Adaptive Radio Channel Allocation for Supporting Coexistence of 802.15.4 and 802.11b

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Abstract — As the explosive growth of the ISM band usage continues, there are many scenarios where different systems operate in the same place at the same time. One of growing concerns is the coexistence of wireless systems [18]. For the successful deployment of mission-critical systems such as wireless sensor networks, it is required to provide a solution for the coexistence. In this paper, we propose a new scheme using multiple radio channels for the coexistence of 802.15.4 LR-WPAN and 802.11b WLAN. To evaluate the effectiveness of the proposed scheme, measurement and simulation study are conducted. The simulation results show that the proposed scheme is effective in performance improvement for multi-hop large-scale network of 802.15.4.

Keywords-component; coexistence; interference; ISM band; 802.15.4; 802.11b

I. INTRODUCTION

The Industrial, Scientific and Medical (ISM) band is widely used among popular wireless network standards such as IEEE 802.15.4 Low-Rate Wireless Personal Area Network (LR-WPAN), IEEE 802.11b Wireless Local Area Network (WLAN), IEEE 802.15.3, and Bluetooth™. Because of the mobility and ubiquitous deployment of wireless systems, there are many scenarios where different systems operate in the same place at the same time. Hand-held PDA can use a Bluetooth device to connect to a laptop with 802.11b WLAN. The ISM band is also used by home appliances such as microwave ovens. The microwave oven in the house can be turned on when cordless phone is being used.

Coexistence is defined as "the ability of one system to perform a task in a given shared environment where other systems may or may not be using the same set of rules" [14]. Especially, for mission-critical applications using wireless systems, the coexistence becomes a top priority issue in system design. For example, if 802.15.4 sensor network system is to be deployed in the hospital building for emergency medical care, a main design issue will be providing the coexistence of 802.15.4 and other wireless systems. In case the other system causes radio channel interference, the sensor network system can not continue the normal operation and may lose critical information such as emergency patient vital signals and emergency patient information.

Growing concern is in the coexistence of 802.1.5.4 and 802.11b. There are many practical situations and scenarios where 802.15.4 and 802.11b systems operate simultaneously. An interesting system is sensor network system employing 802.15.4 technology. Crossbow MICAz™ and Telos tMotes™ system use 802.15.4 as their physical layer [4, 19]. Many practical wireless sensor network systems cover a large area of interest. The examples include wild life habitat monitoring [11], hospital emergency medial care and health monitoring [1], forest fire detection and tracking, traffic monitoring [6] and others. Because those systems have a large coverage area and the same area can have other human activities such as residences and leisure activities, it is reasonably assumed that the 802.15.4 system will be operating with other systems. It is interesting to note that the effect caused by radio interference is not reciprocal when multiple wireless systems operate simultaneously. It is because of the difference in radio transmission range. 802.11b uses a longer range radio than 802.15.4 system. 802.11b WLAN has radio range of 100 m and 802.15.4 LR-PAN has radio range of 10 m [12]. Thus, 802.11b can give radio interference to 802.15.4 system in a large area and from a long distance. Therefore, large-scale 802.15.4 based sensor network system is vulnerable to the interference from 802.11b. Moreover, 802.11b systems are employed in many portable devices including hand-held Personal Data Assistant (PDA) and laptop computers. Due to the omnipresence and mobility of those systems, there is a high chance of operating 802.15.4 and 802.11b in the same environment. There are many situations, where 802.15.4 and 802.11b need operate in the same system. For example, 802.15.4 wireless sensor nodes forward the sensing data to a laptop, which will be send the collected data over 802.11b WLAN to the central computer for processing and further analysis.

In the coexistence of 802.15.4 and 802.11b, the main concern is the performance degradation of 802.1.5.4 caused by the interference of 802.11b. A measurement study reported that over 92 % of the 802.15.4 frames were lost by the interference of 802.11b [18]. In this paper, we propose an adaptive scheme using multiple radio channels to solve the performance degradation of 802.15.4. Especially, the proposed scheme is intended to support coexistence performance issue for large-scale 802.15.4 multi-hop network.

The rest of paper consists of Section II Related Works, Section III coexistence overview, Section IV Adaptive Channel Allocation, Section V Coexistence Experiment, Section VI performance evaluation, and Section VII Conclusions.

II. RELATED WORK

Golmie [7, 8, 9] and Howitt [13] studied the coexistence of Bluetooth and 802.11. Golmie [7] proposed a dynamic scheduling algorithm to reduce the interference between Bluetooth and 802.11. Its main goal is to guarantee system performance requirements such as QoS while reducing the effect of the interference by 802.11. It extends the Bluetooth channel hopping mechanism in a dynamic way that devices in the network maximize their throughput and get the fairness of access. Howitt [13] studied the effect of interference using experiments and analytical models. The experiments intended to evaluate the impact of the interference between Bluetooth and 802.11b. He also built analytical models for the interference caused by 802.11b on Bluetooth and for the interference caused by Bluetooth on 802.11b.

Crossbow Technology Inc. [3] and Steibeis-Transfer Center [18] independently conducted experiments to measure the effect of interference on 802.15.4. The technical document [3] from Crossbow Technology Inc. describes measurement results showing that the packet delivery rate in a MICAz sensor network is dropped significantly by the interference with 802.11b WLAN when they use closely located radio channels. The Steibeis-Transfer Center [18] also conducted a measurement study using commercial devices. According to the study, the coexistence of 802.15.4 and 802.11b can cause significant performance degradation to 802.15.4. Howitt [12] analyzed the coexistence impact of 802.15.4 on 802.11b. He used both analysis and measurement to prove that the 802.15.4 has little or no effect on 802.11b performance. Therefore, the result assures that the coexistence of 802.15.4 and 802.11 needs to be approached to protect 802.15.4.

Wood [20] tries to solve a Denial-Of-Service (DOS) attack in the context of large-scale sensor network. The attack is assumed to use radio interference, called radio jamming attack. They propose a mapping and detection algorithm for jammed regions of sensor network. The mapping protocol provides the application layer the map of the jammed regions hole, which helps to route packets around the jammed regions. The detection and mapping algorithm is executed in a distributed manner. The wireless nodes in jammed region detect a jamming attack autonomously and broadcast the attack to their neighbor to detect and map the jammed area. They proposed a carrier sense defeat mechanism for broadcasting high-priority attack message.

Guo [10] took a different approach to attain low power sensor network. Instead of addressing circuit level issue, he proposed a set of MAC design issues optimized for low power multi-hop sensor networks in the belief that there is a bigger optimization space in higher level design (i.e., MAC layer). An interesting feature of the MAC design is a distributed method to allocate multiple channels. Since the use of multiple channels reduces collisions and retransmissions, it attains low power consumption. It also improves performance: reduced delay and increased throughput. By using a distributed method for multiple channels, it reduces the complexity of the design (i.e., no global synchronization) and eliminates a single point of failure.

	IEEE 802.11		IEEE 802.15.4	
	Ch.	Freq. (GHz)	Ch.	Freq. (GHz)
2.4 GHz ISM Band	1	2.401- 2.423	11	2.405
	2	2.404- 2.428	12	2.410
	3	2.411- 2.433	13	2.415
	4	2.416- 2.438	14	2.420
	5	2.421- 2.443	15	2.425
	6	2.426- 2.448	16	2.430
	7	2.431- 2.453	17	2.435
	8	2.436- 2.458	18	2.440
	9	2.441- 2.463	19	2.445
	10	2.446- 2.468	20	2.450
	11	2.451- 2.473	21	2.455
			22	2.460
			23	2.465
			24	2.470
			25	2.475
			26	2.480

Figure 1. 2.4 GHz ISM Band, IEEE 802.15.4 Channels, and IEEE 802.11 Channels

Most of Previous coexistence studies were focused on experimental measurements with small-scale network. Our approach is different; it addresses the coexistence issue in the context of large-scale sensor network.

III. OVERVIEW OF COEXISTENCE

Fig. 1 shows the channel allocations for IEEE 802.11 and IEEE 802.15.4 in the 2.4 GHz ISM band. IEEE 802.11 has 11 channels and each channel has a frequency range of 22 MHz. On the other hand, IEEE 802.15.4 has total 16 channels. Each channel is 5 MHz apart and has a frequency rage of 3 MHz. The frequency values for IEEE 802.15.4 are the central frequency for the channel. The frequency range of each IEEE 802.11 channel is overlapped with the frequency ranges for four different IEEE 802.15.4 channels. For example, IEEE 802.11 channel 6 has the frequency range between 2.401 MHz and 2.423 MHz, which includes the frequency ranges for IEEE 802.15.4 channel 16 through channel 19. Because of the overlapped frequency range, IEEE 802.11 channel 6 can cause radio interference to IEEE 802.15.4 channel 16 through channel 19 when it is operating in proximity.

The 802.15.4 channel allocation provides a simple provision for coexistence. Channel 24 and 25 use a frequency range outside of the frequency range for 802.11 channels. Therefore, those two channels can be used for a certain environment, in which frequent interference of 802.11 is expected. However, there are many situations, in which it is necessary to use more channels. In case an 802.15.4 system has interference from multiple 2.4 GHz ISM systems, channel 24 and 25 can experience interference. Especially large-scale 802.15.4 systems will be more likely to have the situation.

IV. Adaptive Radio Channel Allocation Scheme

Fig. 2 illustrates a scenario of the coexistence of 802.15.4 and 802.11b, where 802.15.4 nodes form a multi-hop network and a part of the network is being interfered by 802.11b system. The interference area is shown shaded in Fig. 2. Since the nodes are connected in multi-hop mesh network, packets are routed by visiting the nodes on the routing path. Packets can not go through the path in the interference. The basic idea of the adaptive scheme is to make the interference affected nodes to switch to a new clean channel. When packet is entering (marked A in Fig. 2) or leaving (Marked B in Fig. 2) to the interference part of the routing path, the radio channel is switched to a new clean channel (in A) or back to the old channel (in B). The advantage of the proposed scheme is that the same routing path can be used when interference is occurred. The overhead for switching radio channel is very small (e.g., Bluetooth can switch channel at 1600/sec [9, 15]). Since the performance degradation by interference is mainly caused from changing routing path, the adaptive scheme improves the performance and is especially advantageous for large-scale multi-hop sensor networks.

To ensure that all the nodes in same interference switch to the same channel, switching table is used. Each node holds a switching table (SWTB) and all the nodes have the same entries in their table at the initialization. When interference is detected in the area, the node looks up the SWTB to find a new channel. The same table is also used to go back to the previous channel when the interference is diminished.

The nodes in the same interference form a group, which uses the same current channel. The group of nodes is surrounded by border nodes. The border nodes consist of immediate neighbors of the group and provide channel conversion for the group. Since the borders are located outside of the group and the group uses a different channel from the rest, different channels are used when packets are entering or leaving the group. The border nodes help with the channel conversion. When packets are being routed to the group, the borders send packets using the current channel of the group. Again, when packets are routing out of the group, the borders receive the packets using the current channel of the group. With the help of borders, the group and the outside of the group can send and receive packets without changing the existing routing path. To keep the information about neighbor nodes (e.g., neighbor's current channel and neighbor address), each node holds a neighbor table (NTAB). Border node uses NTAB to send and listen to the channel of its neighbor.

The adaptive scheme uses three mechanisms: Interference Detection, Group Formation, and Demolition. Each 802.15.4 node checks for interference on the current channel using the Interference Detection (ID). It can be called periodically or on demand. In case of interference, the node enters into Group Formation (GF). During GF, the nodes in the same interference area form a group and a new channel is selected as the current channel for the group. When the current interference is diminished, the group is torn down and its current channel is switched back to the previous one.

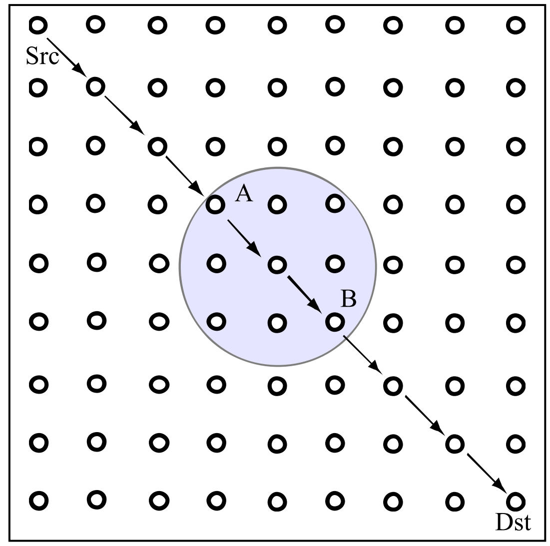

Figure 2. A multi-hop 802.15.4 network

A. Interference Detection

Each 802.15.4 node executes Interference Detection to check that interference is developing in its proximity. One way to assess interference is the use of the clear channel assessment or energy detection provided as RSSI (Received Signal Strength Indicator) services in 802.15.4 PHY [5]. The RSSI services can be called periodically or on demand. The user application can call the clear channel assessment when it detects a sudden degradation of user throughput below a threshold. If the RSSI measurement returns that the energy level on the current channel is above a threshold, channel interference is recognized and the node enters into the procedure for Group Formation.

B. Group Formation (GF)

Every node participating in Group Formation starts broadcasting GF (Group Formation) message to its immediate neighbors telling that it will change its current radio channel to a new one. Depending on the strength of the interference, nodes may or may not receive GF message. On the receipt of GF message, the node needs to decide to become a border node. The decision is being made depending on its channel clearness. Only if the current channel is clear, the node will become the border. The border node enters the sender information (e.g., node address and channel) into the NTAB. The border node sends back a GF reply message to the sender on the new channel. The GF reply message is to confirm the election of the border node. Since a border node needs listen to several channels, it needs separate schedules for each channel. The schedule is exchanged using GF messages and is held in the NTAB.

C. Tear-down

The tear-down process is executed when the current interference is diminished. The nodes in a group periodically check if the previous channel is clear. The previous channel information is kept in the SWTB. If it found that the previous channel is clear and it has a border node, it broadcasts a TD

(Tear Down) message to its immediate neighbors including the border nodes. The border nodes received the TD message is retired from the border node. The other immediate nodes received the TD message either send new TD message to its immediate neighbors or send a TD reply message back to the sender. The TD reply message is to inform the sender that the previous channel is not clear yet and therefore ask the sender to serve its border node. Therefore, the sender becomes the new border node for the neighbor. When the interference is completely diminished, the whole group will be torn down.

V. Coexistence Experiment

To study the impact of coexistence on the performance of the 802.15.4 network, measurements were made in a simple experimental environment as shown in Fig. 3. The experiment uses two networks operating in a close distance: a multi-hop 802.15.4 network and an 802.11b network. The 802.15.4 network consists of a pair of Moteiv Corporation Tmote™ Sky motes. The motes use 250 Kbps 2.4GHz IEEE 802.15.4 Chipcon Wireless Transceiver. Two motes are connected in peer-to-peer connection. Each mote was running a simple application program. One mote periodically sends packets to another at an interval of one second. As an interference source, an Ad-hoc network of 802.11b operates with two DELL Inspiron 6000 laptops with Intel ® PRO/Wireless 2200BG WLAN card. The WLAN card runs in 802.11b protocol with the maximum data rate of 11 Mbps. To generate the highest traffic on the 802.11b network, a 500 MB file was transferred from one laptop to the other using the Window network sharing.

In the experiment, the 802.11b Ad-hoc network used a fixed channel, channel 6, which uses a frequency range between 2.426 MHz and 2.448 MHz. To measure the interference effect, the 802.15.4 network varied the frequency channel: channel 17 and 21. Since the channel 17 of 802.15.4 is within the frequency range of the channel 6 of 802.11b, the maximum interference effect was observed. On the other hand, the channel 21 is unaffected by the 802.11b network. The packet delivery success rate of the 802.15.4 network was measured. When the 802.15.4 network is on channel 21, the number of received packets was sustained 99 % to 100 % of the number of the sent packets. In the interference situation, where the 802.15.4 is on channel 17, the success rate was dropped to about 40 %.

VI. Simulation

To evaluate the effectiveness of the proposed scheme in a large-scale sensor network, a simulation study was conducted. We used the 802.15.4 NS2 simulator developed at the Joint Lab of Samsung and City University of New York [16]. The simulation model for the adaptive scheme was implemented in the MAC layer of the 802.15.4 simulator. For the simplicity of interference modeling, TCL commands were used to specify the 802.15.4 nodes affected by the interference of 802.11b and the time duration of the interference effect.

A multi-hop 802.15.4 network consists of 100 nodes placed 10 m apart on a grid. The size of interference area was varied. Since it was assumed a single source of interference and a uniform strength, all the nodes in the area detect the same strength of interference during the interference duration.

Figure 3. Coexistence Experiment

For the packet traffic generation, two different ways were used: 4-way and one-to-one traffic. The 4-way traffic has four sender and receiver pairs and each sender periodically sends packets to its receiver. One-to-one traffic has difference in using a single pair of nodes. The receivers were located on the other side of the senders in such a way that the interference area is on the shortest path between them. The packet routing is based on AODV (Ad-hoc On-Demand Distance Vector) routing.

The effectiveness of the adaptive scheme was measured with two different metrics: packet delivery success rate and delay. The success rate is the number of received packets divided by the number of sent packets. The delay is the time for packet to travel from sender to receiver. The metrics were measured by varying the size of interference area.

Fig. 4 shows the success rate using one-to-one traffic with packet/sec interval. The interference size represents the number of nodes in the interference. The interference area moves around the center of the field and the interference duration set

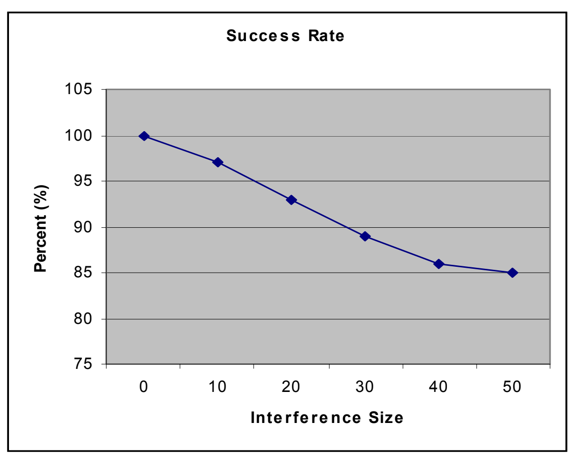

Figure 4. Success Rate

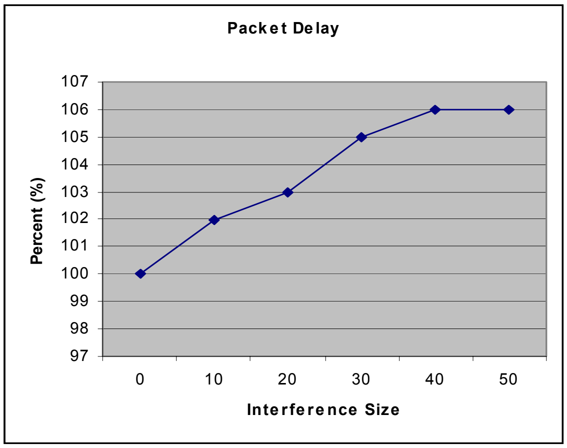

Figure 5. Pakcet Delay

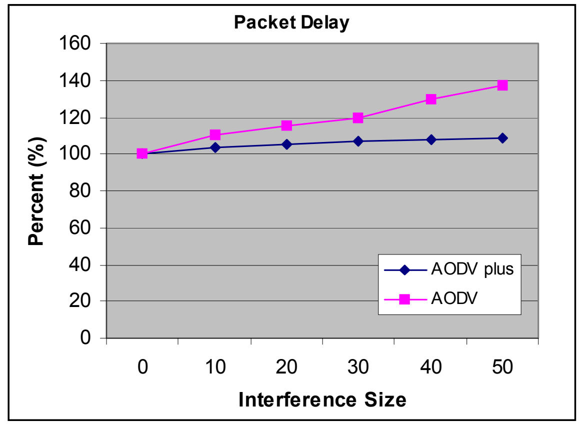

Figure 6. Pakcet Delay

to 10 seconds. The success rate is percentage value relative to without interference. Since packets are not lost in most cases, it sustains a high success rate: between 97% and 86 %.

Fig. 5 presents the packet delay. The percentage value is the delay increase relative to the delay without interference. Since packets are routed through the interference area, the delay is not increased much.

Fig. 6 compares packet delay between AODV and AODV plus the adaptive scheme using the 4-way packet traffic. By employing the adaptive scheme, the routing does not need to find a new path when it hits into interference area. It thus attains lower packet delay.

VII. Conclusions

In this paper, we propose an adaptive scheme designed for addressing the coexistence of 802.15.4, especially in the context of large-scale sensor network applications.

We conducted experiments using a multi-hop 802.15.4 network and an 802.11 Ad-hoc network. We also ran simulations to measure the effectiveness of the scheme. The simulation results show that the adaptive scheme is very effective in reducing the coexistence effect on 802.15.4, especially in large-scale network.

In the future, we are planning to implement the adaptive scheme on TinyOS and 802.15.4-based motes.

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