M.S. THESIS

Adaptive Wi-Fi Power Save Operation Coexisting with LTE-U

LTE-U와 공존하는 적응적인 Wi-Fi 절전 모드

BY

KWON HWI-JAE

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지도교수 최성현
이 논문을 공학석사 학위논문으로 제출함

2019년 2월

서울대학교 대학원

전기 컴퓨터 공학부

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권휘재의 공학석사 학위 논문을 인준함

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Abstract

LTE-Unlicensed (LTE-U) supports LTE downlink operation in 5 GHz unlicensed bands, where Wi-Fi has been a traditional incumbent for a long time. To achieve a fair coexistence with Wi-Fi, LTE-U employs carrier sense adaptive transmission (CSAT), but it does not guarantee a perfectly fair coexistence. Therefore, many studies have dealt with unfair coexistence problems of Wi-Fi and LTE-U. However, in this paper, our experiment results show that a Wi-Fi station not only suffers from unfair coexistence but also wastes energy and air time when it coexists with LTE-U. To cope with this problem, we propose *AWARE*, a station-driven adaptive Wi-Fi power save operation coexisting with LTE-U, which detects LTE-U and adjusts Wi-Fi power state adaptively. We implement *AWARE* on a commercial 802.11n device, and our evaluation shows that a Wi-Fi station achieves almost the same throughput while reducing its power consumption by up to 33% and enhancing the throughput of neighbor Wi-Fi stations by up to 50%.

keywords: IEEE 802.11n, Wi-Fi power save mode, LTE-U

student number: 2017-21811

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Chapter 1

INTRODUCTION

Today, we are witnessing that the demands for mobile traffic are dramatically increasing. In 2016, global mobile data traffic was 7 exabytes per month and it is expected to grow to 49 exabytes per month by 2021 [1]. In order to satisfy such ever increasing mobile traffic demands, telecom operators, who have been exploiting only licensed spectrum for cellular technologies such as 4G Long Term Evolution (LTE), have been investigating the possibility to utilize abundant unlicensed spectrum at 5 GHz, which have been a playground of Wi-Fi for a long time.

As a representative technology to utilize LTE in 5 GHz unlicensed spectrum, LTE-Unlicensed (LTE-U) has been developed by LTE-U forum [2], which is designed to improve user experience by supporting LTE downlink operation through data offload in 5 GHz unlicensed spectrum. Unlike other LTE in unlicensed spectrum technology, such as licensed assisted access (LAA), LTE-U does not require listen before talk (LBT) mechanism. Instead, it uses duty cycled transmission based on medium sensing, which is called carrier sense adaptive transmission (CSAT), to achieve a fair coexistence with other coexisting technologies in unlicensed spectrum such as Wi-Fi.

The use of CSAT provides ease of implement to LTE-U, but it still has some coexistence problems with Wi-Fi, because of imperfect medium sensing and duty cycled transmission [3, 4, 5, 6, 7]. The first problem, which causes unfairness channel occupancy, is well known and can be solved by an LTE-U base station (BS) by enhancing the performance of medium sensing [8, 9, 3, 10]. In contrast, the second problem, which causes collisions with Wi-Fi, has not been studied in depth and it is difficult to solve by an LTE-U BS without modifying CSAT mechanism. Therefore, most studies have focused on a Wi-Fi access point (AP) to handle the second problem [11, 12, 6]. In these studies, a Wi-Fi AP acquires the duty cycle of LTE-U to cope with the coexistence problems.

However, none of these studies proposes a Wi-Fi station-driven solution, which requires low complexity and exploits limited information but can solve the problem directly by station basis. Moreover, none of these studies focuses on the power consumption problem of Wi-Fi coexisting with LTE-U. In this paper, we observe Wi-Fi coexistence performance with saturated LTE-U transmission in various scenarios. Our results show that a Wi-Fi station, which is strongly interfered by LTE-U, cannot receive data successfully when an LTE-U BS transmits. In spite of that, the station keeps wasting energy as well as air time, thus degrading the performance of the whole network.

To address the energy and air time waste problems caused by LTE-U, we propose *AWARE*, a station-driven adaptive Wi-Fi power save operation coexisting with LTE-U. *AWARE* detects LTE-U duty cycle and adjusts power state of the Wi-Fi station according to the duty cycle. Our major contributions are summarized as follows.

- We empirically analyze the impact of LTE-U to Wi-Fi using off-the-shelf 802.11n devices and a software defined radio (SDR) platform. Based on the analysis, we verify that there are not only an unfairness problem but also energy and air time waste problem when Wi-Fi coexists with LTE-U.

- An algorithm for LTE-U detection, which allows a Wi-Fi station to detect LTE-U by oneself without hardware modification, is developed.

- We propose *AWARE*, which detects the duty cycle of LTE-U and adjusts power state adaptively according to detection results.

- *AWARE* is implemented on the open source device driver (*ath9k* and *mac80211*), and evaluated in comparison with baseline 802.11n. Our evaluation shows that *AWARE* reduces power consumption by up to 33% while improving network throughput by up to 50% by effectively adapting power state.

The remainder of the paper is organized as follows. Chapter 2 presents the related work, and Chapter 3 provides the background of LTE-U and Wi-Fi power save mode. In Chapter 4, we analyze the performance of Wi-Fi coexisting with LTE-U to verify the impact of LTE-U to Wi-Fi and needs of adaptive Wi-Fi power save operation. The proposed algorithm *AWARE* is detailed in Chapter 5, and it is evaluated in Chapter 6. Finally, the paper concludes in Chapter 7.

Chapter 2

RELATED WORK

There have been many studies on fair coexistence between LTE-U and Wi-Fi in the literature. Fundamentally, LTE-U is hard to achieve fair coexistence with Wi-Fi because it does not use carrier sense multiple access (CSMA), which Wi-Fi exploits to avoid collision. LTE-U forum [2] demonstrates that CSAT guarantees fair coexistence with Wi-Fi using adaptive duty cycled transmission based on medium sensing [8, 9]. To achieve accurate medium sensing, in [8], the authors propose a medium utilization estimation scheme using Wi-Fi network listening (NL) module. In [3], the authors adopt spectrum manager for Wi-Fi monitoring.

However, many studies deal with unfair coexistence between LTE-U and Wi-Fi even with CSAT [4, 5, 7]. In [4], Wi-Fi station suffers from association unfairness because LTE-U disturbs beacon transmission and reception. The authors of [5, 7] handle the hidden terminal problem when LTE-U and Wi-Fi coexist, showing that when the two technologies are mutually hidden, Wi-Fi experiences significant performance degradation due to continuous transmission failures.

To solve LTE-U/Wi-Fi unfairness problems, the authors in [7] use point or hybrid coordination function (PCF/HCF) mode of 802.11 according to the duty cycle of LTE-U. However, they do not consider how to get the duty cycle in detail. In [6, 11, 12], the authors propose a scheme which allows Wi-Fi devices to detect the duty cycle and resolve the unfairness problems. In [6], an LTE-U BS exploits its users to inform LTE-U duty cycle to Wi-Fi devices. In [11], Wi-Fi AP gets LTE-U duty cycle using LtFi, a new cross-technology communication system between LTE-U and Wi-Fi. In [12], a Wi-Fi AP also detects LTE-U duty cycle by monitoring and processing medium access control (MAC) layer information. However, none of these studies handles the way which allows a Wi-Fi station to get LTE-U duty cycle by oneself. Moreover, none of them deals with Wi-Fi power save operation when Wi-Fi coexists with LTE-U.

Chapter 3

PRELIMINARIES

3.1 LTE-Unlicensed (LTE-U)

LTE-Unlicensed (LTE-U) is a technology which enables LTE operations in 5 GHz unlicensed spectrum [2]. Therefore, it is critical to coexist fairly with other technologies in the unlicensed spectrum, representatively Wi-Fi. In order to achieve a fair coexistence with Wi-Fi, LTE-U scans channels and avoids the primary channels of Wi-Fi. However, if there is no clean channel (i.e., without Wi-Fi), LTE-U uses duty cycled transmission with carrier sense adaptive transmission (CSAT) [8], which ensures compatibility with LTE Release 10/11 user equipment (UE) physical layer (PHY) and MAC layer standards.

Fig. 3.1 shows duty cycled transmission of LTE-U. In a given duty cycle period, an LTE-U BS transmits its signal during ON period (T_{on}) and stays off during OFF period (T_{off}) to avoid interfering with neighboring Wi-Fi devices. CSAT adjusts the duty cycle, which is the ratio of T_{on} to the duty cycle period $T_{on} + T_{off}$, according to channel activity by sensing the medium. To support delay-sensitive data delivery of Wi-Fi, there should be short gaps (via LTE subframe puncturing) within T_{on}. For example, according to [8], the maximum continuous transmission time can be limited to 20 ms with at least 2 ms puncturing between two consecutive 20 ms transmission

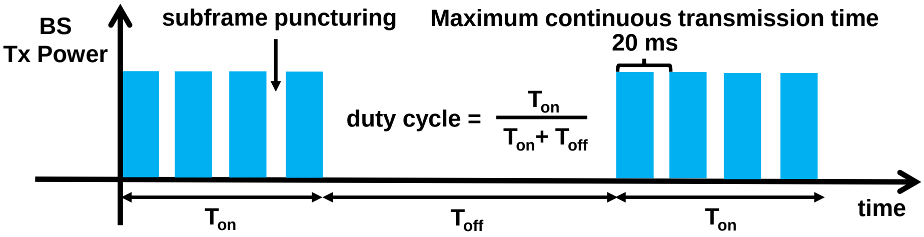

Figure 3.1: Duty cycled transmission of LTE-U.

times and 2 ms puncturing is typically used.

3.2 Wi-Fi Power Save Mode (PSM)

IEEE 802.11 defines two types of power state, namely, awake state and doze state [13]. In awake state, a station is fully powered, and in doze state, the station does not transmit or receive to reduce energy consumption. IEEE 802.11 also defines two types of power management mode, i.e., awake mode (AM) and power save mode (PSM). In AM, a station remains at awake state continuously, while in PSM, the station is usually in doze state and sometimes enters awake state to receive a beacon frame, to transmit packets to or await responses from its AP. When the station receives a beacon with traffic indication map (TIM) indicating buffered data from its AP, the station sends a PS-Poll frame to the AP. If the station then receives an acknowledgement (ACK) frame from the AP, the station enters AM and receives the buffered data.

3.2.1 Static PSM

A station with static PSM remains in PSM continuously. It takes long time for the station to transmit or receive data from AP.

3.2.2 Dynamic PSM

To avoid a long latency of PSM, most chipsets implement dynamic PSM, also called adaptive PSM, which allows devices to get into PSM if no traffic has been delivered to the devices for a certain period (i.e., a timeout event) [14]. Instead of sending a PS-Poll to its AP, the station sends a null frame[1] with power management (PM) bit set to zero to enter AM. Then, the station sends a null frame with PM bit set to one to enter PSM if there is no traffic after a timeout after finishing transmission/reception of its data.

3.3 Automatic power save delivery (APSD)

Automatic power save delivery (APSD) operation is additionally defined in the standard [13]. There are two kinds of APSD, i.e., unscheduled APSD (U-APSD) and scheduled APSD (S-APSD). With APSD, an AP transmits data to a station only during a service period (SP), because the station is supposed to be in doze state during off SP. The SP is scheduled in advance with S-APSD, and the AP transmits data without any a priori frame exchange during SP. On the other hand, with U-APSD, an SP is triggered whenever the station transmits data to its AP, and then the AP also transmits data during the period.

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[1] It is a MAC frame composed of only MAC header and error detection code, but no payload.

Chapter 4

MOTIVATION

In this chapter, we analyze the performance of Wi-Fi coexisting with LTE-U to verify the effects of neighboring LTE-U in target scenarios. In the target scenarios, an LTE-U BS has enough data so that it generates fully saturated traffic during ON period, and a neighboring Wi-Fi station can sense the LTE-U signals using energy detection-based clear channel assessment (CCA).

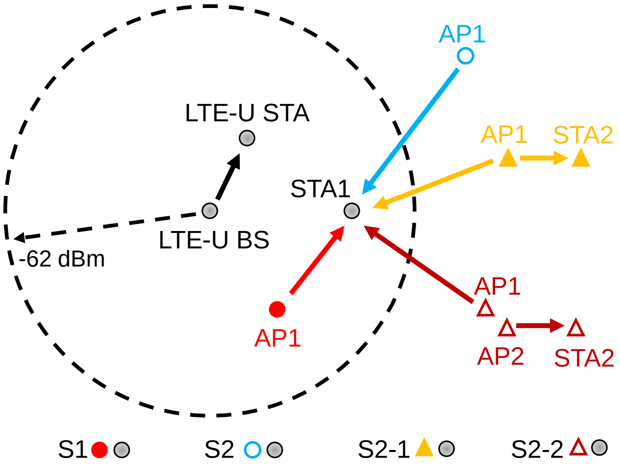


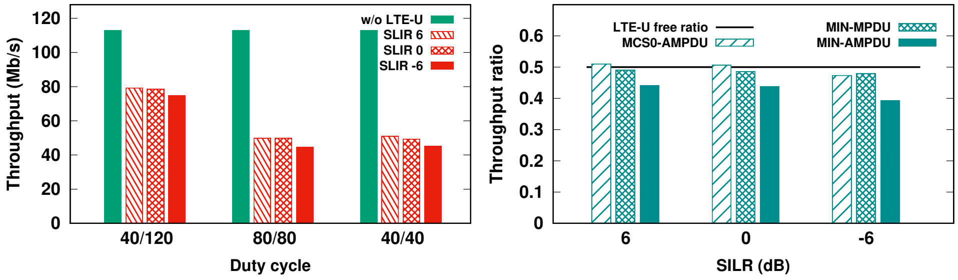
Figure 4.1: Concept diagram of our experiment scenarios. The dashed circle represents the range in which Wi-Fi devices can sense LTE-U.

4.1 Performance of Wi-Fi Coexisting with LTE-U

We have conducted experiments using off-the-shelf 802.11n laptops equipped with AR9380 chipset as Wi-Fi devices, and a SDR platform, i.e., NI USRP with LTE/Wi-Fi Coexistence Application Framework [15] as LTE-U devices. The experiments are composed of two major scenarios, i.e., Scenario 1 (S1) and Scenario 2 (S2, S2-1, and S2-2).

Fig. 4.1 illustrates the concept of our experimental scenarios. The dashed circle represents a range in which Wi-Fi devices can sense LTE-U. In Scenario 1, a Wi-Fi AP can sense LTE-U using energy detection-based CCA, but the AP cannot sense LTE-U in Scenario 2. An LTE-U BS uses modulation and coding scheme (MCS) index 28 (employing 64-QAM and code rate of 0.9257) and the Wi-Fi AP uses Minstrel rate adaptation [16] with aggregate MAC protocol data unit (A-MPDU). Both the Wi-Fi AP and the LTE-U BS transmit fully saturated UDP downlink traffic on the same 20 MHz channel. To express the impact of LTE-U, we newly define *signal-to-LTE-U-interference ratio (SLIR)* as the ratio of the received Wi-Fi signal strength without LTE-U to the received LTE-U signal strength during ON period.

4.1.1 Scenario 1



(a) Throughput

(b) Throughput ratio

Figure 4.2: Downlink throughput and throughput ratio in S1. Note that throughput ratio is only for duty cycle 80/80.

The throughput results obtained by STA1 are shown in Fig. 4.2(a) according to the LTE-U duty cycle and SLIR (dB). In this paper, we represent duty cycle as (ON period/OFF period) where ON period and OFF period are in ms and puncturing period is 2 ms . Without LTE-U, the throughput reaches 113 Mb/s with MCS 15. However, when the LTE-U BS transmits data, the throughput is degraded more than expected. For example, when the duty cycle is 0.5 (80/80 or 40/40), it is expected that the throughput decreases by a half due to air time loss, but the throughput actually decreases more. When the duty cycle is 0.25 (40/120), one would expect that the throughput decreases by 25% due to air time loss, but it decreases more. It means that Wi-Fi not only loses air time to LTE-U but also receives interference from LTE-U at the starting points of both ON period and punctured subframes, because the LTE-U BS starts to transmit at ON period even if the AP is transmitting.

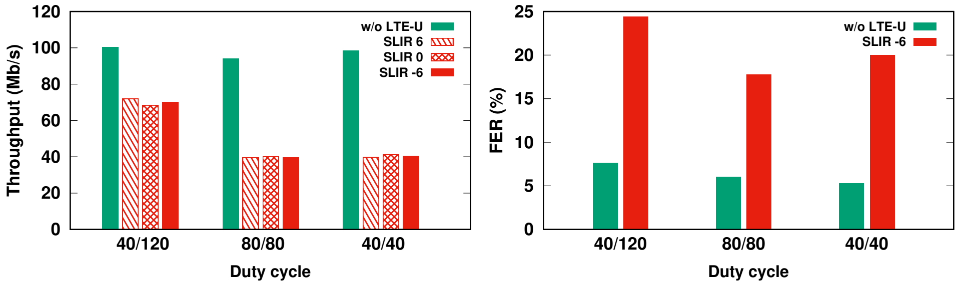
For a detailed analysis, we compare throughput ratio for three cases when LTE-U duty cycle is 80/80 in Fig. 4.2(b). Throughput ratio is the ratio of throughput with LTE-U to throughput without LTE-U and LTE-U free ratio is defined as one minus the duty cycle of LTE-U.

When the AP uses MCS 0 and A-MPDU (*MCS0-AMPDU*), throughput ratio is larger than LTE-U free ratio at SLIR of 6 and 0 dB. The robustness of MCS 0 makes the Wi-Fi station receive data successfully at the starting points of both ON period and punctured subframes when SLIR is high enough. However, when SLIR is -6 dB, throughput ratio becomes smaller than LTE-U free ratio. It is because transmission with MCS 0 does not succeed anymore at the starting points of both ON period and punctured subframes as SLIR decreases. When the AP uses Minstrel algorithm without employing A-MPDU (*MIN-MPDU*), throughput ratio is lower than LTE-U free ratio due to frame errors and the rate adaptation caused by LTE-U interference. In addition, throughput ratio remains almost the same regardless of SLIR because 6 dB is enough to damage a single frame. When the AP uses both Minstrel and A-MPDU (*MIN-AMPDU*), it shows the worst throughput ratio among three cases because frame errors occur more frequently than *MIN-MPDU* due to the long length of A-MPDU and more easily than *MCS0-AMPDU* due to an unstable rate adaptation operation. As a result, even when the AP can sense LTE-U, a Wi-Fi station suffers from severe interference by LTE-U and suffers more severely when using rate adaptation and A-MPDU.

4.1.2 Scenario 2

In Scenario 2, we first experiment S2 to evaluate the impact of LTE-U to a Wi-Fi station. Then, we move on to S2-1 and S2-2 to analyze the impact of LTE-U to the whole Wi-Fi network. In S2-1, a Wi-Fi AP transmits downlink traffic to two stations (STA1 and STA2) so that packets to STA1 and STA2 share the AP transmission queue. In S2-2, there are two pairs of a Wi-Fi AP and a station (AP1-STA1 and AP2-STA2), where each AP sends downlink traffic to its associated STA. AP1 and AP2 are not hidden each other so that they share the channel. In both scenarios, STA2 and AP2 are basically not interfered by LTE-U.

S2

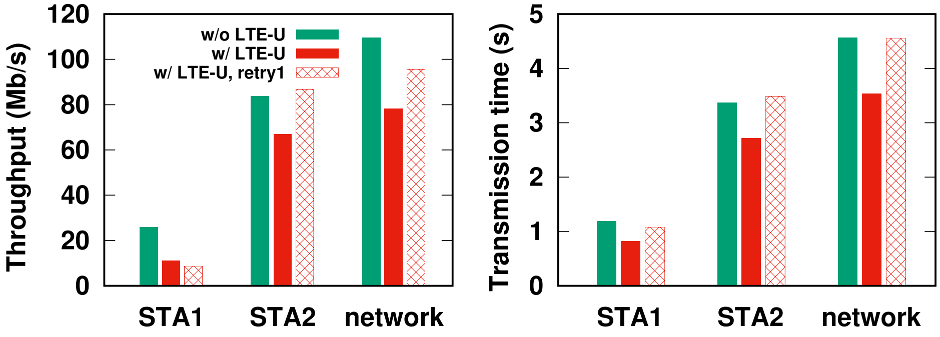


(a) Throughput (b) FER

Figure 4.3: Downlink throughput and FER in S2. Note that FER is only for SLIR -6 dB.

Fig. 4.3 shows the throughput results of STA1 and frame error rate (FER) without STA2 according to SLIR and duty cycle. Similar to S1, the throughput is deteriorated more than expected while FER severely increases . It means that Wi-Fi suffers lots of interference from LTE-U, resulting in low MCS and high FER which is about 17% at least.

S2-1



(a) Throughput in S2-1

(b) Transmission time in S2-1

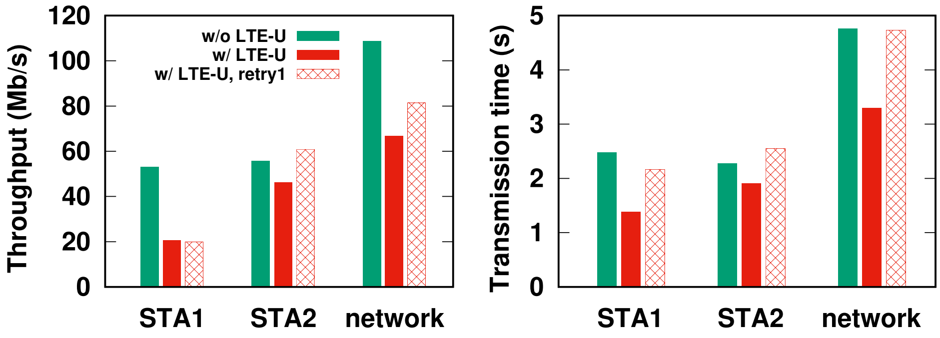
Figure 4.4: Downlink throughput and transmission time in S2-1 when duty cycle is 80/80 and SLIR is −6 dB.

Fig. 4.4(a) shows the throughput results of STA1, STA2, and the whole network (i.e., sum of STA1 and STA2) when the AP transmits downlink traffic and SLIR is −6 dB. With LTE-U whose duty cycle is 80/80, the throughput of STA1 decreases as shown in Fig. 4.4(a). Interestingly, the throughput of STA2 is also deteriorated by about 20% even though STA2 is rarely interfered by LTE-U. Regardless of LTE-U, the FER of STA2 is less than 0.04% and only MCS 15 is used for transmission, meaning that the throughput loss is caused by air time loss.

For a further analysis, we consider the A-MPDU transmission time, excluding overheads such as inter frame spaces (IFSs), backoff time, and block acknowledgement (BA) transmission time, for simplicity. As shown in Fig. 4.4(b), the transmission time of AP1 decreases with LTE-U. In addition, the transmission times of STA2 and the whole network also decrease. It signifies that the air time loss of STA2 does not result from data transmission of STA1 and LTE-U causes severe overhead to Wi-Fi.

As AP fails to receive BA from STA1 for multiple times during LTE-U ON period, AP uses a large backoff counter, thus causing air time loss to both STA1 and STA2. Besides, the large number of retransmission to STA1 reduces the chance of transmission to STA2. Moreover, we observe packet transmission between AP and stations and see that AP transmits request-to-send (RTS) frame several times during LTE-U ON period even though RTS threshold is set to 2,347.[1] However, as AP fails to receive a BA from STA1 continuously due to LTE-U, it transmits RTS as a part of rate adaptation even though LTE-U BS cannot hear that [17]. In addition, when subframe errors occur significantly, we observe that AP transmits RTS without increasing contention window.

To verify the effect of RTS and data retransmission, we change the maximum number of retransmissions from 12 to 1. The throughput results and A-MPDU transmission time using one RTS retransmission and one data retransmission (*w/LTE-U, retry1*) is shown in Fig. 4.4(a) and Fig. 4.4(b). The transmission time of the whole network is almost the same as that without LTE-U. The throughput and transmission time of STA2 slightly increase compared with those without LTE-U. Due to fewer RTS and data retransmissions, STA2 recovers its air time. In addition, as more frame losses occur between AP and STA1, AP gets more chances to transmit to STA2, because AP does not transmit fully aggregated A-MPDU to STA1 for rate adaptation. The throughput of STA1 decreases more than that of *w/ LTE-U* while transmission time is recovered significantly. It is because AP suffers from more frame errors and uses lower MCS, thus getting less chance to transmit to STA1.



(a) Throughput in S2-2 (b) Transmission time in S2-2

Figure 4.5: Downlink throughput and transmission time in S2-2 when duty cycle is 80/80 and SLIR is −6 dB.

S2-2

Fig. 4.5(a) shows the throughput results of STA1 and STA2 when AP1 and AP2 transmit downlink traffic and SLIR is −6 dB. When LTE-U BS transmits traffic using duty cycle 80/80, the throughput of STA1 decreases. Interestingly, the throughput of STA2 also decreases by about 17% even though there is a good link between STA2 and AP2 where AP2 always uses MCS 15 for transmission because of low FER.

It means that frame error is not a main reason for the throughput reduction but air time loss is. To verify that, we calculate A-MPDU transmission time in Fig. 4.5(b). The transmission times of STA1, STA2, and the whole network decrease, thus signifying severe overhead caused by LTE-U. As in S2-1, we measure throughput and calculate transmission time after setting the maximum number of RTS and data retransmissions to one. In Fig. 4.5(a) and Fig. 4.5(b), the throughput and transmission time of STA2 (*w/LTE-U, retry1*) increase with LTE-U. Due to fewer RTS retransmissions of AP1, AP2 recovers air time. In addition, as more frame errors occur in AP1, AP1 has a larger backoff count, thus making AP2 transmit more frames than before. AP1 recovers

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[1] The RTS threshold of 2,347 is a default value of many commercial APs and it means AP will never use RTS for data transmission.

transmission time a lot but throughput is almost the same as *w/ LTE-U*. It is because fewer RTS retransmissions result in more frame errors, lower MCS, and larger backoff count.

4.2 Energy and Air Time Waste Problem

We observe that the performance of Wi-Fi is drastically degraded by LTE-U traffic. A Wi-Fi station can receive virtually no packet successfully during LTE-U ON period even with punctured subframes whether the AP can sense LTE-U or not. In spite of that, the Wi-Fi station keeps sensing channel in order to receive packets, thus resulting in energy waste. Similarly, the AP keeps transmitting packets while wasting air time, thus exacerbating the performance of the whole network.

Therefore, we note that if the Wi-Fi station enters doze state during LTE-U ON period, it can reduce energy consumption without a significant loss of throughput as well as reducing frame errors which occur around LTE-U ON period. In addition, as AP buffers data during LTE-U ON period, it can save air time and enhance the performance of the whole network.

However, existing power save modes cannot operate as stated above. With either static PSM or dynamic PSM, the station cannot enter awake state properly during LTE-U OFF period because their operation hugely depends on beacon reception. Furthermore, dynamic PSM cannot make the station switch to PSM properly during LTE-U ON period either because null frame transmission is disturbed by LTE-U. APSD needs to detect LTE-U duty cycle to set a proper service period. Even if these power save modes make the station enter doze state properly during LTE-U ON duration, station gets back to awake state to receive beacon or transmit uplink packet in the middle of LTE-U ON period. Therefore, we need to develop a new power save operation for the Wi-Fi station to reduce its energy consumption and enhance network throughput in coexistence with LTE-U.

Chapter 5

AWARE: Proposed Algorithm

Based on the motivation discussed in Chapter 4, we propose *AWARE*, an adaptive Wi-Fi power save operation algorithm coexisting with LTE-U. *AWARE* requires no hardware modification so that it can be applied to the existing hardware by just updating the device driver of a Wi-Fi station. The fundamental idea of *AWARE* is that the Wi-Fi station detects LTE-U signal pattern and switch between doze state and awake state adaptively according to the pattern to reduce its energy consumption and save network air time while retaining its throughput almost the same.

Fig. 5.1 shows the overall procedure of *AWARE*. If a PHY header error occurs or n subframes are consecutively lost while the Wi-Fi station receives packets, LTE-U detection is triggered. It is also triggered periodically to reduce power consumption even when the Wi-Fi station does not receive/transmit packets. When LTE-U detection is triggered, *AWARE* gets received-signal-strength (RSS) values using *spectral scan* [1] and then processes and calibrates them to detect LTE-U pattern. Depending on the results of LTE-U detection, the Wi-Fi station switches between doze state and awake state adaptively, which we refer to as "enhanced power save operation" (EPSO). After doing EPSO, it performs LTE-U detection to deal with the disappearance and change

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[1] Linux-based open-source device driver, *ath9k*, provides *spectral scan* operation. Note that scanning the frequency-domain in idle state can be easily supported by any kinds of chipsets.

of LTE-U traffic pattern. Each procedure is detailed in the following.

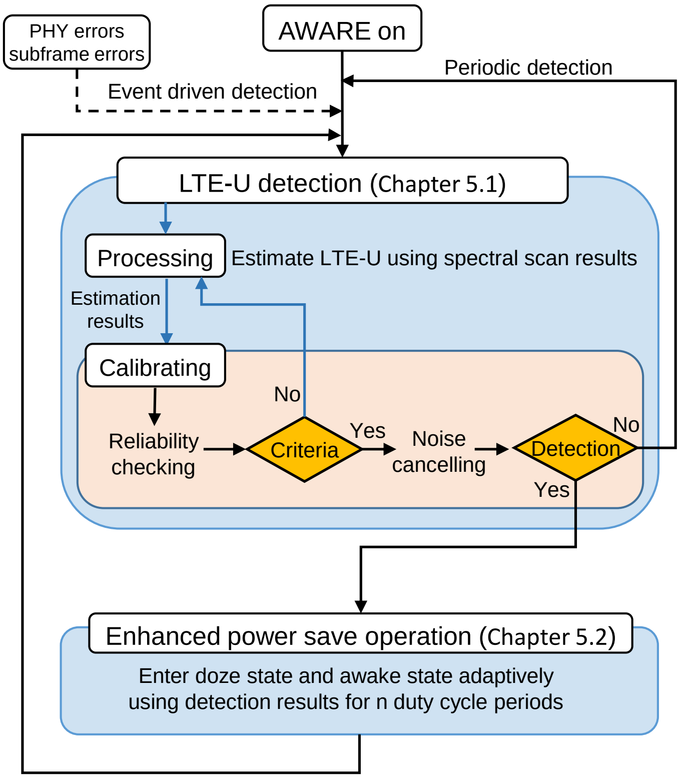


Figure 5.1: Flow chart of *AWARE*.

5.1 LTE-U Detection

To enable EPSO, a Wi-Fi station needs to detect LTE-U signal pattern such as ON period, OFF period, the number of punctured subframes, and puncturing period. As mentioned above, LTE-U pattern is detected by processing and calibrating RSS values which are obtained by conducting spectral scan. Since spectral scan operates only during *idle state* and reports FFT data from the baseband, we can obtain RSS values of non Wi-Fi signals such as LTE-U using the output of spectral scan.

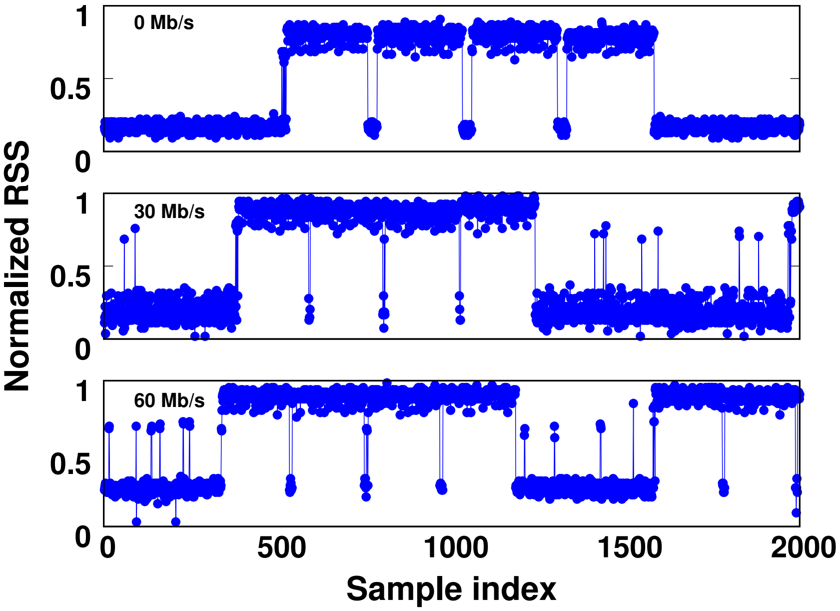


Figure 5.2: Normalized RSS values according to spectral scan sample index when interferer's data rate is 0, 30, and 60 Mb/s.

5.1.1 Processing

During LTE-U detection, a Wi-Fi station triggers spectral scan continuously and records RSS values and its reception time. If there is LTE-U signal, the distribution of RSS values has a kind of regularity according to the pattern of LTE-U signal transmissions. Fig. 5.2 shows a snapshot of the normalized RSS values versus spectral scan sample index according to the data rate of interferer. The interferer is a Wi-Fi AP which cannot sense LTE-U and the strength of the interference is -46 dBm. RSS values are relatively low during OFF period and punctured subframes, and relatively high during ON period.

By using such regularity of RSS values and recorded reception time of each RSS sample, the Wi-Fi station estimates ON period, OFF period, puncturing period, and the number of punctured subframes. Let us define 1) the reception time (in milliseconds)

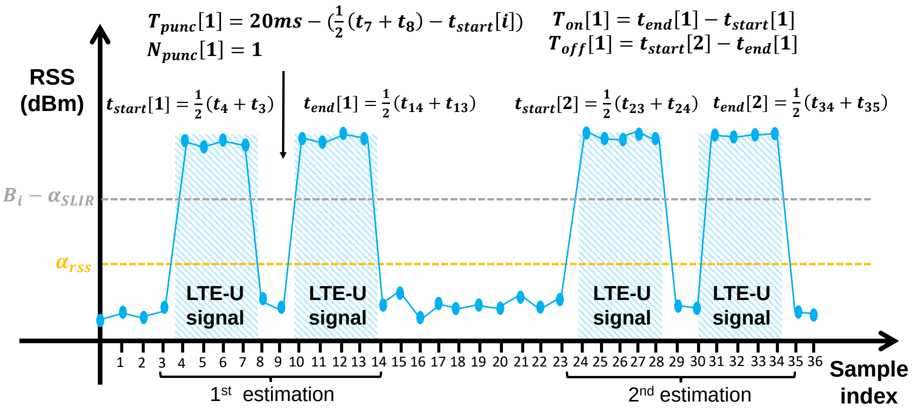


Figure 5.3: Example of processing in LTE-U detection.

of the i-th RSS sample obtained by conducting spectral scan as t_i, 2) the RSS value of the sample as R_i, 3) the RSS value of the most recently received beacon signal as B_i, and 4) the calculated ON period, OFF period, puncturing period, and the number of punctured subframes at the w-th estimation as $T_{on}[w]$, $T_{off}[w]$, $T_{punc}[w]$, and $N_{punc}[w]$, respectively. These values are initialized to zero at first.

If $R_i < \alpha_{rss}$ and $B_i - R_i > \alpha_{SLIR}$ and $R_{i+1} \geq \alpha_{rss}$ and $B_{i+1} - R_{i+1} \leq \alpha_{SLIR}$ for the first time after the $(w-1)$-th estimation, the Wi-Fi station records $\frac{1}{2}(t_i + t_{i+1})$ as $t_{start}[w]$. Note that α_{rss} is the RSS threshold, which determines whether the RSS value is caused by LTE-U, and α_{SLIR} is the SLIR threshold, which indicates the maximum SLIR we want to handle. It can be set considering the strength of LTE-U we want to detect. After that, if $R_j \geq \alpha_{rss}$ and $B_j - R_j \leq \alpha_{SLIR}$ for $j > i$, the Wi-Fi station keeps triggering spectral scan. If not, it checks R_k, where t_k is $t_{start}[w] + 20\,ms \cdot N_{punc}[w]$, to determine whether R_j is caused by puncturing period or not because the maximum successive transmission time in ON period is 20 ms. If $R_k \geq \alpha_{rss}$ and $B_k - R_k \leq \alpha_{SLIR}$, the Wi-Fi station records $t_k - \frac{1}{2}(t_{j-1} + t_j)$ as $T_{punc}[w]$, increases $N_{punc}[w]$ by one, and keeps triggering spectral scan. Otherwise, it stops triggering spectral scan and records $\frac{1}{2}(t_{j-1}+t_j)$ as $t_{end}[w]$ and finishes w-th estimation. Repeating this procedure for several times, $T_{on}[w]$ and $T_{off}[w]$ are calculated by

$$T_{on}[w] = t_{end}[w] - t_{start}[w], \tag{5.1}$$

$$T_{off}[w] = t_{start}[w+1] - t_{end}[w]. \tag{5.2}$$

Fig. 5.3 shows an example of the processing in LTE-U detection for the first and second estimation when there is one punctured subframe in LTE-U ON period.

5.1.2 Calibrating

Since spectral scan only operates during *idle state*, there are two main problems in the processing step. **P1:** The reception time difference of two consecutive RSS samples can be larger if a Wi-Fi station receives or transmits packets. **P2:** Non Wi-Fi signals besides LTE-U or Wi-Fi signal whose preamble is not detected or missed can cause high RSS values. Therefore, in Fig. 5.2, ON period is represented by a smaller number of samples and large RSS values appear more during OFF period as the interferer data rate increases.

Reliability checking: P1 causes unreliable detection because we use the reception time difference of two consecutive RSS samples to calculate $T_{on}[w]$, $T_{off}[w]$, and $T_{punc}[w]$. To solve this problem, we consider $T_{on}[w]$ reliable only when the time difference of two consecutive RSS samples used to calculate $T_{on}[w]$ is less than β_t, and use it for detection, where β_t is the time difference threshold. The same way is applied to $T_{off}[w]$ and $T_{punc}[w]$.

Noise cancelling: P2 also degrades detection performance by impairing the regularity of RSS values. To handle this problem, we sort out noisy values among reliable values which have passed the reliability checking. Assuming that there are n reliable $T_{on}[w]$ values ($w = 1, 2, 3, ..., n$), we define d_{ij} as $d_{ij} = |T_{on}[i] - T_{on}[j]|$. For all j ($j \neq i$), if the number of d_{ij}, which satisfies $d_{ij} > \gamma_d$, is larger than $\left\lfloor \frac{n}{2} \right\rfloor$, we drop $T_{on}[i]$ assuming that it is a noisy value, where γ_d is the distance threshold.

A Wi-Fi station repeats the processing and reliability checking until one of the following three criteria is satisfied.

1. **Runtime criterion:** after the n-th estimation, $t_{end}[n]$ - $t_{start}[0] \geq t_{max}$, where t_{max} is the maximum runtime we set.
2. **Number of estimation criterion:** the number of estimation $n_{estimation} \geq w_{max}$, where w_{max} is the maximum number of estimation we set.
3. **Reliability criterion:** the number of reliable values for ON period, OFF period, puncturing period, and the number of punctured subframes, $n_{on}, n_{off}, n_{punc}$, and $n_{num} \geq r_{min}$, where r_{min} is the minimum number of reliable values, which we want to use for noise cancelling.

After satisfying such criteria, the reliable values pass noise cancelling. If there is no remaining values after noise cancelling, detection fails. Otherwise, the Wi-Fi station averages the remaining values and obtains detection results including $T_{on}, T_{off}, T_{punc}$, and N_{punc}. Furthermore, it obtains the ending time of the most recent ON period from the recorded reception times.

5.2 Enhanced Power Save Operation (EPSO)

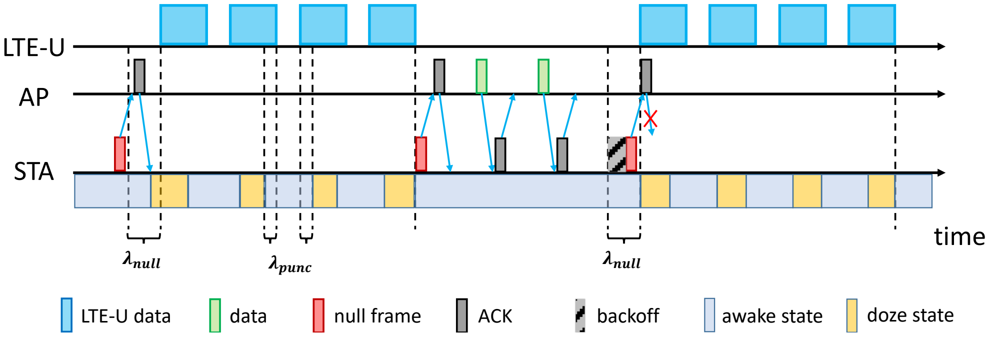


Figure 5.4: Example of enhanced power save operation.

A Wi-Fi station switches between doze state and awake state adaptively based on the results of LTE-U detection. Based on the estimated $T_{on}, T_{off}, T_{punc}$, and N_{punc} are known, the station can predict the starting time O_{start} and the ending time O_{end} of ON period. It can also predict the starting time $P_{start}[i]$ and the ending time $P_{end}[i]$ of puncturing period for each punctured subframe i $(= 1, 2, ..., N_{punc})$. Then, the Wi-Fi station does power save operation at time t according to the following rule.

1. $t = O_{start} - \lambda_{null}$**:** The Wi-Fi station transmits a null frame. If the station receives an ACK before O_{start}, it enters doze state immediately. Otherwise, it enters doze state at O_{start}.
2. $t = P_{start}[i] - \lambda_{punc}$**:** The Wi-Fi station enters awake state immediately to receive a beacon or transmit uplink packets.
3. $t = P_{end}[i] + \lambda_{punc}$**:** The Wi-Fi station enters doze state immediately.
4. $t = O_{end}$**:** If the Wi-Fi station exchanged a null frame and an ACK successfully in 1), it enters awake state and transmits a null frame. Otherwise, it does not transmit a null frame.

To cope with ON period detection error within 1 ms and to transmit a null frame successfully before O_{start}, we define null frame margin as λ_{null}. Since it takes about 0.5 ms to send a null frame and receive an ACK and there can be 1 ms detection error, λ_{null} should be at least 1.5 ms. Since a large λ_{null} is an overhead, we limit it to be under $\delta\%$ of T_{off} and λ_{max}, where δ is a margin ratio and λ_{max} is the maximum null frame margin. Therefore, λ_{null} is calculated as

$$\lambda_{null} = \min\left(\max\left(1.5, \frac{\delta \cdot T_{off}}{100}\right), \lambda_{max}\right). \tag{5.3}$$

Likewise, to cope with puncturing period detection error within 1 ms, we define puncturing margin as λ_{punc} and set it at least 1 ms. The Wi-Fi station repeats the procedure above for n_{epso} times and detects LTE-U again to deal with the disappearance and change of LTE-U traffic pattern. n_{epso} is the iteration time of EPSO, which determines how long the Wi-Fi station runs EPSO. Fig. 5.4 shows an example of EPSO.

Chapter 6

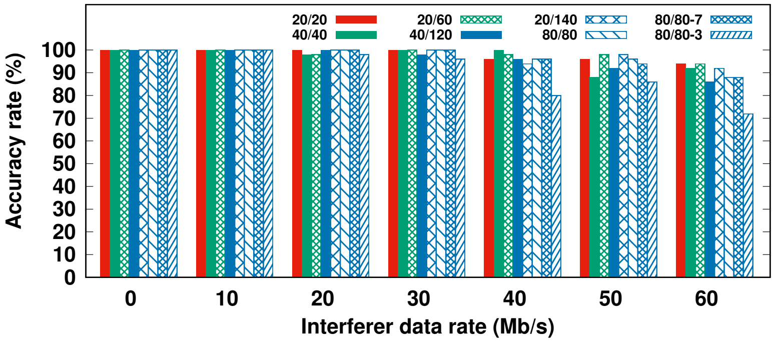
PERFORMANCE EVALUATION

In this Chapter, we present the evaluation results of *AWARE*. We have implemented *AWARE* on off-the-shelf 802.11n laptops equipped with AR9380 NIC by modifying the open source device driver, $ath9k$ [17] and mac80211 [18]. We first evaluate LTE-U detection algorithm, and then evaluate *AWARE* under the scenarios considered in 4.1.

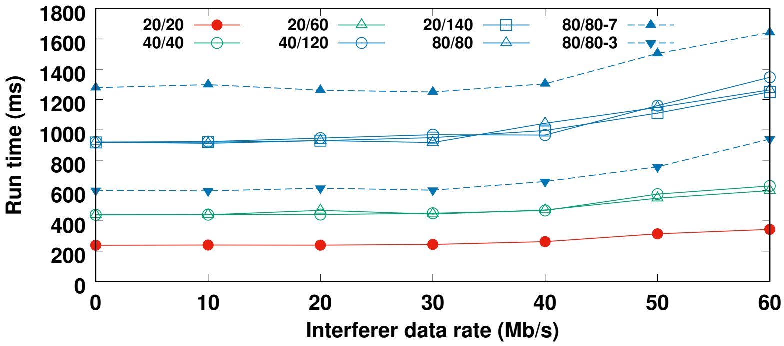
6.1 LTE-U Detection

We evaluate the performance of LTE-U detection algorithm when a Wi-Fi interferer transmits data continuously with various data rates, from 10 to 60 Mb/s, and the interference strength of -46 dBm. This is the worst scenario because it is hard to distinguish continuous and regular interference from LTE-U signal through noise cancelling.

Fig. 6.1(a) shows the accuracy rate of the detection algorithm according to interferer data rate when β_t, γ_d, t_{max}, w_{max} are 0.5 ms, 1 ms, 2 s, and 10, respectively. The accuracy rate is defined as the number of correct detection outcomes over the total number of detection trials. We first compare the accuracy rate with three different r_{min}'s, i.e., 3, 5, and 7, when duty cycle is 80/80 (labelled as *80/80-3, 80/80*, and *80/80-7*). If r_{min} is 5 or 7, the accuracy rate is 100% until the interferer data rate of 30 Mb/s, and it becomes lower than 90% when the interferer data rate is 60 Mb/s. The



(a) Accuracy rate



(b) Run time

Figure 6.1: Detection accuracy rate and run time obtained by the station according to interferer data rate, r_{min} of 3, 5, and 7, and several duty cycles. r_{min} is 5 if there is no indication.

data rate 60 Mb/s means the interference signal occupies more than a half of the air time continuously. Therefore, it is hard to get enough number of reliable values and distinguish noise values at 60 Mb/s. On the other hand, if r_{min} is 3, the accuracy rate is affected by the interference more easily because the algorithm compares only three values to sort out noise values. Therefore, the accuracy rate starts to decrease at the interferer data rate of 20 Mb/s and it becomes 72% at 60 Mb/s. Fig. 6.1(b) shows the run time of the detection algorithm with the same setting as above. The higher the data rate of interferer and the larger r_{min}, the longer run time. It is because frequent interference and large r_{min} make the algorithm hard to get enough reliable values satisfying r_{min}.

We also evaluate LTE-U detection algorithm for various duty cycles when r_{min} is 5. Accuracy rate is decreased when the data rate of interferer becomes higher. However, in most cases, the accuracy rate is higher than 90%, and the minimum average accuracy rate for all data rates is 96%. The run time becomes long when the data rate of interference is high enough to cause detection error. The same duty cycle length results in a similar run time, and it takes more time to detect LTE-U signal as duty cycle period increases. In this paper, we evaluate the detection algorithm with continuous and regular interference patterns which hardly exist in the real world. Therefore, we expect that the performance of detection algorithm will be better in reality.

There exist two types of failure in LTE-U detection. The first one is that there is no output after running the algorithm. In this case, EPSO does not work and waits for the next output of the detection, thus it does not degrade the performance of Wi-Fi station. The second one is that there is a wrong output after running the algorithm. Unlike the first one, this case may be a serious problem since EPSO will run incorrectly based on the wrong detection result. However, more than 98% of the wrong outputs have errors within 1 ms. It means that the Wi-Fi station cannot receive a packet for 1 ms only if there is a packet at that time. Therefore, the wrong detection within 1 ms does not heavily affect the performance of Wi-Fi.

6.2 AWARE

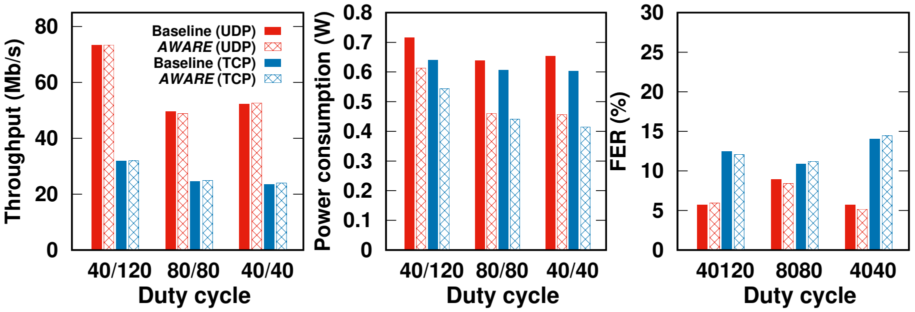
In this section, we evaluate *AWARE* in Scenario 1 and 2, considered in 4.1. A Wi-Fi station detects LTE-U once, and then the station runs EPSO for 5 s while an AP transmits saturated signals to the station. Additionally, we newly define Scenario 3 and 4 in this section, and also evaluate *AWARE* in the new scenarios. In Scenario 3 (S3), we test uplink transmission in situation of Scenario 2. In Scenario 4 (S4), the Wi-Fi station detects LTE-U signal periodically while the AP transmits bursty signals.

The evaluation parameters are listed in Table 6.1.

Table 6.1: Common evaluation parameters

Parameter	Value	Parameter	Value
α_{rss}	-62 dBm	w_{max}	10
α_{SLIR}	6 dB	r_{min}	5
β_t	250 μs	δ	10
γ_d	$1,000$ μs	λ_{max}	$5,500$ μs
t_{max}	2 s	λ_{punc}	$1,000$ μs

6.2.1 Scenario 1



(a) Throughput (b) Power consumption (c) FER

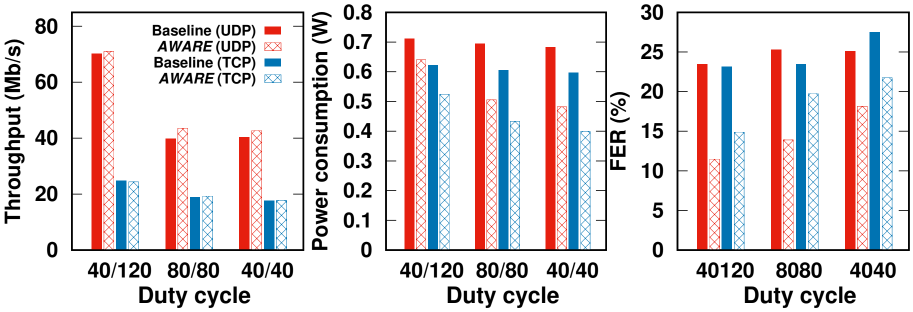
Figure 6.2: Downlink throughput, power consumption and FER according to three different duty cycles in S1.

In Scenario 1, AP1 usually keeps transmitting packets even if STA1 sends a null frame because there are packets in queue before receiving a null frame. We compare the performance of *AWARE* with the baseline 802.11n (*baseline*). Fig. 6.2 shows the throughput, power consumption , and FER of STA1 averaged on different SLIRs (6 dB, 0 dB, and -6 dB). In order to calculate power consumption, we exploit the measurement results in [19], in which the authors measure the energy consumption per transmitted bit of information according to MCS using AR9380. Based on the measurement results and information of transmitted frame size and MCS, we calculate average power consumption for 5 s. For every duty cycle, *AWARE* achieves almost the same throughput and FER compared with *baseline*, while power consumption decreases by up to 31%. It is because STA1 enters doze state and awake state by itself depending on duty cycle while AP1 keeps transmitting packets.

6.2.2 Scenario 2

Different from Scenario 1, AP1 usually buffers new packets after receiving a null frame because it drops the packets which have been queued before receiving the null frame by failing to transmit them.

S2

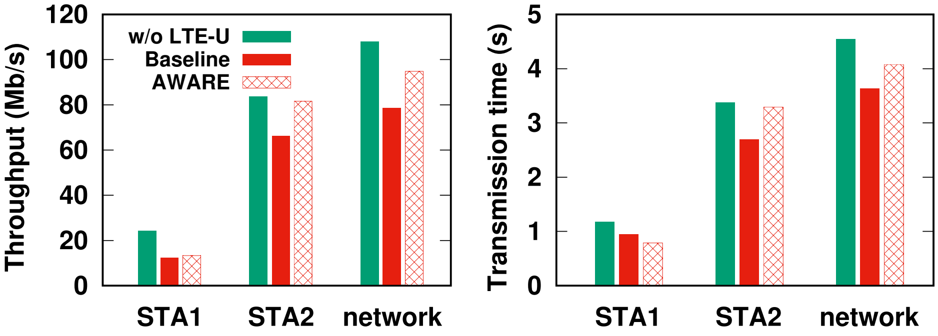


(a) Throughput (b) Power consumption (c) FER

Figure 6.3: Downlink throughput, power consumption and FER according to three different duty cycles in S2.

Fig. 6.3 presents the throughput, power consumption, and FER averaged on different SLIRs (6 dB, 0 dB, and −6 dB). Even though AP1 transmits packets for shorter time than *baseline* by running *AWARE*, it achieves equal or higher throughput than that of *baseline* while achieving up to 33% lower power consumption. It is because as using *AWARE*, the AP buffers the packets during LTE-U ON period, and hence, FER is much more decreased than in Scenario 1 (S1) as shown in Fig. 6.3(c)

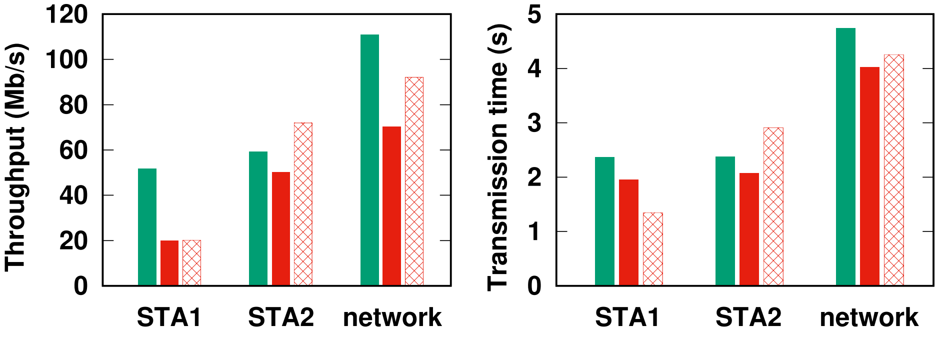
S2-1



(a) Throughput (b) Transmission time

Figure 6.4: Downlink throughput and transmission time of STA1, STA2 and the whole network in S2-1.

Fig. 6.4 shows the throughput and calculated A-MPDU transmission time of STA1, STA2, and the the whole network when the AP1 transmits UDP downlink traffic to STA1 and STA2. The duty cycle of LTE-U is 80/80 and SLIR is -6 dB, respectively. The transmission time of STA1 is decreased while that of STA2 is increased compared to *baseline*. Since AP1 does not transmit packets to STA1 during LTE-U ON period, STA2 takes more air time. In addition, as *AWARE* reduces unnecessary transmission of RTS, STA2 recovers air time. Therefore, STA2 achieves 23% higher throughput than *baseline*. As expected, STA1 maintains the throughput while reducing its power consumption as in Fig. 6.3. However, the transmission time of the whole network is shorter than that without LTE-U. It is because the station sometimes fails to transmit a null frame due to CCA and the AP sometimes keeps transmitting packets even after receiving the null frame as in Scenario 1. The throughput of the whole network is also lower than that without LTE-U, since the transmission time is shorter and STA2 is interfered by LTE-U a little.



(a) Throughput

(b) Transmission time

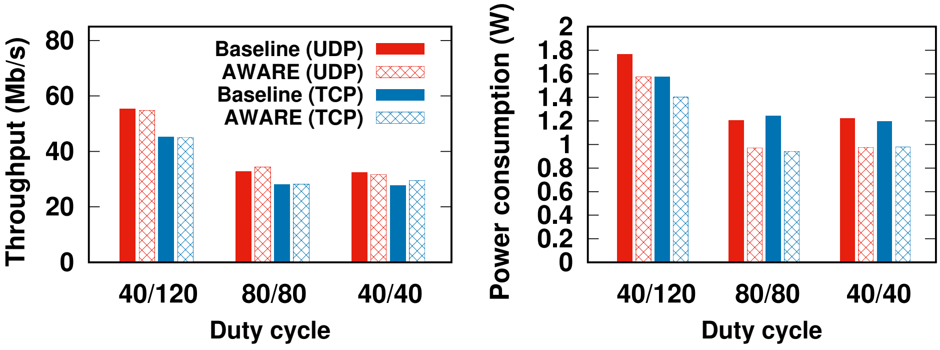
Figure 6.5: Downlink throughput and transmission time of STA1, STA2 and the whole network in S2-2.

S2-2

Fig. 6.5 shows the throughput and calculated A-MPDU transmission time of STA1, STA2, and the whole network when AP1 and AP2 transmit UDP downlink traffic to STA1 and STA2. The duty cycle of LTE-U is 80/80 and SLIR is -6 dB, respectively. Similar to Fig. 6.4(b), STA2 gets more air time as AP1 buffers packets during LTE-U ON period and reduces unnecessary transmission of RTS. Therefore, the throughput of STA2 increases by 43% while STA1 maintains its throughput and reduces power consumption. Compared with S2-1, the throughput of STA2 is increased. The reason is that since STA1 and STA2 share air time more fairly than S2-1, STA2 takes more air time from STA1 when AP1 does not transmit packets to STA1. However, the transmission time and the throughput of the whole network are less than those without LTE-U for the same reason as in S2-1.

6.2.3 Scenario 3

Furthermore, we test the performance of uplink transmission when *AWARE* operates in situation of Scenario 2. The throughput and calculated power consumption results of STA1 are in Fig. 6.6(a) and Fig. 6.6(b), respectively. As expected, STA1 achieves

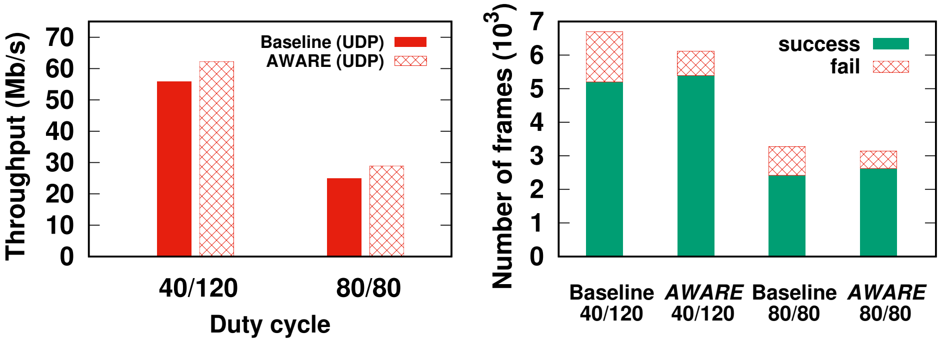


(a) Throughput in S3 (b) Power consumption in S3

Figure 6.6: Uplink throughput and power consumption in S3.

almost the same throughput with *baseline* while reducing power consumption by up to 24%. The reason is that AP1 sends fewer frames than *baseline* but much fewer frame errors occur thanks to *AWARE*.

6.2.4 Scenario 4



(a) Throughput in S4 (b) Number of frames in S4

Figure 6.7: Downlink throughput and number of success or fail frames in S4.

In order to check the performance of *AWARE* when it detects LTE-U periodically, we make the AP transmit packets randomly. The transmission length is randomly selected in 0.1 to 1 s, and the packet interval is randomly selected in 1 to 2 s. *AWARE* detects LTE-U every 2 s and runs EPSO for 15 duty cycles. In Scenario 4, SLIR is

-6 dB, and the AP cannot sense LTE-U signal. Fig. 6.7(a) shows average throughput result obtained by the station, and Fig. 6.7(b) presents the number of frames which AP fails or succeeds to transmit. *AWARE* achieves slightly higher throughput than *baseline* even though the AP transmits fewer frames because the number of successful frames is larger than or equal to that of *baseline*. When the AP transmits bursty traffic, the station succeeds to send a null frame more often than in the previous scenarios, and hence, *AWARE* reduces frame errors more effectively.

Chapter 7

CONCLUSION

In this paper, we have verified that a Wi-Fi station not only suffers from unfairness problem but also wastes energy and air time, thus degrading the whole network performance when it coexists with LTE-U. To solve these problems, we propose *AWARE*, which adjusts power state of the Wi-Fi station adaptively according to LTE-U detection results. *AWARE* can be implemented easily by updating the device driver of Wi-Fi stations without hardware modification. Our evaluation shows that *AWARE* enhances the whole network throughput by up to 50% compared with the baseline while it reduces the power consumption of Wi-Fi station by up to 33% by adapting power states effectively according to LTE-U duty cycle. Our future work will include detecting LTE-U traffic in Wi-Fi secondary channel and adjusting bandwidth according to LTE-U traffic.

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초 록

LTE-Unlicensed(LTE-U)는 Wi-Fi가 오랫동안 사용하던 5 GHz 비면허 대역에서 LTE 하향링크 동작을 지원한다. 비면허 대역을 사용하는 Wi-Fi와의 공평한 공존을 하기 위해 LTE-U는 carrirer sense adaptive transmission(CSAT)을 이용하지만, 이는 공평한 공존을 완벽하게 보장하지 않는다. 따라서 많은 연구들은 Wi-Fi와 LTE-U의 불공평한 공존 문제를 다룬다. 이 논문에서, 우리는 실험을 통해 LTE-U와 공존하는 경우에 Wi-Fi 단말이 불공평한 공존 문제뿐만 아니라 에너지 낭비와 매체 점유 시간 낭비문제를 겪는다는 것을 확인했다. 이러한 문제를 해결하기 위해 우리는 *AWARE*를 제안한다. *AWARE*는 하드웨어의 수정없이 단말기에서 동작하는 적응적인 Wi-Fi 절전 동작이다. 우리는 상용 802.11n 장비에 *AWARE*를 구현하여 기존의 Wi-Fi와 성능을 비교하였다. *AWARE*를 통해 효과적으로 Wi-Fi 단말기의 파워 상태를 조절하여 Wi-Fi 단말기의 전력소모가 약 33% 절약되었고 동시에 Wi-Fi 단말기의 데이터 전송률이 약 50% 증가하였다.

주요어: IEEE 802.11n, Wi-Fi 절전모드, LTE-U

학번: 2017-21811