

Increasing the Life-time of 802.15.4-based Wireless Sensor Networks

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Abstract—This paper investigates a dynamic spectrum access (DSA) scheme for low power wireless sensor networks (WSN) in an open spectrum where multiple systems coexist and interfere with each other. Low transmission power and a simple communication protocol are significant obstacles to the operation of low power WSN in the open spectrum. As a result, available spectrum is more scarce for a low power WSN than for the other coexisting systems. To address this, we are proposing a new DSA scheme with an energy efficient channel switching criterion that can improve the expected throughput by chasing the low interference channel. OPNET-based system level simulation results, designed under the framework of ZigBee and IEEE 802.15.4, demonstrates that the proposed DSA scheme shows improved energy efficiency and throughput compared to conventional ZigBee systems.

Index Terms—Dynamic spectrum access, cognitive radio, energy efficiency, wireless sensor network

I. INTRODUCTION

ZigBee, an emerging wireless technology based on the IEEE 802.15.4 specification, has enabled the development of interoperable commercial products, an important step in meeting the scalability and low-cost requirements of wireless sensor networks (WSN) [1]. One of the main objectives of WSNs is to increase lifetime of the sensors, since the sensor node cannot utilize the external power supply, in general. Recently, low-power communication schemes have been extensively researched as an option for maximizing the lifetime of sensors by reducing active time and the use of low standby and active power [2].

Most WSNs work in an open spectrum, such as the industrial, scientific, and medical (ISM) band. The open spectrum allows a variety of license-exempt systems to be assigned for use [3]. The term ‘license-exempt’ means that anyone can

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deploy equipments without a license, as long as it conforms to Federal Communications Commission (FCC) guidelines [4]. However, if too many systems attempt to use the open spectrum, the WSNs may suffer heavy interference. Their low transmission power and simple protocol stack make low-power WSNs vulnerable to interference.

Dynamic spectrum access (DSA) represents a promising solution for avoiding interference in low-power WSNs. It allows the WSN to find the available spectrum and transmit data without harmful interference from the coexisting systems. A number of DSA schemes have been proposed for use under coexisting open spectrum models [3] [5]. In [3] [5], the coexisting systems are categorized into wide band systems and narrow band systems. The access models for these systems are analyzed using a Markov chain model [6] by assuming that each system can perfectly detect the others. However, this model does not reflect the inherent priority caused by the asymmetry of transmission power among the coexisting systems. Although each system senses the spectrum occupancy before transmission, high-power systems cannot perfectly detect low-power systems because of the sensitivity limitation of spectrum sensing [7]. Thus, a higher power system will be able to access the spectrum even though it is occupied by a lower power system, which will then cause strong interference to low power systems, such as WSNs.

To address this issue, we are proposing a new energy-efficient DSA scheme in this paper that improves WSN throughput and energy efficiency. The proposed DSA is designed to satisfy two main objectives. The first is to chase the low interference channel. In the open spectrum, wireless local area networks (WLAN) are the most dominant interferer for WSNs [8]. A WSN can suffer WLAN interference if it operates within the WLAN channel. Multiband spectrum

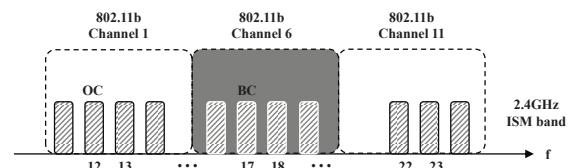


Fig. 1. ZigBee and WLAN channels in the 2.4GHz ISM band. WLANs use non-overlapping channels(i.e., channels 1, 6, 11).

sensing has a potential to provide a WSN with frequency agility, and adopting it into the ZigBee framework makes it possible to avoid interference. The second objective is to reduce the number of channel switches. A WSN can find and access a vacant channel by conducting frequent channel switching; however, this consumes a great deal of energy in changing operating channel, which can in turn reduce the lifetime of the sensors [9]. Therefore, we are also proposing a channel switching decision criterion which considers the power consumption needed for channel switching as a way to prevent wasting energy through frequent channel switching.

II. SYSTEM MODEL

We consider a ZigBee WSN with a star topology consisting of one central coordinator and multiple sensor nodes¹. When the sensors receive the beacon from the coordinator, they extract the scheduling and operating channel (OC) information from the beacon. The sensor nodes then transmit data during the contention access period (CAP) with CSMA/CA.

For the sake of simplicity, we will use a simple but expandable system model of WLAN interference. We investigate the performance of the proposed scheme in the following WLAN traffic model: inter-arrival time (T_i) as an exponential distribution ($P_{arrival}(t) = 1 - e^{-\lambda t}$), and service time (T_s) as a uniform distribution ($P_{service}(t) = \mu t/2$). The traffic model is assumed to have an arrival rate λ and a service rate μ . Based on a Markovian traffic assumption, the exponential arrival model is able to represent most wireless packet transmissions, such as WLANs [10]. Within the coexisting WLAN system, each WLAN access point is assigned to use a non-overlapping channel with a 22MHz bandwidth [8]. As shown in Fig. 1, in order to avoid co-channel interference, two simultaneously communicating WLANs in close proximity are assigned to different non-overlapping channels. WLANs are coexisting with WSN in the ISM band, and the average service and inter-arrival time information of WLAN is assumed to be known at the WSN coordinator.

III. ENERGY EFFICIENT DYNAMIC SPECTRUM ACCESS

In order to achieve frequency agility, we propose a spectrum sensing-based energy-efficient DSA scheme. The proposed

¹Although the ZigBee can support various network topologies, such as mesh, the multi-hop mesh topology is not reasonable for body area network due to energy inefficiency

DSA scheme consists of the three steps outlined below.

A. Step 1: Spectrum Sensing

Fig. 2 shows the modified frame structure of a ZigBee system with spectrum sensing. Spectrum sensing is a repetitive process which requires extra energy consumption from low battery powered sensors. This means that implementing spectrum sensing in all the nodes in a WSN may not be an efficient approach in terms of energy consumption. The answer, therefore, is to make the coordinator responsible for spectrum sensing [11]. During the sensing period τ_s , it senses the spectrum occupancy of the coexisting WLAN using the channel that overlaps with OC. The coordinator senses not only the OC but also the additional backup channel (BC) so as to watch for a state of the other WLAN channels (not overlapped with the OC). The BC is a destination of a channel switch performed as the third step of the proposed DSA. We adopt an energy detector for both OC and BC sensing. At the IEEE 802.15.4 specification, energy detection is inherently used for a scan process. The specification determines the number of samples as $M_s = 8symbols$ and the sensing threshold as $\varepsilon = receiversensitivity + 10dB$ [1].

B. Step 2: State Counter Update

Based on the sensing information obtained in the first step, the coordinator updates the OC and BC state counters. When the WSN is initially aligned, the coordinator sets state counters (cnt_{OC} , cnt_{BC}) to zero, respectively. The state counter represents the number of same sensing results (busy and idle) obtained consecutively. In other words, as shown in Fig. 2, the coordinator adds *one* for cnt_{OC} and/or cnt_{BC} if the sensing result of each channel is the same as that of the previous sensing period. Otherwise, it initializes the counters by setting cnt_{OC} and/or cnt_{BC} to *one*. Based on the state counters, the coordinator calculate the residual service time and/or inter-arrival time of each channel in terms of the number of superframes.

C. Step 3: Operating Channel Decision

In this step, the coordinator determines its *actions*, whether to *switch* the OC to a BC or *stay* in the OC by comparing the expected energy efficiency given as

$$E_{act}^{eff} = \frac{\mathbf{E}[thru]}{P_{sum}}, \quad act = \{stay, switch\}, \quad (1)$$

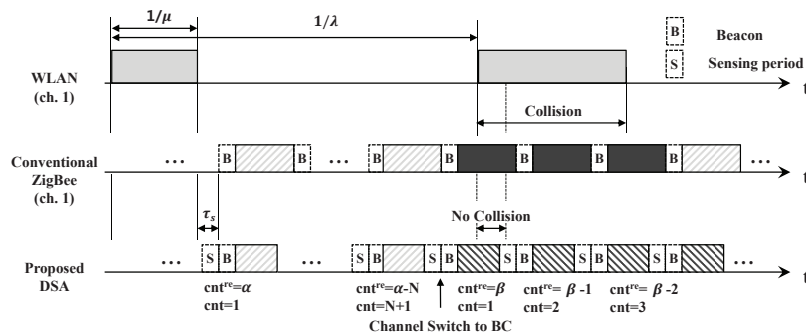


Fig. 2. Frame structure of the proposed DSA scheme and conventional ZigBee.

where $P_{sum} = P_{Tx} + P_{Rx} + P_{CS}$ denotes the sum of the transmission power P_{Tx} , the receive power P_{Rx} and the channel switching power consumption P_{CS} , i.e., the total WNS power consumption. The WSN consumes additional P_{CS} power when it switches channels, i.e., $P_{CS} = 0$ if the WSN does not change OC to a different channel. $\mathbf{E}[thru]$ represents the expected throughput after the decision to switch channels, and is expressed as

$$\begin{aligned} \mathbf{E}[thru] &= R_{Tx} \times cnt^{re}, \\ &= R_{Tx} \times \left(\frac{\mathbf{E}[T_{CH}^{state}] - T_{CS}}{T_{sup}} - cnt_{CH}^{state} \right), \quad (2) \\ CH &= \{OC, BC\}, state = \{idle, busy\}, \end{aligned}$$

where R_{Tx} is transmission rate and $\mathbf{E}[T_{CH}^{state}]$ denotes the expected time for the busy and idle period of WLANs. cnt^{re} is the residual counter, which denotes a residual service time and/or inter-arrival time of each channel in terms of the number of superframes. T_{sup} is the superframe duration and T_{CS} is the time required for the channel switching process.

The coordinator obtains information on one out of four possible states that (OC,BC) can be in: (idle, idle), (idle, busy), (busy, idle), and (busy, busy). The coordinator derives an expected energy efficiency based on the (OC, BC) state information. The proposed channel switch criterion is summarized for each possible state as follows:

- case 1** : (OC, BC) = (idle, idle)
stay if $P_R \times cnt_{OC}^{re} > cnt_{BC}^{re}$ otherwise switch,
- case 2** : (OC, BC) = (idle, busy)
switch if $cnt_{OC}^{re} < 1$ and $\frac{\mathbf{E}[T_{OC}^{busy}]}{T_{sup}} P_R > cnt_{BC}^{re}$
otherwise stay,
- case 3** : (OC, BC) = (busy, idle)
stay if $P_R \times cnt_{OC}^{re} < 0$ or $cnt_{BC}^{re} < 0$
otherwise switch,
- case 4** : (OC, BC) = (busy, busy)
stay if $P_R \times cnt_{OC}^{re} < cnt_{BC}^{re}$ otherwise switch,

where, $P_R = \frac{P_{Tx} + P_{Rx} + P_{CS}}{P_{Tx} + P_{Rx}}$ denotes the ratio of power consumption for stay to that for switch.

In case 1, the coordinator chooses a channel with a longer expected idle period so as to obtain a higher expected throughput. Note that this does not involve simply comparing the residual idle periods. Because the power consumption needed for switching channels cannot be ignored, the OC residual counter carries more weight, the amount of P_R , than BC. When the OC is idle and BC is busy, the coordinator evaluates the expected OC throughput. If the residual counter is too small to assign a superframe, the coordinator compares the average busy period of the OC with the residual busy period of the BC, then switches to the BC when the former is larger than the latter. This strategy can reduce the inactive period of the WSN by chasing the low interference channel more quickly.

In case 3, the coordinator decides to stay within the OC when the OC busy period might be finished shortly or the BC idle period is not worth for the WSN to switch channels at the

TABLE I
SIMULATION PARAMETERS

Parameter	Value
WLAN inter-arrival rate $\lambda_1, \lambda_2, \lambda_3$	1/30, 1/40, 1/60(sec)
WLAN transmission power	0(dBm)
Beacon interval T_{sup}	0.92 (sec)
Channel switch time T_{CS}	0.0072 (sec)
ZigBee Tx current	17.4 (mA)
ZigBee Rx current	18.8 (mA)
ZigBee operating voltage	2.85 (V)
Channel switch energy	0.5 (mW)
Power ratio P_R	1.0532
Sensor battery capacity	100mWh
Sensor data rate	50kbps

expense of the extra power. In case 4, the coordinator selects whichever channel might become idle sooner.

IV. SIMULATION RESULTS

This section presents simulation results obtained by evaluating the performance of the proposed DSA scheme. In our simulations, we modeled the sensor and coordinator node physical and media access control layer as defined in the specification IEEE 802.15.4-2006 on an OPNET platform [12]. We used the power consumption model of a Texas Instruments CC2430 ZigBee module [13]. We assume that a WSN consists of one coordinator and four sensors. Three WLAN devices are assumed to coexist with the WSN in the 2.4GHz ISM band. The distances between the WSN and the three different WLANs are assumed to be the same. The system parameters of the WSN and WLANs are summarized in Table I.

Fig. 3 compares the throughput of the proposed DSA scheme with a conventional ZigBee system and random frequency hopping (RFH) with spectrum sensing for varying average service times of $1/\mu$. The conventional ZigBee system randomly chooses one operating channel out of three possible channels, then stays in the channel to the end. RFH is a simplified DSA model, which changes its OC every superframe duration and transmits only if the OC is idle. As shown in Fig. 3, WSN throughput decreases as $1/\mu$ increases because this means the total number of low interference channels has become small. We can also see that the proposed scheme outperforms the others. While the proposed DSA scheme can chase the low interference channel, the conventional ZigBee

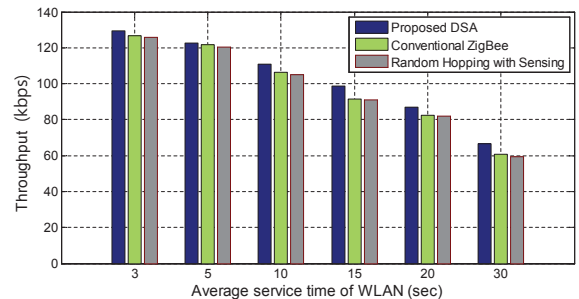


Fig. 3. Throughput comparison with conventional ZigBee system and random frequency hopping with spectrum sensing.

system cannot. Additionally, the throughput gain of the proposed DSA increases to 9.7% at most, as μ increases, which reveals the benefit of the proposed DSA.

Fig. 4 depicts the energy efficiency of the proposed DSA. Similar to the throughput performance, the energy efficiency of the WSN decreases as $1/\mu$ increases because probability of data collision is increased by the WLAN systems. Compared with conventional ZigBee, the energy efficiency gain achieved with DSA increases as $1/\mu$ increases. When the average WLAN service rate is low ($1/\mu = 3$), the probability that all WLANs are in the idle state increases. Therefore, the conventional ZigBee can transmit data without interference with a high probability. On the other hand, when the available vacant spectrum becomes scarce ($1/\mu = 30$), the collisions that occur with the WLAN traffic cause performance degradation. This situation highlights the efficiency of the proposed DSA - it is able to chase low interference channel by estimating the residual idle period using the spectrum sensing information. In spite of the additional power consumption required for channel switching, the proposed DSA is able to improve energy efficiency. Additionally, we can see that the energy efficiency achieved with RFH is less than that for conventional ZigBee, because too much energy is being wasted for channel switching, whereas, the proposed DSA can avoid this by preventing unnecessary channel switching.

Fig. 5 compares the WSN life-time of the proposed DSA with conventional ZigBee. As $1/\mu$ increases, the WSN life-time increases. This is because the number of transmissions

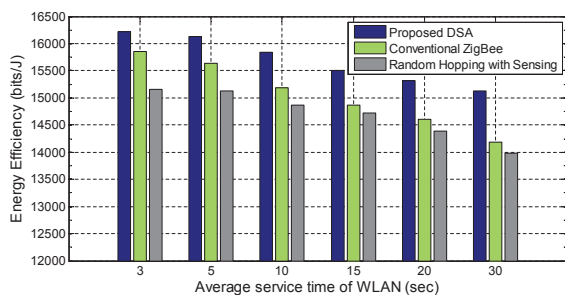


Fig. 4. Energy efficiency comparison with conventional ZigBee system and random frequency hopping with spectrum sensing

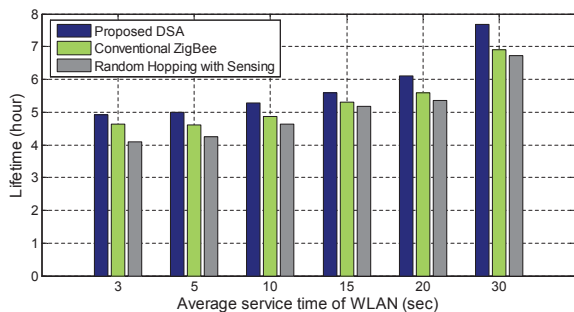


Fig. 5. Lifetime comparison with conventional ZigBee system and random frequency hopping with spectrum sensing.

is reduced by CSMA/CA. When $1/\mu = 30$, the proposed DSA improves about the WSN life-time by about 15% over conventional ZigBee. This results directly from the proposed DSA being able to reduce collisions by chasing the low interference channel. The simulation results allow us to deduce that the proposed DSA scheme improves life-time of a WSN by achieving higher energy efficiency.

V. CONCLUSION

We investigated an energy efficient DSA scheme for an IEEE 802.15.4 ZigBee-based WSN in an open spectrum. With the goal of achieving WSN frequency agility, we proposed a new spectrum sensing frame structure for ZigBee WSNs. Additionally, an energy-efficient channel switching criterion was proposed that determines the operating channel by comparing the WLAN achievable energy efficiency and reduces unnecessary channel switch.

We were able to show that the life-time of the proposed DSA increases as the average service time increases, since it is able to reduce the collisions with WLANs by chasing the low interference channel more efficiently. OPNET-based system level simulations verify that the proposed DSA scheme with channel switching criterion improves throughput, energy efficiency and life-time compared to the conventional ZigBee and random frequency hopping schemes.

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