석사 학위논문

Efficient Power Management in Multi-Link Operation on IEEE 802.11be Networks

IEEE 802.11be 의 멀티링크 동작에서 효과적인 전력 관리를 위한 선택적인 링크 활용 기법

2022 년 8 월

서울대학교 대학원
전기정보공학부
윤예린

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이 논문을 석사 학위논문으로 제출함

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윤예린의 석사 학위논문을 인준함

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Abstract

Multi-Link Operation (MLO) is the fundamental feature in Wi-Fi 7 that helps to enhance the throughput in communication. While Wi-Fi 6 aimed High Efficiency (HE), Wi-Fi 7 focuses on the Extremely High Throughput (EHT) to provide communication between the devices that require fast wireless networks, such as virtual reality (VR). MLO allows the devices to use multiple links to transmit data, and hence the throughput is expected to increase by the multiple of the numbers of links. However, the more devices obtain high throughput through multi-link, the more devices consume much power. Thus, among many aspects of MLO, this paper explores the Power Save Mode (PSM), the feature added to most Wi-Fi devices. PSM has two states which are the awake state and the doze state. When data is being transmitted, it stays in the awake state. When there is no data to send or to receive, the device enters the doze state. On the other hand, wireless networks are vulnerable to interferences and PSM performance can heavily depend on the channel state. The performance of PSM may degrade due to the interferences, and this paper proposes a method to maintain the performance of PSM in MLO in the situation where the link channel states vary.

Keywords : Multi-Link Operation (MLO), Power Save Mode (PSM), Wi-Fi 7, IEEE 802.11be, Interference, Channel state

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I. Introduction

Wi-Fi has played an integral role in today's wireless communication. Wi-Fi development has aided the world by providing a standard degree of connectivity.

IEEE 802.11be, Wi-Fi 7 is the new Wi-Fi standard that is ready to be commercialized, and it will provide a significant leap in performance over IEEE 802.11ax, Wi-Fi 6. IEEE 802.11be focuses on the Extremely High Throughput (EHT) for higher usage of applications such as virtual reality, augmented reality, 4K streaming, and 8K streaming. IEEE 802.11be standard supports Multi-Link Operation (MLO) that boost the performance. MLO enables the Multi-Link Devices (MLDs) to use multiple channels at once. This paper explores the Power Save Mode (PSM) operation in MLD. Wi-Fi PSM is the built-in technique in most devices to avoid draining the power-limited battery-based devices. PSM is considered the fundamental feature of Wi-Fi that enhances the performance of the devices. The service of WLAN is widely offered in public and domestic areas, and it provides a variety of services on devices such as video streaming and VoIP. As a consequence of the extensive usage of WLAN, the ratio of the device's battery consumption caused by WLAN has increased drastically. IEEE 802.11be includes PSM in Wi-Fi to mitigate the large consumption of batteries. It includes the PSM operation in MLO by modifying slight features of the original PSM where each link in Multi-link Device (MLD) operates in PSM independently. However, we have encountered a problem that MLD may face in a certain environment. The wireless links have varying interference levels, and using all links without considering the channel capacity may degrade Wi-Fi performance. This paper aims to use the MLD's benefit, dynamic link selection, to maximize the power saving at the STA while maintaining the throughput. Chapter 2 analyzes other related works and chapter 3 explains the background knowledge of MLO and PSM. In chapter 4, we introduce a problem that may be encountered under a certain circumstance and propose a new scheme to overcome the analyzed issue in Chapter 5. Chapter 6, 7, and 8 demonstrate the simulation results, an evaluation, and a conclusion.

II. Related Work

Various studies on Power Save have been made in many different areas. [1], [2], [3],and [4] are the studies of Power Save in single link devices. [1] observes the studies of PSM that have been made and compares various schemes. [2], [3], and [4] improve the power saving mechanism by spotting the problem caused by the contention-based mechanism, such as a hidden terminal, and proposing a new scheme.

[7], [8], [9], [10],and [12] address the problems encountered when implementing MLO. [7] addresses the coexistence challenge and proposes solutions, [9] introduces a traffic manager to distribute the incoming traffic and reduce the congestion. [10] suggests that Multi-Link Single-Radio (MLSR) is more effective in reducing latency while guaranteeing fairness with single link nodes and [12] resolves how to distribute traffic across multiple links.

[11] measures the power consumption on the device and analyses the actual amount of power consumed in different PSM states.

III. Background

III.1 Multi-Link Operation (MLO)

MLO is the newly added feature of the medium access control (MAC) layer in IEEE 802.11be, and it is a new approach being attempted for the first time in EHT. MLO enables devices to transmit and receive across different channels simultaneously; for example, a 2.4 GHz radio, a 5 GHz radio, and a 6 GHz radio. The main objective of MLO is the simultaneous use of various.

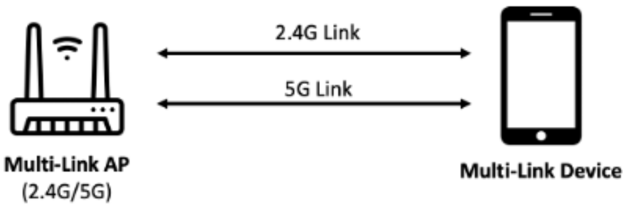

Fig. 1 Example of MLO Application

As shown in Fig. 1, MLO enables link aggregation at the MAC layer, where a link is mapped to a channel. The purpose of MLO is to augment the throughput, lower latency, and increase reliability. Data can be split over links and sent simultaneously. The parallel transmission of a different part of data shortens the transmission time and brings higher throughput and lower latency. Instead of splitting data, MLO can send duplicated packets over multiple links. Although one link fails to transmit the data, the other links that send the same data can still successfully transmit the data and increase the system's reliability. MLO can assign data flows to specific links based on app needs.

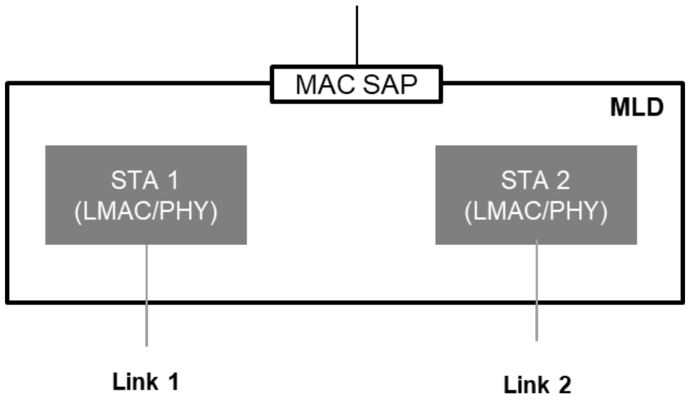

Fig. 2 MAC-layer of MLO

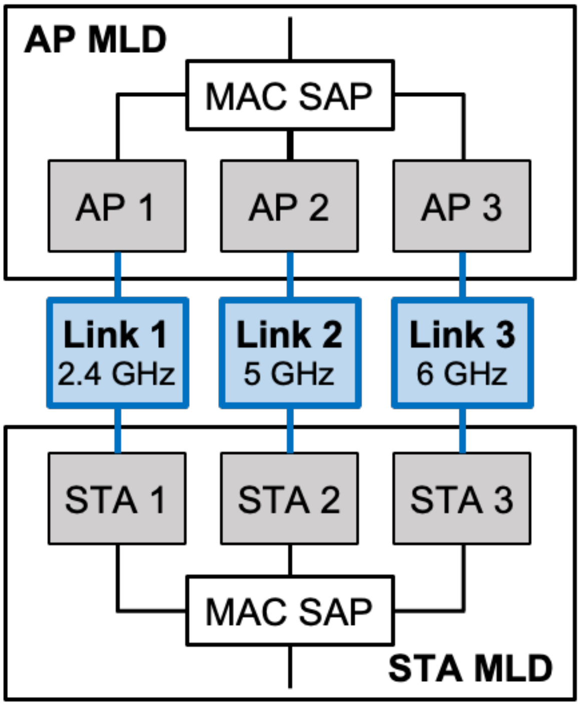

Fig. 3 System Architecture of MLO

Fig. 2 demonstrates a MAC-layer of MLO for concurrent multi-link utilization. MLO exposes only one Service Access Point (SAP) to the upper sublayer of the data link layer.

MLO brings many advantages over Single-Link Operation (SLO) as it uses the multiple links. It uses the existing physical (PHY)-layer and Lower MAC (LMAC) and only modifies the Upper MAC (UMAC). Each affiliated STA contains its own PHY and LMAC components. MLD has one UMAC aggregating all the affiliated STAs and provides Logical Layer Control (LLC) with a single MAC SAP. Furthermore, in the current wideband operation in IEEE 802.11be which also allows the network to use bigger bands, the channel access process is only available through the primary channel, but MLO can run channel access processes across multiple channels. MLO brings more opportunities to access the channels by exploiting all the possible channels, while the wideband operation access opportunity only depends on the primary channel's state.

Fig 3. represents the system architecture of MLO. MLD is the EHT device that operates under MLO, and Single-Link Device (SLD) is the device that communicates under Single-Link Operation (SLO). MLD is affiliated with more than one STA, and each link of an MLD is regarded as a single STA. SLD is affiliated with a single STA. There are two types of MLDs depending on STAs: an AP MLD and a non-AP MLD. AP MLD is the device affiliated with STAs that are APs, and non-AP MLD is the one affiliated with STAs that are not APs. For ease of understanding, non-AP MLD is noted as STA MLD in the paper. MLD BSS is formed by connecting each affiliated APs with each affiliated STAs using independent channels.

III.2 Power Save Mode (PSM)

Wireless LAN is one of the significant factors that consumes an incredible amount of power from the device's battery. To mitigate this problem, almost all devices put the devices' WLAN state into a SLEEP state when there is no network traffic with PSM. In PSM, there are two modes, awake mode and sleep mode. When the device is awake, it can transmit or receive data. When the device is in sleep mode, the device does not transmit/receive any data. The device saves energy by putting the device into the sleep mode when there is no data transmission and makes sure it receives data by occasionally waking up when there is data to transfer or receive.

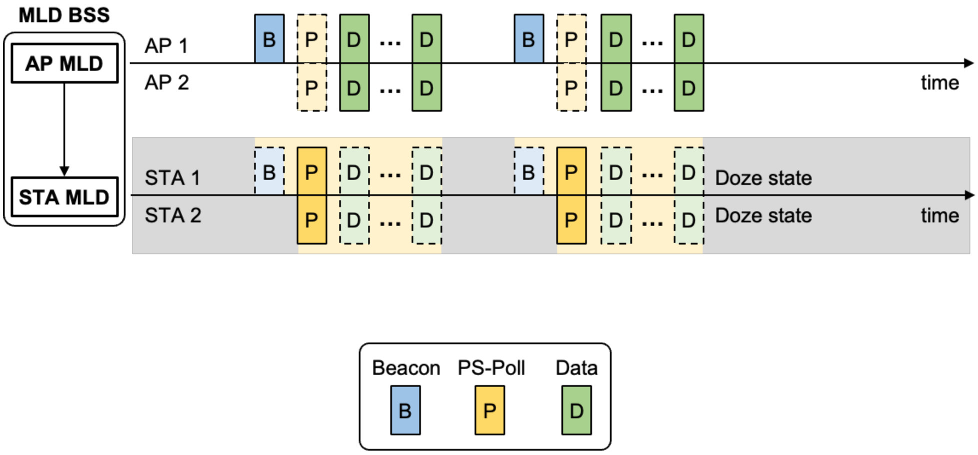

Fig. 4 PSM operation in MLO

Fig. 4 demonstrates the operation of PSM in MLO in a time axis. Access Point (AP) periodically broadcasts a management frame called a beacon, allowing the AP to notify its presence to nearby devices. A beacon is triggered by default every 102.4 ms on AP, and it advertises wireless network information such as supported PHY rates, supported QoS, and much more. Traffic Indication Map (TIM), which is included in the beacon frame, is an Information Element (IE) informing whether AP has buffered frames. Once a station (STA) receives and processes the beacon, it checks the Partial Virtual Bitmap under the TIM IE for their Association ID (AID). AID is unique to every STA and AP, and it is given during the association process of STA and AP. STA processes the beacon and looks at its TIM value using its AID. For example, if an STA has AID 3, it looks at the

TIM bit of AID 3. If the TIM is set to 1, the STA knows there are packets buffered, and it proceeds to send a Power Save Poll (PS-Poll). On the other hand, if it is 0, there are no buffered packets.

PS-Poll is sent from STA to AP to notify AP that it is now awake and ready for the transmission of packets. Then, AP sends the data until the end of the transmissions. Once all the packets from the queue are transmitted, the STA goes back to its sleep mode.

In MLD, the beacon is sent on any link and the information contained in the beacon is shared by all MLD STAs. The beacon frame also notifies which link needs to wake up. Once the beacon is received on one of the links can wake up and send PS-Poll to the AP. The other links that did not receive the beacon will also be indicated that they have packets to receive. Waking up and sleeping procedures are the independent processes within the MLD. Each MLD decides whether to wake up or stay in a sleep state.

IV. Problem Statement

A wireless network, especially a Wi-Fi network, is vulnerable to the environment. Many factors affect Wi-Fi performance, such as physical barriers and frequency interference. This paper considers frequency interference as the main factor causing the change in channel conditions. Wi-Fi uses the unlicensed band, which leaves the system vulnerable to any device using the same band and causes interferences. These devices include a non-Wi-Fi device (neighbour's network, Bluetooth, and many more). The interference degrades the network's performance, and transmission failure may occur more frequently.

When the transmission failure occurs, the network assumes that the packet failure has occurred due to collisions with other transmissions. In the case of a collision, the chance for packet transmission to succeeding increases as many transmissions are attempted. Therefore, the AP retransmits the packets repeatedly until the transmission success occurs. However, a retransmission only increases the burden when the channel condition is unstable due to the interference and further degrades the channel.

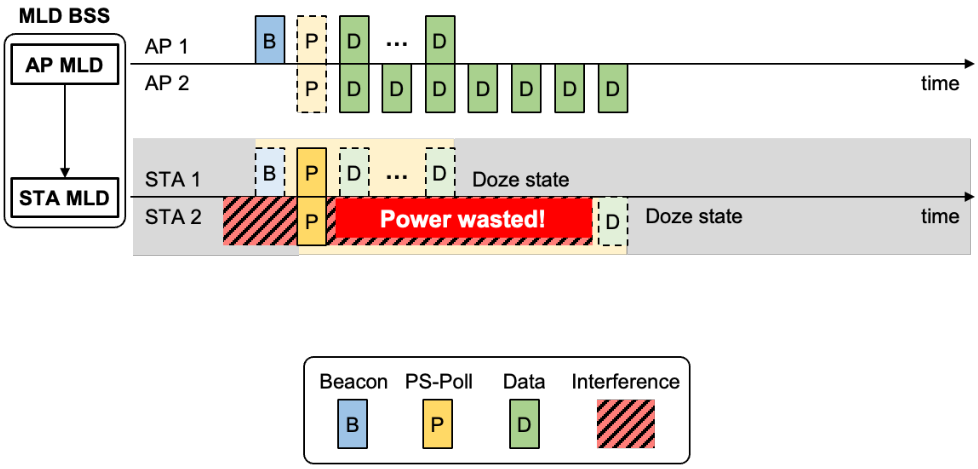

Fig. 5 Possible outcome of PSM operation following the IEEE 802.11be draft

IEEE 802.11be amendment has stated to control the PSM of each MLD affiliated device individually. Fig. 5 demonstrates the likely outcome of the PSM performance following the amendment considering the occasional existence of interferences on both links 1 and 2, and we call this a naive scheme. In naïve scheme, all affiliated STAs wake up to send PS-poll without considering the interference. For example, MLD AP sends the beacon on link 1 and STA 1 on link 1 receives the beacon, STA 1 and STA 2 wake up to send the PS-poll. In the meantime, link 2 is experiencing an unstable channel state, and hence the retransmission occurs. STA on link 1 returned to the doze state after receiving data, but STA on link 2 stays in the awake state for an extended period and consumes more power than expected. The power wastage can be avoided if the MLD can decide whether to wake up a specific link depending on its channel condition.

V. Proposed Scheme

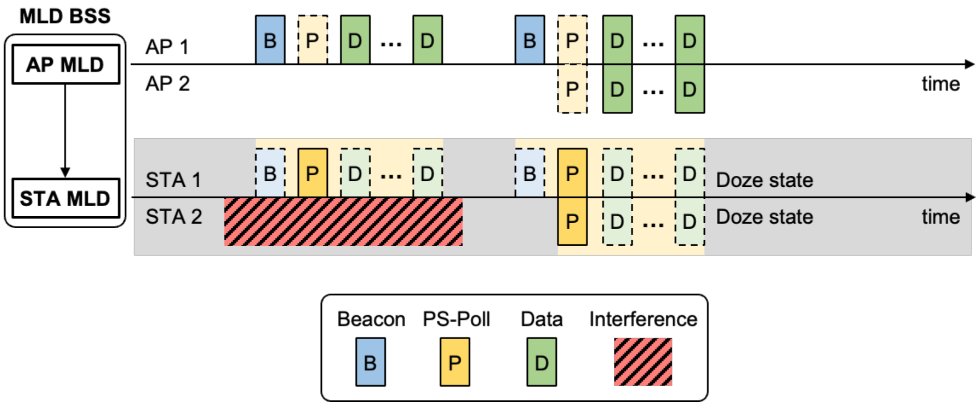

Fig. 6 Proposed Scheme

$$\text{Success Ratio} = \frac{\#\text{ of packets transmitted successfully}}{\#\text{ of packets transmitted}} \tag{1}$$

We introduce a novel scheme that selectively wakes up the link, depicted in Fig. 6. MLD AP remembers the channel state of each link, and when sending a beacon, it notifies which link needs to wake up for the subsequent transmission. MLD AP judges the link-state based on the previous and the current transmission success ratio depicted as (1). MLD AP sums up the previous and the current variables to estimate the upcoming link channel state in a weighted sum manner to maintain the historical data with putting more weight on the current ratio to make it closer to the real-time value as

$$SR = previous\ success\ ratio \times 0.3 + current\ success\ ratio \times 0.7 \quad (2)$$

where SR is a predicted success ratio. These ratios are updated at every end of the data transmission.

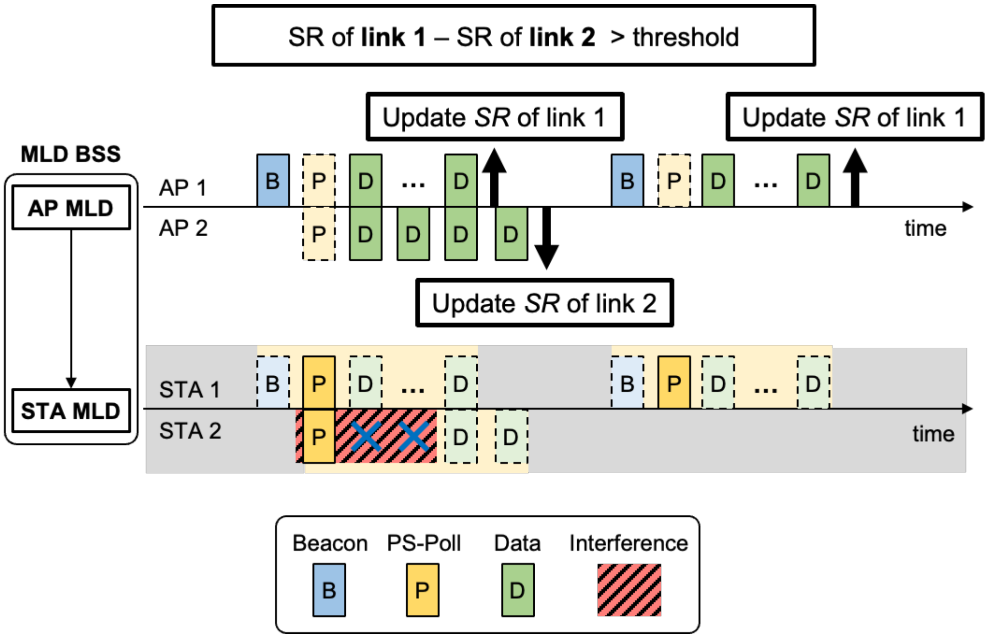

Fig. 7 Link state estimation algorithm - After association

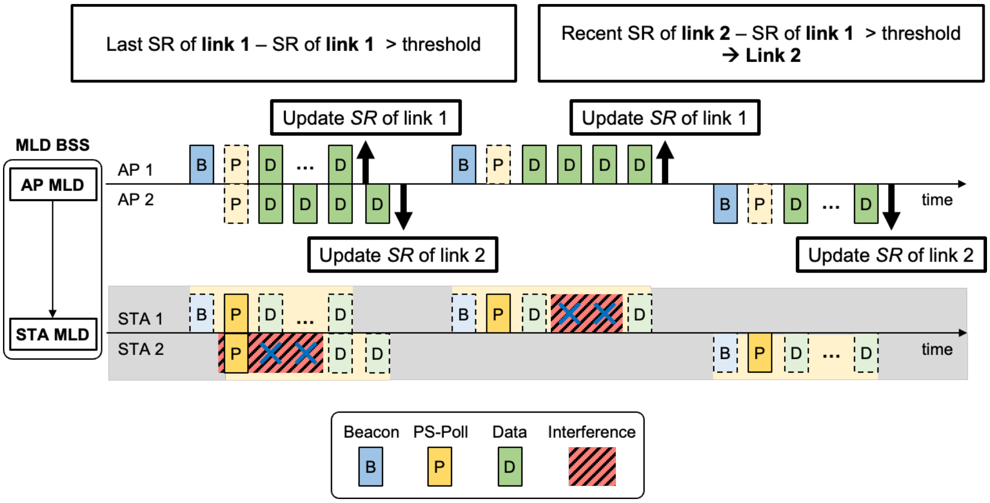

Fig. 8 Link state estimation algorithm - Interference while single channel is used 1

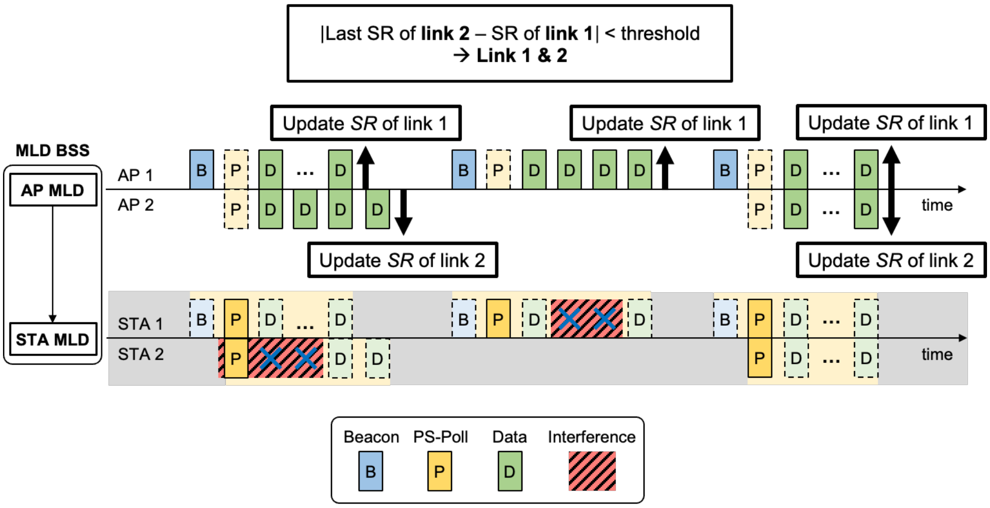

Fig. 9 Link state estimation zlgorithm - Interference while single channel is used 2

Fig. 7, 8, and 9 show the link selection method of the proposed scheme. Fig. 7 shows the case when there is not enough historical data after association and hence uses both links for transmission. When the STAs on both links are awake, the estimated link states of both links are compared for the next wake up. When the difference between these two values is bigger than a threshold value, the STA connected by the link with a higher SR wakes up and receives data when the TIM value of its AID is set to 1 in the next beacon received. However, if the difference between SRs of two links are under the threshold, STA MLD continues to use both links. As seen in Fig. 8 and 9, when only one STA affiliated with STA MLD is awake to receive the packet, AP MLD compares the STA's last SR and the current SR to decide the next wake up of STA. AP uses the same link if the difference of the SR of the STA is smaller than the constant. On the other hand, if the difference is higher than the constant, AP compares the last SR of the other link and the current SR of the awake link. AP decides to wake up the other link if it has a higher success ratio in the next beacon frame. If two links show similar SR values, both links will be used. When a single link is used for an extended period, the information on the other link may be outdated as the STA has been sleeping for a long time. To gain the information on the link, the STA needs to wake up and receive data.

Therefore, we wake up the other link with a five percent probability to update the success rate of the link that has not been used for a long period.

VI. Evaluation

VI.1. Simulation Setup

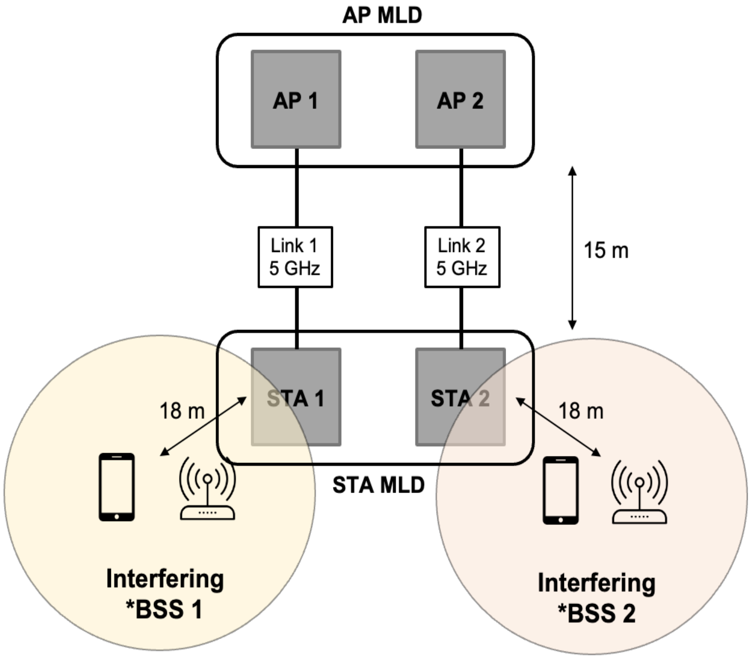

Fig. 10 Simulation scenario

We implemented MLO with PSM on the most popular Network Simulator, ns3, to show the performance of the selective transmission. We have put an interfering Basic Service Set (BSS) on each link and compared the performance of the naïve and the proposed scheme. The level of interferences has differed under different scenarios, and we checked the outcome using two metrics: sleep duration and the number of successfully transmitted packets.

VI.2. Doze State Verification

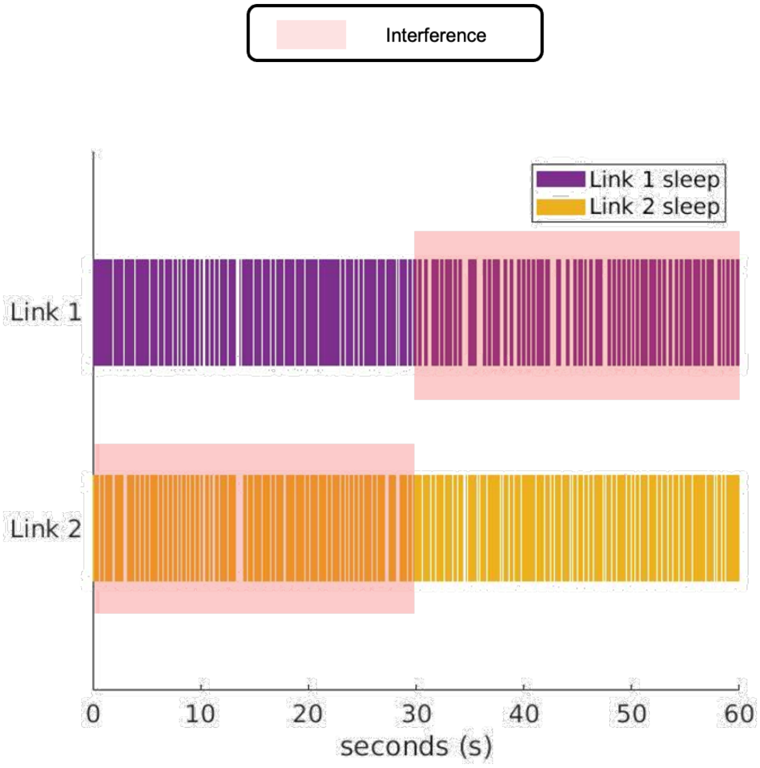

Fig. 11 Doze state verification in Naïve Scheme

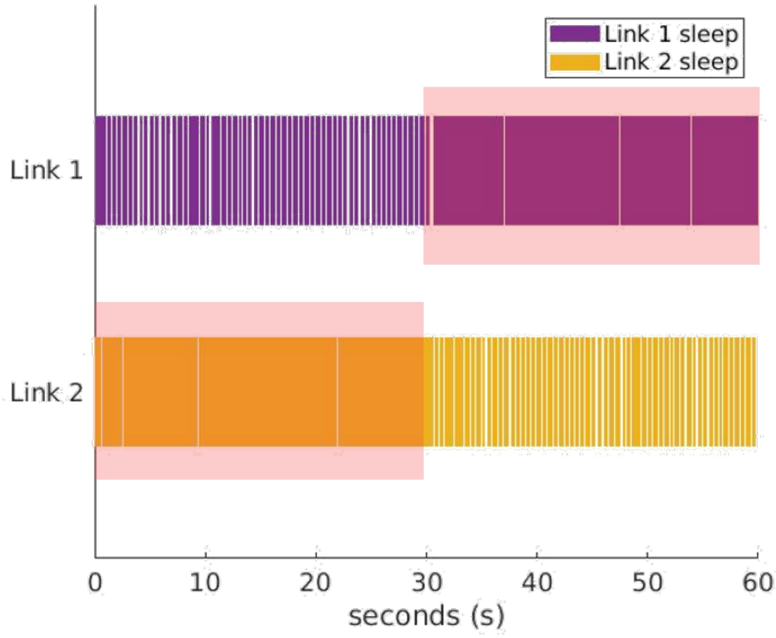

Fig. 12 Doze state verification in proposed scheme

We want to verify the effectiveness of the proposed scheme compared to the naïve scheme. Fig. 11 and 12 show the sleep duration of each STA in naïve and proposed schemes. We have differed the level of interference of each link at 30 seconds. In the first 30 seconds, there is no interference on link 1, while there is interference on link 2, and for the last 30 seconds, there is no interference on link 2, and there is interference on link 1. In the naïve scheme, we see that the link experiencing interference wakes up more in the proposed scheme, and the one without interference wakes up more frequently. On the other hand, the proposed scheme mitigates waking up the unstable link and only wakes up the link without interference. From this result, we verify that, when using our proposed scheme, the STA only wakes up when the level of interference is low and saves up more energy for the device. Furthermore, the proposed scheme can find the best link in the situation where the interference pattern is not regular.

VI.3. Awake State Duration

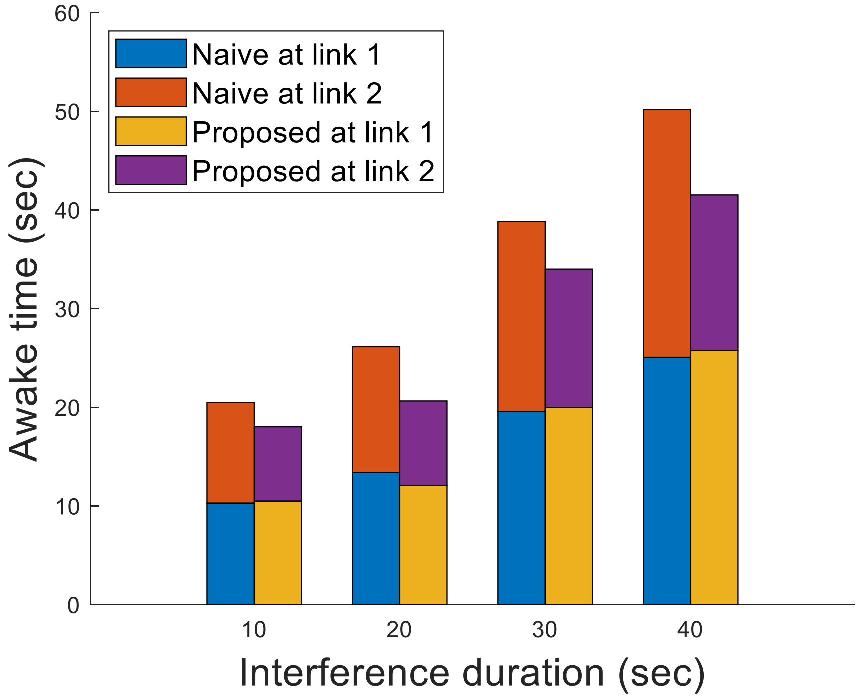

Fig. 13 Awake time on each link under random interferences

Fig. 13 shows the second experiment where the start time of the existence of interferences varies randomly. We observe how effectively the proposed scheme mitigates waking up the link under random interference and compare its performance with the naïve scheme. The interference duration is varied from 10 to 40 seconds in each link during 60 seconds simulation time. Each bar represents the wake-up time of each link in the naïve and proposed scheme. In the naïve scheme, both STAs wake up for the same period. The proposed scheme shows difference between two links as the wake-up duration of each link is different depending on the interferences. We can observe that the proposed scheme alleviates the interferences although the interference occurs randomly and unexpectedly.

VII. Discussion

We have verified the performance of the system on ns3 that the proposed scheme intelligently avoids interference by estimating the channel state and wakes up less frequently. The device under the proposed scheme effectively saves more energy by putting the STAs under interference into sleep and waking up the other link. The proposed scheme minimizes the throughput degradation through waking up both links in case there is no interference, or the interference levels are close.

Although we have built the ns3 and showed the performance of the proposed scheme, the exact power consumption prediction is left unknown. The actual power usage can only be measured through the hardware implementation as the power consumption depends on the device, the frequency of changing the state from a doze to a wake-up state, and many other factors. The power measurement is left to future work. This paper deals with the two links as it is a common scenario in MLO. This work could be extended to three-link cases or adapted to the dynamic link number usage.

VIII. Conclusion

In this paper, we have analyzed the problem in MLO when operating in PSM and proposed a novel scheme to overcome the link degradation problem that may be caused in Wi-Fi under certain scenarios such as naïve scheme due to interferences. The proposed scheme successfully mitigates the usage of links under interference and chooses the best link. Through the analysis of the IEEE 802.11be amendment, our proposed scheme ameliorates the performance of MLO in power saving while not violating any features defined in the standard. The proposed scheme is verified through a trustworthy simulator ns3 and showed improved performance over the naïve scheme. As there are many devices operating under Wi-Fi 7 consume much power and require battery saving system, we expect this work to be used in many devices that communicate via Wi-Fi 7.

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초 록

Wi-Fi 6 은 HE(High Efficiency)를 목표로 표준화가 진행됐다면 Wi-Fi 7 은 가상 현실(VR)과 같이 빠른 데이터 통신과 높은 처리량을 요구하는 어플리케이션을 지원하기 위해 EHT(Extremely High Throughput)에 중점을 둔다. 본 논문에서는 Wi-Fi 7 에 추가된 기술들 중 다중 링크를 사용하여 전송하는 기법인 MLO(Multi-Link Operation)에 대해 연구한다. 특히, 기존 Wi-Fi 장치에서 사용중인 절전 모드(PSM)가 MLO 에 적용될 때 발생하는 문제점을 살펴보고 해결하는 것을 목표로 한다. PSM 에는 깨어 있는 상태와 잠자기 상태의 두 가지 상태가 있으며, 데이터를 송수신 할 때 깨어 있는 상태를 유지하고 송수신할 데이터가 없으면 장치가 잠자는 상태로 진입한다. 앞선 PSM 의 동작을 통하여 장치는 데이터를 교환하지 않을 때 발생하는 불필요한 전력을 절약할 수 있다. 주변에 간섭이 없는 상황에서는 PSM 로 동작하는 MLO 가 높은 처리량을 얻기 위해 모든 링크에서 데이터를 수신하는 방식이 이상적이다. 하지만 무선 네트워크는 간섭에 취약하고 채널 상태에 큰 영향을 받기 때문에, 위 방법으로 동작할 시 PSM 의 성능이 저하될 수 있다. 이에, 본 논문에서는 링크 채널 상태가 다양한 환경에서의 MLO 가 PSM 의 성능을 유지하는 방법을 제안한다.

주요어 : Multi-Link Operation(MLO), Power Save Mode(PSM),

Wi-Fi 7, IEEE802.11be, interference, channel state

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