenomenon and studies of legacy end-to-end routing protocol designs, two new routing algorithms are developed to consider correlation of continuous links in multihop communication and to generate probabilistic level for the forwarding path.

To resolve the discrepancy between the expected performance of WSN applications and real performance of network protocol, [32] proposes a link metric called *competence*, which characterizes wireless links over a longer time duration. Lin et al. also combine competence with existing transient estimation methods in routing algorithm designs. To enhance the performance of wireless network, authors have further developed a route framework based on feedback control solutions in a distributed manner. Instead of investigating long-term wireless link property, [33] proposes a metric, β, to measure short period wireless link property: burstiness. Through experiments on ZigBee testbeds, authors discover that very intermediary wireless links are bursty, which means that their delivery quality fluctuates between poor and good. Authors also note that link burstiness affects protocol performance and β can predict the effects. Investigation of β allows researchers to figure out how long a protocol should pause after meeting a packet loss to reduce its transmission cost. By using β as a reference to set a single constant in normal sensor network data collecting protocols, WSNs can greatly reduce their average transmission cost.

With extensive studies having been done to explore wireless link, current researchers have named three considerable properties of wireless link of WSN. In following paragraphs, we will discuss these impactive wireless link properties in terms of *irregularity*, *asymmetry*, and *correlation*.

Wireless Link Irregularity. Wireless link irregularity is a common and significant phenomenon in WSN. It results in irregularity of radio range and variations in packet loss in different directions. A simplified example is shown in Figure 3; given the yellow star as a premier sender, we can easily discover that the radio range of sender is not a perfect circle. Although all the receivers (denoted as black rectangles) are in the same radius, there are still some receivers that cannot receive spectral frame from sender due to wireless link irregularity. The impact of wireless link irregularity on protocol performance can be investigated through a running system. Nevertheless, few researchers have actually explored this direction because of two reasons: the huge cost of performance evaluations with sensor networks keeping scaling up and the poor repeatability of radio performances' result due to uncontrolled environments. As a result, simulation based techniques are treated as effective methods to evaluate the performance of network protocols.

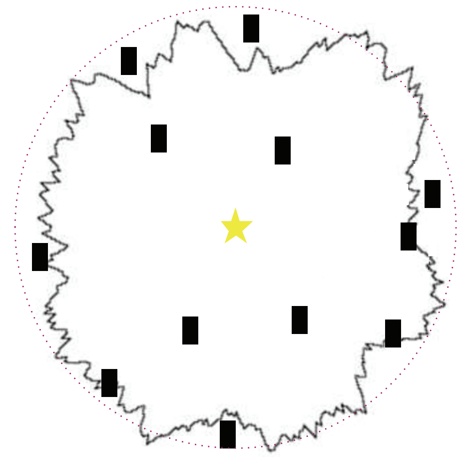

Figure 3: Wireless link irregularity.

The paper [35] verifies the existence of radio irregularity by using empirical data harvested from the Mica2 [36] platform. The results demonstrate that the patterns of wireless link are mostly random. However, it exhibits three main properties of wireless link: nonisotropic, continuous variation, and heterogeneity. Nonisotropic means that the radio signal from a transmitter suffers different path loss in various directions. The fact of continuous variation shows that the path loss keeps changing with increasing variation of the delivery direction from a transmitter. Eventually, heterogeneity denotes that differences in hardware calibration and battery status can lead to different signal sending powers, hence different received signal strengths (RSS). Further based on detailed experimental data, authors develop a radio model for simulations, called radio irregularity model (RIM). RIM considers both the nonisotropic properties of the propagation radio and the various physical characteristics of sensor devices. By leveraging the RIM, the impact of radio irregularity on some existing well-known MAC and routing protocols is analyzed. Evaluation results show that radio irregularity has a significant impact on routing protocols but a relatively small impact on MAC protocols. Eventually, six solutions are proposed to deal with radio irregularity. Hwang et al. [37] also mention that even though legacy circular sensing model has been widely used to estimate performance of WSN applications in existing analysis and simulations, this kind of model fails to provide true performance of applications due to complex properties of environment and wireless link irregularity caused by insufficient hardware calibration. Therefore, authors develop two complementary in situ sensing area modeling (SAM) techniques, P-SAM and V-SAM, which can be applied in the real-world settings. P-SAM aims to provides precise sensing area models for sensor nodes using controlled or monitored events, while V-SAM is proposed to formulate continuous sensing similarity models using natural events in an environment. With these two models, authors conduct an investigation that focuses the impact of wireless link irregularity on WSN application's performance. With systematical modeling of wireless link irregularity, we can better characterize wireless link and hence provide chance to efficiently utilize the shared spectrum.

Wireless Link Asymmetry. Wireless link asymmetry is a considerable outcome of wireless link irregularity. Due to various signal loss in different direction of sensor nodes, it is highly possible that transmitter can successfully send the packet to the receiver but not vice versa. In other words, wireless link asymmetry is one of the ways in which wireless link irregularity manifests itself at the higher layer [38]. Performance of protocols that use path-reversal techniques to establish an end-to-end communication has been seriously restricted by wireless link asymmetry.

To explore wireless link asymmetry, [39, 40] conduct extensive experiments of packet delivery performance on the widely used sensor platforms: Micaz [86] and Telos [41]. Through empirical study, Srinivasan et al. get two observations: (i) while there are many ephemeral asymmetric links, very few links are asymmetric over long period of time and (ii) these long-term asymmetric links are due to noise level differences and RSSI asymmetries. With these two observations, authors state that nodes can leverage noise level and information of RSSI asymmetry to select neighbors and trim their neighbor tables to achieve efficient routing. Authors also note that identifying wireless link asymmetry as one key characteristic of a network can help researchers understand how protocols may work in that network and it can give insights into why some protocols work differently on various networks. Eventually, authors suggest several ways in which current practices could be easily changed that would greatly improve the efficiency, performance, and lifetime of sensor networks.

Wireless Link Correlation. In early studies of flooding algorithm development, researchers have proposed many effective and reliable designs to achieve communication efficiency in WSN. However, link independence, a design premise of flooding algorithm, has restricted further performance enhancement. The reason is that the design premise requires the sender to receive costly acknowledgements (ACKs) from each receiver, and these ACKs introduce significant overhead. To achieve reliable flooding, [42] firstly exploits the link correlation to reduce large amount of ACKs by using the concept of collective ACKs. Collective ACKs allow the sender to ensure the success of a transmission to a receiver based on the ACKs from other neighbor receivers by utilizing the link correlation among them. Specifically, the authors use the conditional packet reception probability (CPRP) to quantify the correlation among links. The CPRP is the probability of a node successfully receiving a packet, given the condition that its neighbor also receives the same packet. To better denote the mechanism of collective ACKs, a simple example is shown in Figure 4. Authors use $P_s(R1 \mid R2)$ to denote the CPRP between $R1$ and $R2$. We assume $P_s(R1 \mid R2) = 100\%$,

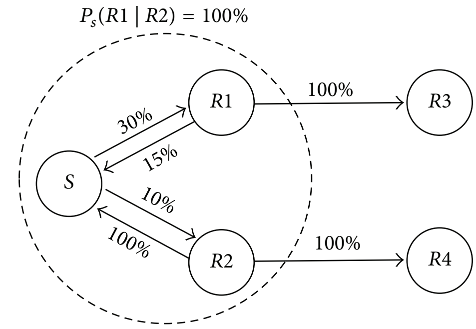

Figure 4: Example of collective ACKs.

which means that if $R2$ receives a packet from S, $R1$ would also receive that packet. In traditional flooding protocols, the sender S regards the receivers' packet receptions as independent. To achieve reliability of broadcasting, S needs to keep transmitting interested packet until it receives ACKs from both $R1$ and $R2$. Due to the low link quality from $R1$ back to S (15%), S might conduct many redundant retransmissions. However, collective ACKs allow node S to stop the transmission earlier if $R2$ receives the flooding packet with a smaller number of retransmissions than expected. For example, if $R2$ receives the packet at the first transmission and rebroadcasts, node S can immediately terminate the retransmission to $R1$, based on the assumption $P_s(R1 \mid R2) = 100\%$. Therefore, in this case, the number of transmissions at node S can be reduced to one. We can easily find out that, by utilizing the link correlation, collective ACKs can improve the efficiency of reliable flooding protocol.

There are also many other works [34, 43–46], which leverage the finding of link correlation to enhance spectrum utilization. In [43], authors present a metric, κ, which captures interlink correlation. κ can be used for characterizing the type of network that currently presents and help clients to choose protocol for the certain network. Through reasonable selection of network protocol, the performance of wireless communication is improved. The paper [44] demonstrates that spectral utilization can be improved by considering link correlation. Specifically, Guo et al. first experimentally confirm the existence of link correlation and statistically prove that the spectral usage for broadcasting can be greatly enhanced by enabling nodes with higher correlation receive packets simultaneously. An innovative flooding scheme called correlated flooding is then developed so that nodes with high correlation are grouped and then assigned to a common sender. Grouped receivers' receptions of a broadcasting packet are only acknowledged by a single ACK. This unique feature effectively mitigates the ACK implosion problem so as to save spectral occupation on both data packets and ACKs.

Moreover, existing studies assume that existence of spatial link correlation makes the measured channel status at one point reusable over a long period of time. However, through digging into the empirical data, [34] demonstrates an interesting phenomena called ephemeral link correlation, Which means that some link correlations are stable within a short time duration while greatly decrease afterwards. By exploiting the ephemeral link correlation, authors design and implement a real-time transmission scheduling system named *PreSeer*, on the railway platform for cargo delivery. *PreSeer* can intelligently schedule wireless transmission of a sink node relying on future channel status measured by sink nodes placed ahead of it on the same train. With efficient scheduling strategy of wireless transmission, the spectrum utilization is significantly improved. Besides that, [45] develops *CorLayer*, a MAC layer solution based on link correlation to achieve efficient and reliable broadcast. By applying a triangular blacklisting principle, *Corlayer* uses only one-hop neighbor information to rule out links that are poorly correlated. Incorporated with the *CorLayer*, broadcast algorithms will automatically formulate clusters for links that have relatively higher correlations, which means that a broadcaster requires fewer transmissions to ensure a packet being delivered to all of its covered receivers. The spectrum utilization is improved because of significant reduction on redundant transmissions for reliable broadcasting. Aforementioned works all measure link correlation at the link layer; correlation is solely determined by the similarity of reception success and failure patterns between links. For better capturing link correlation, [46] proposes a framework, which utilizes signal to interference plus noise ratio (SINR), a PHY layer information to accurately capture and model link correlation. Compared with conventional metric such as RSSI and link quality indicator (LQI), proposed SINR model can capture link correlation in full, enabling better utilization of the phenomenon for protocols lying on top of it.

2.3. Balance Energy Consumption and Spectrum Utilization. Currently, modern WSN systems suffer three considerable constraints, which are spectral bandwidth, preserved energy, and data throughput. These constraints restrict the overall performance of wireless communication and therefore hamper the designed purpose of WSN applications. Keeping high duty cycle of sensors nodes will surely increase the spectral utilization. However, frequent waking up from sleep mode can rapidly exhaust energy stored in sensor nodes and starve available channels of limited spectral resource. Meanwhile, whether this kind of spectral utilization is meaningful for shared ISM band still needs to be explored deeply. A lot of researches have been done to balance the energy consumption and spectrum utilization, and we will talk about these works in the following paragraphs.

Limited energy storage has always been the bottleneck of WSN application. The paper [47] presents design and implementation of an entire integrated set of protocols and application modules for energy efficient surveillance, which allows collaborative sensor nodes to detect and track the locations of mobile vehicles in an energy efficient manner. The paper [48] develops a lightweight algorithm of adaptive transmission power control (ATPC) for WSN. In ATPC, a model for all neighbors of individual sensor node is constructed to denote the relationship between link quality and transmission power. With this model, authors leverage a feedback-based transmission power control algorithm to actively control individual link quality while achieveing more energy saving with a customized capability. The paper [49] also argues that lifetime maximization is one of the most significant purposes in the development of WSN based monitoring applications. Cao et al. propose a strategy of node duty cycle scheduling to ensure a bounded-delay sensing coverage meanwhile extending WSN applications' lifetime. Their duty cycle scheduling guarantees that every target point in the monitored geographical area is supervised within some bounded detection delay. The design is then optimized for some uncommon events detection. Besides that, the proposed system enables a tunable tradeoff between sensor nodes energy consumption and events detection delay while keeping guaranteed sensing coverage for each point. The paper [50] notes that it becomes extremely difficult to design an optimal protocol, which resolves the challenge of energy constraint and can be well fit in the dynamic network topology and unpredictable traffic patterns of WSNs. Therefore, adaptive application-independent data aggregation (AIDA) is presented to implement data aggregation in a time sensitive manner. The design encapsulates data aggregation decision into a framework added between the data link layer and the network layer. Without any modifications of currently existing MAC and network layer protocols, AIDA leverages the broadcast nature of wireless communication and the queuing delay to assemble network units into an aggregation. By using a novel adaptive feedback scheme, AIDA then schedules the delivery of this aggregation to the MAC layer for future transmission.

With development of energy harvesting techniques, implementation of sustainable sensor networks (SSN) to support long-term surveillance application is turning to be feasible. In contrast to battery based sensor network, the goal of SSN is to effectively utilize ambient energy. Energy conservation becomes unpromising when a sensor network can harvest sufficient energy from outside environment since energy conservation devices are always limited in storage and are usually leakage-prone. Rather than pushing the limits of energy capacity, researchers aim at energy-synchronized designs to balance energy supplies and demands. Therefore, energy saving with reduced performance during energy adequate periods is actually wasteful and counterproductive. In other words, in SSN, wireless communication applications should try to consume as much energy as possible while maintaining their sustainability. To accomplish this design goal, a creative approach named energy synchronized communication (ESC) [51] is proposed to dynamically synchronize node activity with available energy storage, so as to improve spectrum utilization in a global sensor scope. By exploiting a staircase effect of delay during energy synchronization, ESC is also able to reduce communication delay at each node in consistent time and is implemented as a distributed middleware between the data link layer and network layer. Moreover, to build distributed energy storage that can effectively maximize the lifetime of sensor network systems, [52] presents a technique, *eShare*, that conducts energy sharing among embedded sensor devices. eShare provides a hardware design of energy storage and routing devices, related energy access, and networking protocols. With energy sharing, efficiency of energy storage devices is significantly improved and the problem of early depletion of individual energy storage devices can be avoided. By extending the lifetime of WSNs, the spectrum utilization in shared ISM band is greatly improved.

3. Combined Technology

It is a well-explored fact that the performance of WSN applications can be greatly affected by cross technology devices working on the same frequency band [61, 62, 87]. Therefore, to achieve friendly coexistence of devices with various physical layers in shared ISM band, researchers have presented a great number of works, which aim to mitigate CTI. In this section, we will firstly present an innovative concept called *cross technology sensing* in Section 3.1 and illustrate already published works, which leverage this concept. Then a widely used mechanism, spectral interference avoidance that improves spectral utilization, will be discussed in Section 3.2. Meanwhile, we will provide detailed description of the applications, which apply this mechanism. Eventually, in Section 3.3 we will demonstrate another technique named multiple-input multiple-output (MIMO), which exploits multipath propagation to mitigate CTI and enhance the spectrum utilization.

3.1. Cross Technology Sensing. Several works have explored the concept of cross technology sensing. The core idea of this concept is that communication between wireless devices, which have various physical layout and work on different standard (e.g., IEEE 802.11, IEEE 802.15.1, and IEEE 802.15.4), can be accomplished by energy packet sensing [53, 54], received signal strength (RSS) measurement [55–57], and CTI identification [58–60].

The paper [53] notes that even if devices have fundamentally distinct physical layers, they can still communicate with each other through energy packet sensing. A novel framework named *Esense* is designed to sense and interpret energy patterns on the air. Through measurement of Wi-Fi traffic traces from real-world deployments, Hwang et al. design an alphabet set, which contains series of signature packet sizes which can be later investigated in *Esense*. With analysis of harvested energy profiles, *Esense* enables communication between Wi-Fi and ZigBee devices. The paper [54] also wants to leverage the capability of energy sensing to coordinate heterogeneous devices without modifying their PHY layer modulation schemes or spectrum widths. To achieve this design goal, authors present *GSense*, which prepends legacy packets with a customized preamble that contains multiple energy pulses. The preamble leverages the quiet period between signal pulses to convey coordinate information and can be detected by neighboring nodes even when they have incompatible PHY layers.

For better facilitation of Wi-Fi access point (AP) selection and mobile localization, a system called *WiBee* [55] is presented to create real-time Wi-Fi radio maps by using ZigBee sensors node. To overcome the challenges of transmission collision and capture failure of high frequency frame and time synchronization, authors develop a gateway-assisted method to estimate Wi-Fi RSS values at each ZigBee sensor node. To map RSS values with a specific Wi-Fi AP in the actual setting, WiBee searches the pattern of ZigBee RSS samples for the target Wi-Fi AP signature pattern. To further exhibit the empirically study of constructing a radio map for indoor environments, [56] builds an experimental setup with spectrum sensors, such as USRP2 [63], WARP [88], and TelosB [41]. Given consideration of severe challenge from complex properties of indoor scenario in terms of interference and propagation, a real-time approach to measure dynamic environmental properties is further provided.

In order to achieve the purpose of spectrum radio map generation, both two previous techniques take advantage of non-Wi-Fi sensor nodes to measure the RSS value of a Wi-Fi AP. It is also feasible to conduct the measurement in a reversed way. The paper [57] develops *Airshark*, a system that discoveres non-Wi-Fi devices in real-time with only normally used Wi-Fi card. To differentiate non-Wi-Fi device instances (e.g., ZigBee, analog cordless phone, Bluetooth, Xbox, and microwave ovens), Airshark only utilizes the functionality of commodity Wi-Fi hardware to gather limited signal information (spectral samples). Because of occasionally missing spectral samples, a light-weight identification mechanism is employed to improve robustness of proposed system.

To assist the discovery of Wi-Fi AP when Wi-Fi clients leave current network coverage, existing solutions need to significantly change the infrastructures of network or to greatly depend on context information that is not cost-effective to obtain. To address these concerns, [58] presents *ZiFi*, which leverages ZigBee radios to detect the existence of Wi-Fi networks through unique interference patterns created by Wi-Fi beacons. With the help of CTI caused by such coexistence, ZiFi enables ZigBee nodes to detect the CTI signatures generated by Wi-Fi signals. Therefore, mobile devices can use the ZigBee RF to detect the existence of Wi-Fi AP in a purely receptive manner, which has shorter delay is and less overhead. The paper [59] presents *SoNic*, a CTI identification system that enables resource-limited sensor nodes to detect the source of interference they are exposed to and select an appropriate mitigation strategy. SoNic equips a classification (decision tree) method, which considers corrupted ZigBee packets, rather than using costly continuous spectrum sampling.

3.2. Spectral Interference Avoidance. A widely applied mechanism to deal with CTI is spectral interference avoidance. Extensive applications that rely on this mechanism have been developed to enable CTI reduction in terms of MAC, white space leveraging, and spectral band management. We will demonstrate these three methods and related studies in the following paragraphs.

Media Access Control. The intuitive way to avoid interference is MAC. However, the CTI is raised because of heterogeneous physical layer and power state asymmetry of devices. Cross technology devices cannot recognize each other, which means that one type of wireless device will not stop its transmission even when another type of device is occupying the shared spectrum. Therefore, to perform MAC in cross technology scenario, wireless devices need to resolve the physical limitation so that identification among different devices can be accomplished. Some works have provided methods such as CSMA based design [64] and multiheader mechanism [65].

To make WPAN devices more visible for WLAN devices or users, [64] proposes an enhanced CSMA based method called cooperative carrier signaling (CCS). CCS exploits the inherent cooperation among ZigBee nodes to harmonize their coexistence with Wi-Fi. In detail, CCS uses an extra ZigBee node to broadcast a carrier signal (called busy tone) concurrently with the on-duty ZigBee nodes. Thus by increasing Wi-Fi's awareness of ZigBee, the interference between ZigBee and Wi-Fi is mitigated.

With the experimental findings of symmetric asymmetric region interference, [65] presents *BuzzBuzz*, a MAC layer solution that enables ZigBee nodes to coexist with Wi-Fi networks. BuzzBuzz includes two mechanisms, namely, multiheaders (MH) and forward error correction (FEC) to address the problem of packet loss due to Wi-Fi interference. To ensure survival of ZiBbee nodes, which are exposed in presence of Wi-Fi interference, the MH employs redundant headers to provide ZiBee nodes more chances to identify received frames. Furthermore, combined with FEC, which corrects bit errors in ZigBee packet, the number of packet retransmissions is greatly reduced and hence improves the packet delivery ratio. Also through experimental analysis on the impact of external interference on state-of-the-art WSNs MAC protocols, [66] discovers two mechanisms, which include the use of multiple hand-shaking attempts coupled with packet trains and suitable congestion backoff schemes to better tolerate interference. Authors also embed these mechanisms within a legacy X-MAC implementation and show that they significantly improve the packet delivery rate while keeping the power consumption at an acceptable level.

Based on the premise of mutual discerning between cross technology devices, [67] proposes two coexistence mechanisms called overlap avoidance schemes, which rely on traffic scheduling techniques that reduce interference between various wireless applications operated in the shared ISM band. The first scheme is applied at the Wi-Fi end to alleviate collision that may caused by a BT traffic, and the second mechanism is used at the BT point to mitigate interference from other BT links. Apart from the usage of centralized controller, two schemes are implemented in an arbitrarily collaborative mode. With minor modification on IEEE 802.11 standard and BT specification, proposed mechanisms are capable of reducing interference between collocated and noncollocated BT and Wi-Fi devices.

White Space Leveraging. Several works [68–70] have confirmed the fact that the Wi-Fi channel is not constantly busy during Wi-Fi devices' activation. A typical trace of channel usage of the Wi-Fi is shown in Figure 5. We can easily note that the Wi-Fi traffic is highly bursty while leaving abundant white spaces between IEEE 802.11 frames. Taking advantage of unused white space can surely assist the coexistence of unlicensed wireless devices in ISM band so as to improve the ISM band utilization. However, it is extremely insufficient to rely on existing coexistence mechanisms such as CSMA to exploit the white space. There are two main reasons. Firstly, Wi-Fi transmitters cannot identify ZigBee frames and thus will not suspend their errands even when there exist ongoing ZigBee transmissions. Secondly, even if the problem mentioned above is resolved (e.g., by adopting energy-based clear channel assessment (CCA) [71, 72]), there is still a large area in which ZigBee transmitters can sense Wi-Fi transmitters but not vice versa because the transmit power of Wi-Fi is much higher than the power of ZigBee.

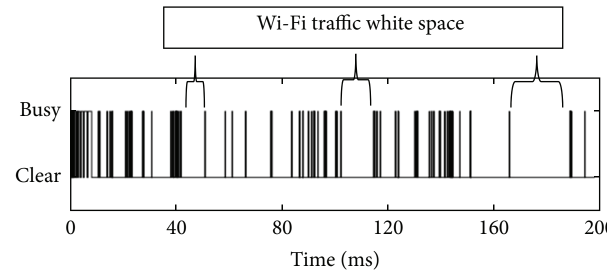

Figure 5: Wi-Fi channel state trace.

To address these two challenges, [73] proposes a novel approach that enables ZigBee links to achieve assured performance in the presence of heavy Wi-Fi interference. First, based on statistical analysis of real-world network traces, the authors present a Pareto model to precisely characterize the white space in Wi-Fi traffic. Later, by modeling the performance of ZigBee link in the presence of Wi-Fi interference, a new ZigBee frame control protocol called *WISE* is developed to achieve the desired trade-offs between link throughput and delivery ratio. Based on proposed Pareto model, WISE can predict the size of white space in ongoing Wi-Fi traffic and arbitrarily change the size of ZigBee frames to maximize link throughput while obtaining the desired packet delivery ratio.

Besides that, by exploring CCA mechanism, [74] develops a management framework, *WiCop*, which can effectively control the temporal white spaces between Wi-Fi transmissions. Specifically, the WiCop employs a fake Wi-Fi preamble-header broadcast into the physical layer to mute other Wi-Fi interferers for the duration of wireless body area networks (WBAN) devices' active interval. Meanwhile, the WiCop leverages direct sequence spread spectrum (DSSS) nulling strategy with repeated Wi-Fi physical layer preamble to silence other Wi-Fi interferers throughout the duration of WBAN devices active interval. After applying these two strategies, the Wi-Fi temporal white spaces can be utilized for delivering low duty cycle WBAN traffic and hence expand the ISM band utilization.

Spectral Band Management. Early works [75, 76] try to avoid CTI in shared wide-band (ISM) network context by transmitting narrow-band (e.g., Wi-Fi, ZigBee, and BT) devices' frames below noise level and restricting narrow-band devices in a contiguous unoccupied band. However, this approach automatically sacrifices wide-band applications' working range and performance. To address the above drawbacks, the mechanism of band management is proposed to build cross technology friendly network through band division and band aggregation [77–79]. The band division is to separate the wide shared band into subbands, and band aggregation aims to weave subbands and then later assign combined subbands to wireless devices for specific usage request.

In [77], a wireless architecture for frequency division named *virtual duplex* is proposed to conduct arbitrary division for spectral band. Virtual duplex divides spectrum resources into two subbands, which are allocated to corresponding download and upload traffic, respectively. Through separating upload and download traffic at the link layer, spectrum resource can be divided in an equal or weighted manner with an arbitrarily tunable bandwidth allocated to each channel to ensure an independent spectral resource share. Separation between upload and download link increases spectral efficiency by mitigating asymmetrical contention and provides spectral traffic scalability and robustness.

To achieve both friendly coexistence environment and unimpaired band utilization, [78] implements a split wide band interferer friendly technique (SWIFT) that ensures coexistence of narrowband devices in ISM band. When narrowband devices claim the band usage or leave the network after finishing their tasks, SWIFT will build high throughput wireless link by aggregation of noncontiguous unoccupied frequency bands. Because of less CTI and high throughput of wireless link, the ISM band is better utilized.

Moreover, [79] notes that current 802.11 physical layer design is not developed for the cosurvival of different width channels. Overlapped narrowband channel traffic may block the whole wide-band channel, resulting in seriously inefficient spectrum utilization and even starvation of WLANs on the wide-band. Given these considerations, Zhang et al. propose adaptive subcarrier nulling (ASN). ASN is built on the 802.11 orthogonal frequency-division multiplexing physical layer but enables the radios to detect, transfer, and decode packets through spectral fragments or subbands. ASN opportunistically divides the channel into subbands, separates busy subbands, aggregates clear subbands, and transmits packets using aggregated bands. Through better utilization of idle subbands, the wireless communications achieve efficient spectral usage.

3.3. MIMO Based Technique. MIMO, an emerging technique in wireless communication, takes advantage of multiple antennas at both the transmitter and receiver sides to improve spectrum utilization [80, 81]. Compared with single-input and single-output (SISO) shown in Figure 6, multiple antennas can be used to conduct smart antenna technology [82], which spreads the transmission power among several antennas to either harvest a diversity gain that improves the link reliability (against fading) or obtain an array gain that significantly improves the spectral efficiency. By exploiting multipath propagation, MIMO increases the capacity of a spectral link. As an essential component of many standards such as IEEE 802.11, long-term evolution (LTE), and 4 G, MIMO has been proverbially applied in current wireless communication industry. Before advanced technique details being discussed, [83] explores the capacity limit of multiple antenna multicast. Assume that the amount of antennas or users is increased to infinity, Jindal et al. theoretically model the capacity of the multicast channel and expected delivery rate. Authors also investigate the optimal tradeoff between subset size of users and transmission rate. In the rest of this section, we will demonstrate several advanced MIMO based applications, which aim to improve spectrum utilization in presence of serious CTI problem [84, 85].

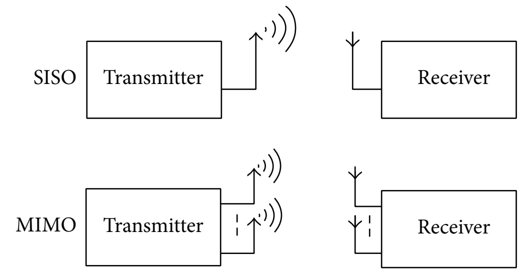

Figure 6: SISO versus MIMO.

Recent studies state that Wi-Fi interference has been a serious problem for low power wireless sensing application like WSNs. ISM band becomes increasingly crowded with various technologies, and hence many 802.11 APs may not find an interference-free channel. To handle such interference, *TIMO* [84], a MIMO based design, is developed to enable 802.11n to survive in the environment filled with high-power cross technology interference. Different from already proposed MIMO based approaches, which require all concurrent wireless traffic be from the same technology, TIMO can exploit MIMO capability to decode interested signal under interference caused by signals belonging to different technologies, therefore enabling harmony coexistence among diverse technologies sharing the same frequency band. Authors implement a prototype of TIMO in GNURadio-USRP2 [63] and demonstrate that TIMO enables 802.11n to communicate in the presence of interference from baby monitors, cordless phones, and microwave ovens and improve the situation of complete disconnecting to operational communication.

Moreover, [85] also notes that legacy methods often change the physical layer of wireless devices to achieve coexistence among cross technologies. However, it is not cost-effective to modify or replace existing infrastructure due to widely extensive installment of ZigBee nodes and uncooperative Wi-Fi users. To achieve harmony cross technology coexistence without changing original systems, [85] presents *ZIMO*, a sink-based MIMO approach to achieve coexistence of ZigBee and Wi-Fi networks while maintaining the ZigBee data packets as interested signal. ZIMO explores the challenge of protecting long period ZigBee traffic in presence of short duration Wi-Fi interference. To address such challenge, ZIMO properly exploits chances that resulted from differences between Wi-Fi and ZigBee traffic and bridges the gap between interested data and cross technology signals. Specifically, ZIMO sink acts as a sniffer that can recover the interfered Wi-Fi packets. Besides that, extracting precise channel coefficients of Wi-Fi and ZigBee will enhance other coexistence techniques such as aforementioned TIMO.

With more harmony coexistence environment and higher throughput of wireless link created by MIMO based technique, WSN applications can achieve better performance and more efficient spectrum utilization.

4. Conclusion

In this survey, we discuss the spectrum utilization in WSN. We first introduce currently crowded situation of ISM band, which WSN applications mainly work on. Then our concern on cross technology interference against performance of wireless communications application is noted. We demonstrate the importance of efficient spectrum utilization in WSN. Furthermore, through comprehensive classification and detailed description of more than 80 existing works, we provide an essential structure for current research status in the given scope. Overall, this survey (i) illustrates works that explore three major wireless link properties: irregularity, asymmetry, and correlation; (ii) covers studies in widely used wireless network systems: Wi-Fi, ZigBee, and their combined applications; and (iii) introduces two widely used techniques for efficient spectrum utilization in WSN: spectral interference avoidance and MIMO. We would like to leverage this survey to give researchers summarized insights and inner merits of these proposed studies.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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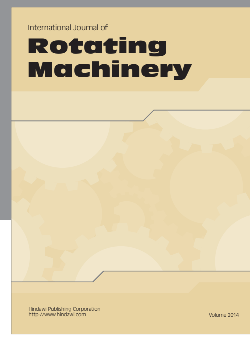
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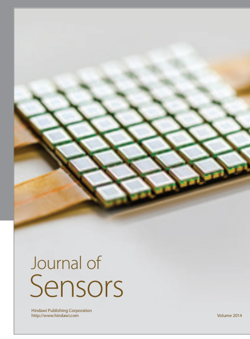
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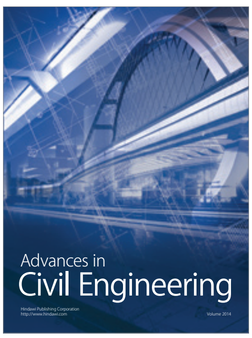
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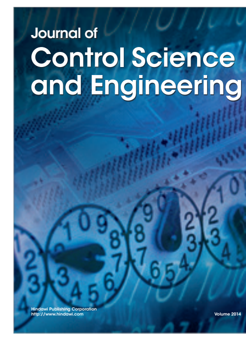
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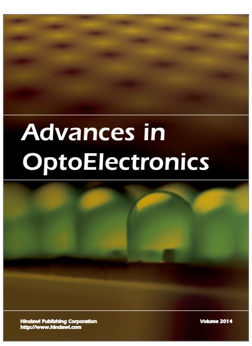
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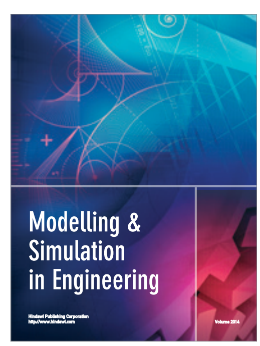
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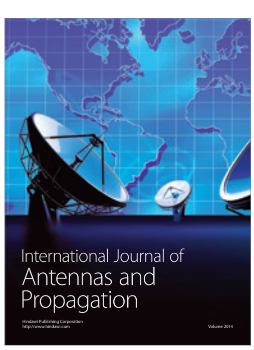
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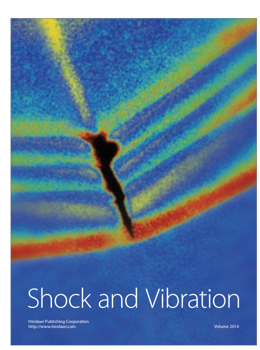
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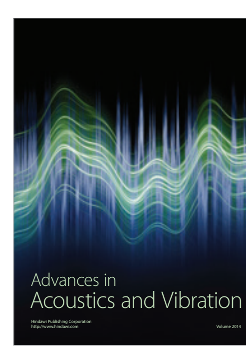
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