A Time-slot Based Coordination Mechanism Between WiFi and IEEE 802.15.4

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Abstract. Both WiFi and IEEE 802.15.4 are wide-spread wireless communication technologies utilized particularly in indoor environments such as home, offices and buildings. Since these wireless networks are normally operating in the license-free Industrial Scientific Medical (ISM) frequency band and share the same wireless medium, where no coordination mechanism is available to guarantee communications, unavoidably it leads to interference among them. In order to address this problem, this paper proposes a time-slot based coordination mechanism between WiFi and IEEE 802.15.4, which is achieved by introducing Access Suppression Notification (ASN) frame into IEEE 802.15.4. The static scheduling algorithm is designed and the experiments show that proposed coordination mechanism demonstrates an overall improvement in both IEEE 802.15.4 packet loss ratio and packet transmission rate.

Keywords: WiFi · IEEE 802.15.4 · Cross interference
Coordination mechanism · Time-slot

1 Introduction

Wireless networks are making life easier, smarter and more convenient. With the development of Internet of Thing (IoT), various network technologies are introduced to meet different performance requirements in term of data throughput, communication distance and power consumption. One popular wireless technology is IEEE 802.15.4 which is a Low-Rate WPAN (LR-WPAN) standard in physical and link layers with features of low-power consumption, flexible topology, high receiver sensitivity and long commutation distance [6]. Base on IEEE 802.15.4, many wireless protocol network stacks are developed, such as ZigBee [3], 6LoWPAN [1], Rime [7], Thread [2] and so on. WiFi (IEEE 802.11) is a widely adopted WLAN technology that is a simple and universal way to connect wireless devices, e.g. smart phones, laptops, TVs and digital camera to the Internet. Thus, it is necessary to have both IEEE 802.15.4 and WiFi available in IoT. However, most of those wireless networks operate in the license-free Industrial

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Scientific Medical (ISM) frequency band and share the same wireless medium, where no coordination mechanism is available to guarantee communications, unavoidably leading to interference among them. Many works are investigated to address the interference by analysing Packet Error Rate (PER) [8,10,15,20]. IEEE 802.15.4 has negligible impacts on WiFi [12], while IEEE 802.15.4 is excessively interrupted by WiFi network due to the much higher transmission power of WiFi [9,14,16]. In some worst-case scenarios, WiFi devices possibly jams IEEE 802.15.4 communications [9].

There are extensive studies about the interference mitigation among the wireless technologies in 2.4 GHz band. For example, [19] suggests that a wireless node can detect the interference and retreat from the interference by dynamic channel switching and dynamic power management. Similarly, [13] claims that dynamically adjusting radio transmission power helps maximize spectrum utilization and avoid interference. However, in some situations where these two radio modules are designed into one box and near each other, IEEE 802.15.4 channel switching and WiFi radio power adjusting are not an effective way to mitigate the interference [18]. Thus, a CTS (Clear To Send) blocking way [9] is proposed to protect the IEEE 802.15.4 communication, in which a WiFi CTS frame is sent to block WiFi traffic before transmitting any IEEE 802.15.4 data. Reference [11] optimizes the idea of [9] and resolved possible hidden nodes problem by introducing a helper AP. Unlike the method in [9], the node sends RTS (Request To Send) instead of CTS. However, it is not realistic to put an extra WiFi radio in to a tiny IEEE 802.15.4 sensor. Our method is to introduce time slot concept to coordinate their transmissions. Namely, they are transmitted at different time slots.

The major contributions of the paper are as follows. Firstly the paper proposes a time-slot based method to separate these two types of traffic. Secondly a new control frame called Access Suppression Notification (ASN) is introduced into IEEE 802.11.5. finally a unified coordination control architecture is designed and practically implemented to fulfil the above method and control.

The following paper is organized as follows. Section 2 introduces the newly proposed ASN frame, based on which Sect. 3 presents the overall time-slot frame structure and coordination control architecture. A static time-slot scheduling algorithm is also described in this section. Section 4 gives an experimental evaluation of the overall proposal with respect to the IEEE 802.15.4 performance under WiFi traffic from two aspects: Packet Loss Ratio (PLR) and Packet Transmission Rate (PTR). The paper is concluded in Sect. 5.

2 ASN Command Frame

The Access Suppression Notification (ASN) frame is designed in IEEE 802.15.4 to be sent by coordinator to notify its child nodes that following specific duration is suppressed to access medium. Such a duration is called Suppressed Medium Access Duration (SMAD). In order to be compatible with the nodes that do not support ASN MAC command, IEEE 802.15.4 communication is not thoroughly blocked when in SMAD, but access medium in SMAD may experience reduced channel quality and high PLR, because of the possible cross interference from WiFi or other wireless technology. In other word, the transmission in SMAD is more like to be interrupted. The ASN frame from the coordinator allows child nodes to pick advised, safe and guaranteed time slots when sending data.

According to [4], four frame types are defined in IEEE 802.15.4, including Beacon frame, Data frame, ACK frame and MAC command frame. There are nine command frame types, with command frame identifier from 0x01 to 0x09. The ASN frame is added as a command frame that uses a reserved command frame identifier 0x0a.

Table 1. ASN Command frame format

Bytes: 7/9	1	1	Variable
MHR field	Command frame identifier (0x0a)	Suppressed medium access duration	Schedule list

This ASN MAC command format is illustrated in Table 1:

- The Frame Type subfield of the Frame Control field shall be set to three, indicating MAC command frame.
- The Security Enable field, Frame Pending field and Acknowledgement request of the Frame Control field shall be set to zero.
- The PAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the PAN ID compression subfield, the Source PAN Identifier field shall be omitted. If the Destination PAN Identifier is not a broadcast PAN identifier (i.e., 0xffff), the ASN is just limited in one PAN. Otherwise, all the nearby PANs are affected.
- The Source Address field should contain the short address of the coordinator.
- The Supressed Medium Access Duration is an unsigned 8-bit integer, covering 1 255 ms. 0 is reserved. The time beyond SMAD is called Normal Medium Access Duration (NMAD).
- Schedule list is a serial of unsigned 8-bit integers, covering 1 255 ms for each byte. 0 is reserved. This list indicates several possible moments that next ASN frame will occur. This helps to implement Energy efficient algorithms on child nodes with ASN MAC command support. The Schedule list not always exists. An ASN frame without schedule list means the next ASN frame may be sent anytime. The child nodes, who enabled ASN support, must listen this MAC command in the entire NMAD.

3 Proposed Time-slot Based Coordination Mechanism

3.1 Time-slot Design Based on WiFi CTS and IEEE 802.15.4

CTS frame is used to block nearby WiFi nodes from sending any data, except for the one that is chosen and allowed to send without worry about interference from other nodes. In this paper, CTS frame is forced to send and block nearby WiFi communications. With the introduction of ASN frame, if these two frames is sent in a coordinated way, they can be used to synchronize WiFi and IEEE 802.15.4 traffic and allow these two wireless traffic to access medium in separated time slots without interference.

Figure 1 depicts how to realize time slots by using CTS and ASN command frames. Basically, IEEE 802.15.4 traffic is depressed when in WiFi slot by Sending an ASN frame. WiFi CTS should be sent just before the finish of the SMAD, so WiFi transaction is blocked and IEEE 802.15.4 starts working without worry about cross interference from WiFi. Before WiFi activates again, another ASN frame shall be sent to curb IEEE 802.15.4 communication. Thus the WiFi and IEEE 802.15.4 are separated in different time slot. The time slots with only WiFi traffic is WiFi slots and the slots with only IEEE 802.15.4 traffic is called 802.15.4 slots. By dynamic and cautious adjustment of both kinds of time slots, time-slot based resource scheduling algorithms can be implemented.

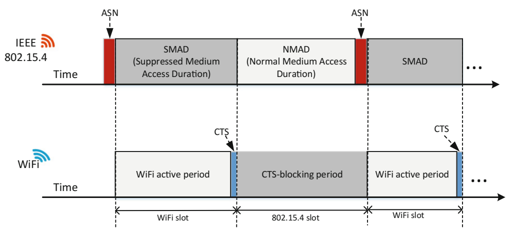
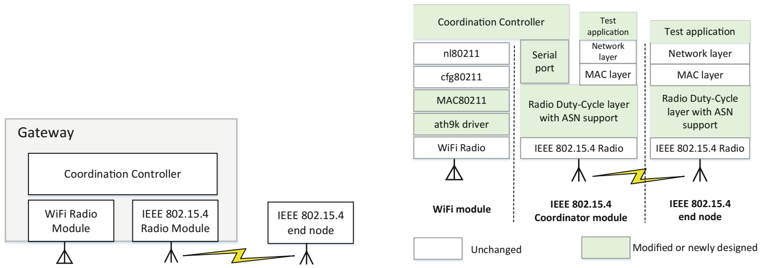


Fig. 1. Time-slot based coordination by using WiFi CTS and IEEE802.15.4 ASN

3.2 Overall Coordination Control Architecture

Figure 2a describes the overall architecture of the gateway and IEEE 802.15.4 end node. The gateway, integrating WiFi radio module and IEEE 802.15.4 radio module, runs a Coordination Controller (CC). By utilizing CTS frame and proposed ASN frame, CC is able to schedule WiFi and IEEE 802.15.4 traffic into separated time slots.

The detail design of the architecture is in Fig. 2b. Generally, CTS is directly controlled by hardware. Thus OS does not provide any interface to send CTS. In order to send arbitrary CTS frame, OS kernel modifications are necessary. The implementation is based on AR9331 [5] SoC with OpenWRT OS. AR9331 integrates a 802.11 b/g/n radio module. As shown in Fig. 2b, MAC80211 and ath9k driver for the WiFi module are modified to enable WiFi CTS frame injection. The proposed IEEE 802.15.4 ASN frame is implemented in Contiki-OS, thanks to its flexible radio control, rich features, support of simulation. We design new Radio Duty-Cycle (RDC) layer to enable ASN support. the RDC layer in IEEE 802.15.4 coordinator module provides control API by serial port, allowing CC to send signal to it. Once the RDC layer receives the signal from serial port, it sends out proper ASN fame and blocks its upper MAC layer data transmission for a specific period. The transmitted ASN frame will be received by IEEE 802.15.4 end node and the RDC layer in the end node will also block its upper MAC layer data transmission. Thus the ASN is implemented and able to suppress IEEE 802.15.4 traffic. Specifically, the ASN command frame is implemented on CC2538 [17] chip. The CC2538 chip is connected to the AR9331 by serial port. Test applications are also designed to evaluation the coordination mechanism performance.



(a) Overall architecture (b) architecture detail

Fig. 2. Coordination control architecture

3.3 Static Time-slot Scheduling

The key is to decide the length of WiFi slot and that of 802.15.4 respectively. Since this paper focuses on the description of the operational procedure of the coordination scheme it adopts a static method to decide the lengths. Namely, they are fixed to 32 ms, as depicted in Fig. 3.

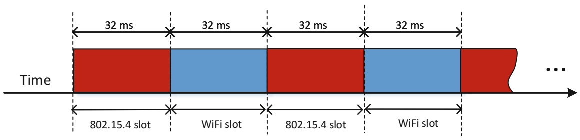
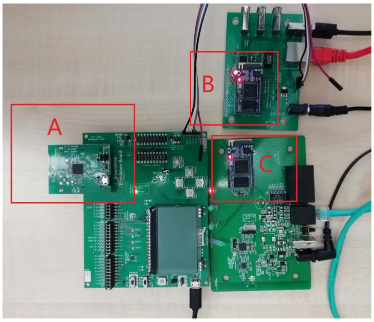


Fig. 3. Static Time-Slot Scheduling

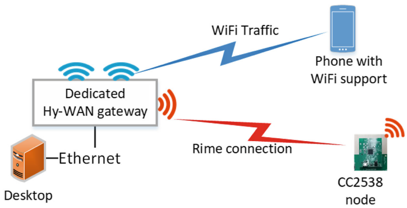
4 Experimental Evaluation

4.1 Experiment Setup

Figure 4a demonstrates a dedicated gateway implementation dedicated designed for static time-slot scheduling algorithm. Specifically, the gateway is built with three components: (A) CC2538 radio module running specially designed IEEE 802.15.4 MAC with ASN command frame support, (B) dedicated WiFi module with modified kernel and able to send CTS control frames, (C) normal WiFi module running WiFi Access Point (AP) and generating WiFi traffic. Of these three modules, Module B and C are able to integrated into one WiFi module. The reason why these two modules are separated is to get more accurate experiment results by minimizing impact of limited CPU computing power.



(a) Gateway for experiment



(b) Experiment topology

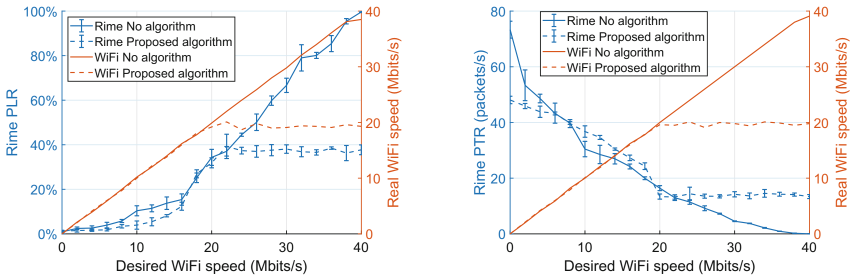
Fig. 4. Test bed

The experiment adopts Rime as an upper network layer on IEEE 802.15.4. As shown in Fig. 4b, the experiment platform consists of a desktop PC, a gateway, a phone and a CC2538 node. The desktop is used to access the gateway and also retrieve statics from the gateway. The WiFi traffic is generated by iperf3 which is installed in both the gateway and the phone. IEEE 802.15.4 traffic is generated and recorded by customized program running on CC2538 module. We designed two programs to evaluate Rime PLR and PTR. They are:

- Packet Loss Ratio of 802.15.4 Rime Data: In this experiment, the CC2538 node sends out Rime broadcast packets with sequence number every 15 ms, and the packet number is set to 1000 for each run. Three runs are performed at each WiFi speed. Then different Rime PLR data are collected and calculated under two conditions with or without static time-slot scheduling algorithm.
- Unicast Packet Transmission Rate of 802.15.4 Rime Data: In this experiment, the CC2538 node sends out Rime reliable unicast packet to the gateway. The unicast packets are transmitted under the guarantee of an up-four-times retransmission mechanism. The transmission is successful if the packet is transmitted within four retransmissions; otherwise, the transmission is timeout. The successful transmissions are counted with a time period of 100 seconds in each run. Similarly, three runs are performed at each WiFi speed. Then Rime PTR with static time-slot scheduling algorithm is compared with the PTR without the algorithm.

4.2 Packet Loss Ratio of 802.15.4 Rime Data

As shown in Fig. 5a, this experiment introduces desired WiFi speed and real WiFi speed concepts. The desired WiFi speed means the WiFi traffic that the iperf3 program intends to generate. However, the real generated wifi traffic may be different, because the channel capacity is limited and there are possibly multiple wireless technologies sharing the same medium and they may compete with each other. The experiment is conducted in WiFi channel 6 and ZigBee channel 17, and these two channels overlap in spectrum and are expected to interfere each other. Desired WiFi speed is set from 0 to 40 Mbits/s with a speed step of 2 Mbits/s. At each WiFi speed, statistics are collected and Rime PLR is calculated. Meanwhile, the real WiFi speed is also recorded. Similarly, we test and collect data when running static time-slot based resource scheduling algorithm. Thus, Fig. 5a is acquired.



(a) Rime PLR versus Desired WiFi Speed (b) Rime PTR versus Desired WiFi Speed

Fig. 5. Experimental results

The figure depicts that overall Rime PLR with proposed algorithm is lower than that without any algorithm. More detailed analysis can be done by dividing the graph into three parts according to various desired WiFi speed ranges:

- Effective phase (0–16 Mbits/s): WiFi traffic is not crowded and the real WiFi speed in both situations is basically equal with the desired WiFi speed. Average of Rime PLR without scheduling is 7.41%, while Average of Rime PLR with scheduling is 4.39%. The proposed algorithm is obviously effective by reduce Rime PLR from 7.41% to 4.39% without affecting WiFi traffic.
- Transition phase (18–22 Mbits/s): WiFi traffic is medium. Both PLR lines raise rapidly over this range. There is no obvious difference between two PLR lines. At the end of this range, scheduled WiFi time slot are almost fully used.
- Stable phase (24–40 Mbits/s): WiFi traffic becomes more crowded. The PLR without proposed algorithm keeps growing rapidly, while the PLR with the scheduling algorithm keeps at around 37%. Proposed algorithm shows improved performance of Rime PLR. When taking real WiFi speed into consider, the low PLR for proposed algorithm is at the cost of WiFi speed reduction. The scheduling algorithm periodically sends out CTS frames, which

blocks WiFi traffic periodically and creates time slots for Rime to send out broadcast. With scheduling algorithm, WiFi has used up all allocated time slot, thus real WiFi limited at around 19 Mbits/s. Such a mechanism works like applying protection to Rime traffic when there are two much WiFi traffic.

Although the figure shows that static time-slot based resource scheduling algorithm has an improved performance in term of Rime PLR, there still are some limitations and flaws on algorithm implementation. In an ideal implementation of the algorithm, a very low PLR, such as 2%, over all the WiFi speed ranged is expected, because the ideal scheduling will effectively separate Rime traffic from WiFis and they will never interfere each other. The experiment shows that high WiFi traffic affects the scheduling and results in an increase of PLR.

4.3 Unicast Packet Transmission Rate of 802.15.4 Rime Data

Different from WiFi of which speed is measured in unit of Mbits/s, however, in IEEE 802.15.4, application message tends to be short and only care about whether the message is successful transmitted or not, rather than the bitrate. Thus it is more reasonable to measure Rime traffic speed by successful transmitted packets per second (packets/s). Figure 5b can be study over four desired WiFi speed ranges:

- ASN suppress phase (0–8 Mbits/s): Static scheduling algorithm does not help improve Rime PTR performance, instead it reduces the performance. This is caused by periodical ASN frames that static scheduling algorithm sends to suppress Rime traffic. When no scheduling algorithm is introduced, Rime PTR reach a fast speed at 73.32 packets/s while desired WiFi speed is zero, but PTR drop dramatically once any WiFi traffic is introduced. With the scheduling algorithm, PTR is limited at 48.08 packets/s, and this value slightly drop when there is a little WiFi traffic. These two lines meet and merge quickly when WiFi traffic at 6 Mbits/s.
- Effective phase (10–16 Mbits/s): Advantages of the static scheduling algorithm starts showing up in this range. The scheduling algorithm separates WiFi and Rime traffic in different time slots. This improves PRT by avoiding potential cross interference.
- Transition Phase (18–20 Mbits/s): with proposed algorithm, the WiFi slot usage starts reaching its limit and PTR decreases rapidly, and very soon it is stable at 13.9 packets/s.
- Stable phase (22–40 Mbits/s): Under the static scheduling, WiFi has fully used its time slot and reached an stable state that real WiFi speed is about 19 Mbits/s and PTR is about 13.9 packets/s. If without scheduling, the PTR keeps dropping until almost 0 packets/s with the increase of the WiFi traffic. The proposed algorithm improves Rime PTR at the cost of reduction of real WiFi speed. The scheduling protects Rime traffic and avoids that WiFi takes up all the medium. If no scheduling protection, WiFi traffic blocks Rime transmission and causes Rime network failure.

In summary, the scheduling algorithm implementation demonstrates an overall improvement of Rime unicast PTR. However, the implementation still needs to be improved. An ideal implementation should give an stable Rime PTR that should be half of maximum PTR. In this experiment, the maximum PTR is 73.32 packets/s and ideal implementation should give a stable PRT at about 36.66 packets/s, but the PTR drops to around 14.9 packets/s when WiFi traffic uses up all its scheduling time slot. In result, the algorithm works as expected in low WiFi traffic situation, but it is not efficient enough when there is too many WiFi traffic.

5 Conclusion

This paper introduces ASN fame into IEEE 802.15.4 and proposes a time-slot based coordination mechanism between WiFi and IEEE 802.15.4. ASN frame is implemented on Contiki-OS by designing new RDC sublayer. Rime is chosen as a network layer on top of IEEE 802.15.4. The mechanism is evaluated in term of Rime broadcast PLR and Rime unicast PTR over various WiFi transmission speed. According to the experiment, proposed coordination mechanism demonstrates an overall improvement in both IEEE 802.15.4 Rime PLR and Rime PTR. Especially, the mechanism shows an distinct improvement in effective phase. However, current implementation still has limitation, because there is no obvious improvement in transition phase. In stable phase, the Rime performance is also improved but at cost of reducing WiFi speed. Currently implementation of coordination mechanism is in an static manner. In the future, the additive scheduling algorithms will be studied.

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