Equitas: Fairness-Aware Dynamic Link Selection for EMLSR Operation in IEEE 802.11be

Ching-Lun Tai, Shyam Krishnan Venkateswaran, and Raghupathy Sivakumar

School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, United States

Emails: {ctai32, shyam1, siva}@gatech.edu

***Abstract*—Commercialized as Wi-Fi 7, the IEEE 802.11be extremely high throughput (EHT) amendment is aimed to further boost the network performance. As a key feature in the IEEE 802.11be EHT amendment, multi-link operation (MLO) allows an operation over multiple links. Having a modest hardware demand while providing sufficient benefits, the enhanced multi-link single-radio (EMLSR) operation is the most promising MLO option, but it confronts a link selection issue which is less explored in previous works. Therefore, in this paper, we propose *Equitas*, a fairness-aware dynamic link selection heuristic method for EMLSR operation, taking link quality into account while considering both throughput and fairness. Through the link quality assessment and fairness-aware probabilistic link selection processes, *Equitas* is an efficient scheme to a unique multiple knapsack problem which aspires to achieve weighted proportional fairness with a balance between throughput and fairness under the constraints of EMLSR operation. Simulation results confirm the superior performance of *Equitas* in terms of throughput and fairness. Besides, we explore the effect of different weight update choices on the fairness performance of *Equitas*.**

***Index Terms*—IEEE 802.11be (Wi-Fi 7), multi-link operation (MLO), enhanced multi-link single-radio (EMLSR) operation, weighted proportional fairness, link quality**

I. Introduction

With an ever-increasing traffic demand, Wi-Fi has been a popular wireless local area network (WLAN) solution ubiquitously deployed around the globe. By 2025, the global economic value of Wi-Fi is expected to reach around 5 trillion USD [1]. As new applications with more stringent requirements emerge, recent Wi-Fi networks have become more dense and congested. Therefore, the IEEE 802.11be extremely high throughput (EHT) amendment, commercially known as Wi-Fi 7, is proposed to provide several advanced features in support of an improved network performance [2].

In the IEEE 802.11be EHT amendment, multi-link operation (MLO) [3] is a key feature which leverages a new architecture called multi-link device (MLD) to enable an operation over multiple links for both station (STA) and access point (AP). Specifically, an STA MLD or an AP MLD hosts multiple interfaces. For an STA MLD, each interface uses a link to communicate with a corresponding interface of the AP MLD. Within an MLD, each interface operates at a different frequency band, and the contention of an interface for a transmit opportunity (TXOP) through the channel with enhanced distributed channel access (EDCA) should be independent of the other interfaces. Previous works on MLO have investigated its impact on latency, reliability, and throughput (e.g., [4]–[6]) and its coexistence with legacy devices (e.g., [7]–[9]).

With different configurations, there are multiple types of MLO. Among all types of MLO, the enhanced multi-link single-radio (EMLSR) operation is the most promising option, since it requires less hardware support in addition to the conventional single-radio operation [10] while providing most of the benefits from a multi-radio operation [11]. An EMLSR operation between the AP MLD and an STA MLD encompasses two phases: link listening, where the AP MLD selects a link (from multiple links) for STA MLD, and frame exchange, where the frames are exchanged over the selected link. Therefore, it leads to a critical link selection question: *How should the AP MLD select a link for each STA MLD?*

Despite the importance of link selection for promising EMLSR operation, this timely issue has been less explored in the existing literature. In [12], a link selection policy called single link less congested interface (SLCI) is proposed and can be applied to EMLSR operation, selecting the link with least channel busy percentage (from multiple links) for each STA MLD. While the SLCI policy may facilitate load balancing over multiple links, it quantifies link quality with only channel busy percentage and does not take other critical metrics such as fairness into consideration.

In this paper, we propose *Equitas*, a fairness-aware dynamic link selection heuristic method for EMLSR operation as a pioneering work. *Equitas* features a comprehensive assessment of link quality and jointly considers throughput and fairness for link selection. Structurally, *Equitas* takes two processes, link quality assessment and fairness-aware probabilistic link selection. Highlighting a polynomial computational complexity, *Equitas* acts as an efficient scheme to a unique multiple knapsack problem [13] with the objective of achieving weighted proportional fairness [14], which strikes a balance between throughput and fairness, under the constraints of EMLSR operation based on assessed link quality.

The remainder of this paper is organized as follows. We outline the system model in Sec. II and depict the problem formulation in Sec. III. In Sec. IV, we introduce *Equitas* and present its computational complexity. Simulation results are included in Sec. V. Finally, Sec. VI concludes the paper.

II. System Model

In this section, we briefly describe the system model.

Consider an MLO-enabled Wi-Fi network composed of an AP MLD and M STA MLDs, where each MLD owns L interfaces, with both downlink (DL) and uplink (UL) traffic.

For each STA MLD, it connects its lth interface to the lth interface of the AP MLD over its lth link with a DL or UL transmission through the lth channel at the lth frequency band, $l = 1, 2, ..., L$. An illustration of the MLO-enabled Wi-Fi network is shown in Fig. 1.

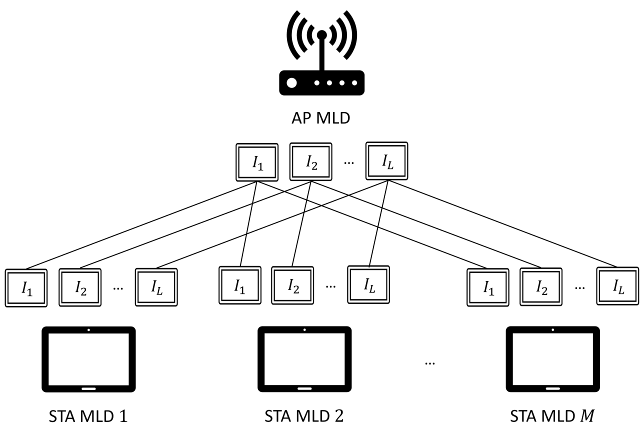

Fig. 1. An illustration of MLO-enabled Wi-Fi network, where I_l represents the lth interface and each solid line between interfaces represents a link

For EMLSR operation, define a time window as a period of time of duration τ where the AP MLD and M STA MLDs follow a link selection (determined by the AP MLD) $\{\Phi_l\}_{l=1}^{L}$, where $\Phi_l \subseteq \{1, 2, ..., M\}$ is the set of indices of STA MLDs whose lth link is selected.

Following a link selection $\{\Phi_l\}_{l=1}^{L}$, a time window consists of one or more EMLSR operations, where each EMLSR operation between the AP MLD and an STA MLD includes two phases: link listening and frame exchange. An EMLSR operation begins with the link listening phase, where an STA MLD listens on its L links, with one spatial stream in each link. Suppose the STA MLD belongs to Φ_l. Then, after gaining a TXOP, the lth interface of the AP MLD transmits a multi-user request to send (MU-RTS) Trigger frame to the lth interface of the STA MLD (over the lth link of the STA MLD). After the reception of a clear to send (CTS) frame from the STA MLD, the AP MLD initiates the frame exchange phase, where the STA MLD aggregates its L spatial streams toward its lth link. Upon the completion of the frame exchange phase, the link listening phase restarts and a new EMLSR operation begins. By the end of a time window, any ongoing EMLSR operation stops. An example of EMLSR operation in a time window is shown in Fig. 2.

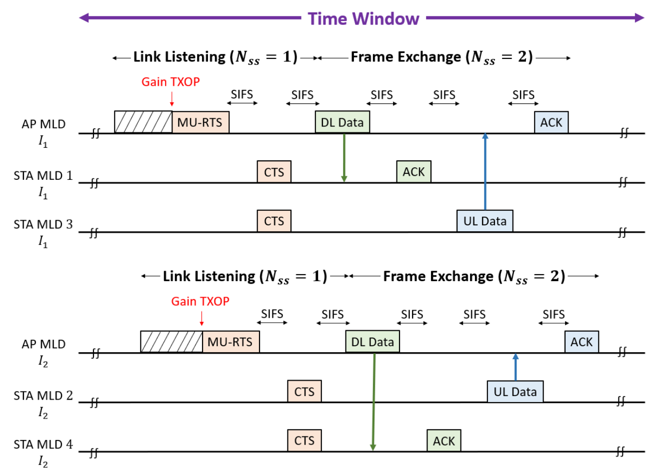

Fig. 2. An example of EMLSR operation in a time window with $(M, L) = (4, 2)$ and $\Phi_1 = \{1, 3\}, \Phi_2 = \{2, 4\}$, where I_l represents the lth interface and N_{ss} represents the number of spatial streams in the selected link of an STA MLD in a phase

III. Problem Formulation

In this section, we formulate the main problem which necessitates an efficient fairness-aware dynamic link selection heuristic method for EMLSR operation.

From Sec. II, the AP MLD determines a link selection for EMLSR operation, i.e., $\{\Phi_l\}_{l=1}^{L}$, in a centralized manner at the start of each time window.

Denote the total number of bytes to be transmitted DL and UL for the mth STA MLD as $b_m^x, m = 1, 2, ..., M$. Besides, denote the maximum number of bytes that can be transmitted through the lth channel as $r_l, l = 1, 2, ..., L$. Then, there are two natural constraints:

- Each STA MLD has at most one selected link out of its L links, i.e., $\sum_{l=1}^{L} \mathbf{1}_{\{m \in \Phi_l\}} \leq 1, m = 1, 2, ..., M$, where $\mathbf{1}_{\{m \in \Phi_l\}} = \begin{cases} 1, & m \in \Phi_l \\ 0, & \text{otherwise} \end{cases}$ is an indicator function.
- There is a limit of maximum number of bytes that can be transmitted through each channel, i.e., $\sum_{m \in \Phi_l} b_m^x \leq r_l, l = 1, 2, ..., L$.

From a fairness perspective, if some m'th STA MLD is not accommodated in the link selection $\{\Phi_l'\}_{l=1}^{L}$ for a time window, i.e., $\sum_{l=1}^{L} \mathbf{1}_{\{m' \in \Phi_l'\}} = 0$, then the STA MLD should be more favored for accommodation in the link selection for the next time window. Particularly, each STA MLD is assigned a weight, which becomes larger when the STA MLD is not accommodated for more consecutive time windows. Denote the weight of the mth STA MLD as $w_m, m = 1, 2, ..., M$. The weight w_m is initialized as unity, i.e., $w_m = 1$, and will be updated in each time window. To strike a balance between throughput and fairness, the AP MLD determines a link selection $\{\Phi_l\}_{l=1}^{L}$ with an objective of achieving weighted proportional fairness [14], which is equivalent to $\max_{\{\Phi_l\}_{l=1}^{L}} \sum_{l=1}^{L} \sum_{m \in \Phi_l} w_m \cdot \log(b_m^x)$, where $w_m \cdot \log(b_m^x)$ is the weighted utility contributed by the mth STA MLD.

Consequently, we formulate the following main problem:

At the start of each time window, given total number of bytes to be transmitted DL and UL b_m^x and weight w_m, $m = 1, 2, ..., M$, determine a link selection $\{\Phi_l\}_{l=1}^{L}$ for the optimization problem (1) below.

$$\max_{\{\Phi_l\}_{l=1}^{L}} \quad \sum_{l=1}^{L}\sum_{m\in\Phi_l} w_m \cdot \log(b_m^x) \tag{1a}$$

$$\text{subject to} \quad \sum_{l=1}^{L} \mathbf{1}_{\{m\in\Phi_l\}} \leq 1, m=1,2,...,M \tag{1b}$$

$$\sum_{m\in\Phi_l} b_m^x \leq r_l, l=1,2,...,L \tag{1c}$$

where the objective function (1a) results from the goal of achieving weighted proportional fairness, and the constraints (1b) and (1c) are inherent in EMLSR operation.

There are M batches of bytes of numbers $\{b_m^x\}_{m=1}^{M}$ and L channels of maximum byte limits $\{r_l\}_{l=1}^{L}$. Consider each batch of bytes as an item of finite size and each channel as a knapsack of limited volume. Interestingly, the optimization problem (1) is a multiple knapsack problem, which is NP-hard [13]. This motivates us to develop a polynomial-complexity heuristic method.

For the AP MLD, denote its stored measurements of signal-to-noise ratio (SNR), total number of bytes that have been received DL and UL, and channel busy percentage, respectively, for the lth link of the mth STA MLD as $\xi_{m,l}, b_{m,l}^r, c_{m,l}, l=1,2,...,L, m=1,2,...,M$. According to these measurements, the AP MLD can assess the link quality of the lth link of the mth STA MLD, denoted as $\psi_{m,l}$. Therefore, we incorporate the link quality into the development of an efficient fairness-aware dynamic link selection heuristic method for EMLSR operation to the optimization problem (1).

IV. *EQUITAS*: Fairness-Aware Dynamic Link Selection for EMLSR Operation

In this section, we propose *Equitas*, an efficient fairness-aware dynamic link selection heuristic method for EMLSR operation to the optimization problem (1) formulated in Sec. III, and analyze its computational complexity. At the start of each time window, *Equitas* determines a link selection $\{\Phi_l\}_{l=1}^{L}$ via two processes: link quality assessment (Sec. IV-A) and fairness-aware probabilistic link selection (Sec. IV-B).

A. Link Quality Assessment

To begin with, the AP MLD exploits its stored measurements to assess the link quality through the link quality assessment process, as illustrated in Algorithm 1.

Specifically, the AP MLD stores the measurements of SNR $\xi_{m,l}$, total number of bytes that have been received DL and UL $b_{m,l}^r$, and channel busy percentage $c_{m,l}$, $l=1,2,...,L, m=1,2,...,M$. Define the channel idle percentage as

$$\rho_{m,l} = 1 - c_{m,l}. \tag{2}$$

For the lth link of the mth STA MLD, we evaluate how its measurements $(\xi_{m,l}, b_{m,l}^r, \rho_{m,l})$ perform compared to all measurements by computing their respective empirical cumulative distribution function (eCDF) value as

$$\bar{\xi}_{m,l} = |\{\xi_{m',l'} : \xi_{m',l'} \leq \xi_{m,l}\}|/ML, \tag{3}$$

Algorithm 1: Link Quality Assessment

Input: $\xi_{m,l}, b_{m,l}^r, c_{m,l}, l=1,2,...,L, m=1,2,...,M$
for $m=1:M$
  $\rho_{m,l} = 1-c_{m,l}, l=1,2,...,L$
end for
for $m=1:M$; **for** $l=1:L$
  $\bar{\xi}_{m,l} = |\{\xi_{m',l'} : \xi_{m',l'} \leq \xi_{m,l}\}|/ML$
  $\bar{b}_{m,l}^r = |\{b_{m',l'}^r : b_{m',l'}^r \leq b_{m,l}^r\}|/ML$
  $\bar{\rho}_{m,l} = |\{\rho_{m',l'} : \rho_{m',l'} \leq \rho_{m,l}\}|/ML$
  $(l'=1,2,...,L, m'=1,2,...,M)$
  $\psi_{m,l} = \bar{\xi}_{m,l} \cdot \bar{b}_{m,l}^r \cdot \bar{\rho}_{m,l}$
end for; **end for**
Output: $(\psi_{m,1}, \psi_{m,2}, ..., \psi_{m,L}), m=1,2,...,M$

$$\bar{b}_{m,l}^r = |\{b_{m',l'}^r : b_{m',l'}^r \leq b_{m,l}^r\}|/ML, \tag{4}$$

and

$$\bar{\rho}_{m,l} = |\{\rho_{m',l'} : \rho_{m',l'} \leq \rho_{m,l}\}|/ML, \tag{5}$$

where $l'=1,2,...,L, m'=1,2,...,M$. For each of the three eCDF values $\bar{\xi}_{m,l}, \bar{b}_{m,l}^r, \bar{\rho}_{m,l} \in [0,1]$, a larger value indicates a better performance in the lth link of the mth STA MLD.

Finally, we compute the product of the three eCDF values (between zero and unity) as an assessment of the link quality of the lth link of the mth STA MLD, expressed as

$$\psi_{m,l} = \bar{\xi}_{m,l} \cdot \bar{b}_{m,l}^r \cdot \bar{\rho}_{m,l} \in [0,1]. \tag{6}$$

B. Fairness-Aware Probabilistic Link Selection

Upon obtaining the assessed link quality, the AP MLD proceeds to determine a link selection through the fairness-aware probabilistic link selection process, as illustrated in Algorithm 2.

In a heuristic manner, we first create an order in which the M STA MLDs will be addressed, and then we address them one by one according to the order. Denote the remaining number of bytes that can be transmitted through the lth channel as $r'_l, l=1,2,...,L$. Then, we initialize $\Phi_l=\varnothing, r'_l=r_l, l=1,2,...,L$, which will be updated when the AP MLD selects a link for an STA MLD.

With the goal of maximizing the objective function (1a), which is the sum of weighted utility, it is reasonable to greedily address an STA MLD with a higher priority if it contributes a larger average weighted utility per byte. We compute the average weighted utility per byte contributed by the mth STA MLD as

$$u_m = w_m \cdot \log(b_m^x)/b_m^x. \tag{7}$$

Sorting the M STA MLDs by $\{u_m\}_{m=1}^{M}$ in descending order, we create an order of indices of STA MLDs to be addressed as $j_1, j_2, ..., j_M \in \{1,2,...,M\}$ with $u_{j_1} \geq u_{j_2} \geq ... \geq u_{j_M}$. According to the order, the AP MLD takes M iterations to address the M STA MLDs.

During the mth iteration, the AP MLD addresses the j_mth STA MLD.

Algorithm 2: Fairness-Aware Probabilistic Link Selection

Input:
$b_m^x, w_m, (\psi_{m,1}, \psi_{m,2}, ..., \psi_{m,L}), m = 1, 2, ..., M$
$r_l, l = 1, 2, ..., L$
Initialization: $\Phi_l = \varnothing, r_l' = r_l, l = 1, 2, ..., L$
for $m = 1 : M$
  $u_m = w_m \cdot \log(b_m^x)/b_m^x$
end for
Sort in descending order:
$u_{j_1} \geq u_{j_2} \geq ... \geq u_{j_M}, j_1, j_2, ..., j_M \in \{1, 2, ..., M\}$
for $m = 1 : M$
  $\Lambda_{j_m} = \{l : r_l' \geq b_{j_m}^x, l = 1, 2, ..., L\}$
  if $\Lambda_{j_m} = \varnothing$
    $w_{j_m} \leftarrow w_{j_m} + 1$
  else
    $w_{j_m} = 1$
    $\psi_{j_m} = \sum_{l \in \Lambda_{j_m}} \psi_{j_m,l}$
    $\alpha_{j_m,l} = \psi_{j_m,l}/\psi_{j_m}, l \in \Lambda_{j_m}$
    $l_{j_m}^* \sim \text{Cat}(\Lambda_{j_m}, \{\alpha_{j_m,l}\}_{l \in \Lambda_{j_m}})$
    $\Phi_{l_{j_m}^*} \leftarrow \Phi_{l_{j_m}^*} \cup j_m$
    $r'_{l_{j_m}^*} \leftarrow r'_{l_{j_m}^*} - b_{j_m}^x$
  end if
end for
Output: $w_m, m = 1, 2, ..., M, \Phi_l,\ l = 1, 2, ..., L$

To identify the available links for the j_mth STA MLD, we obtain the set of link indices which correspond to a sufficient remaining number of bytes that can be transmitted through the channel, written as

$$\Lambda_{j_m} = \{l : r_l' \geq b_{j_m}^x, l = 1, 2, ..., L\}. \tag{8}$$

If $\Lambda_{j_m} = \varnothing$, i.e., there is no available link for the j_mth STA MLD, then the j_mth STA MLD cannot be accommodated in the link selection for the current time window. In this case, we increment the weight of the j_mth STA MLD by 1, updated as

$$w_{j_m} \leftarrow w_{j_m} + 1. \tag{9}$$

With an increase in its weight, the j_mth STA MLD will be more favored for accommodation in the link selection for the next time window.

On the other hand, if Λ_{j_m} is non-empty, i.e., there exists at least one available link for the j_mth STA MLD, then the j_mth STA MLD will be accommodated in the link selection for the current time window. In this case, we reset its weight w_{j_m} into 1. Subsequently, we conduct a probabilistic link selection, where the AP MLD selects a link belonging to Λ_{j_m} with a probability dependent on its assessed link quality. With the soft decision design, the j_mth STA MLD has a greater chance of utilizing its better-quality link while potentially exploring the other available links (to avoid a fixed use of a specific available link).

For the probabilistic link selection, we would like to construct a categorical distribution where the probability of selecting a link index $l \in \Lambda_{j_m}$, denoted as $\alpha_{j_m,l}$, is dependent on its corresponding assessed link quality $\psi_{j_m,l}$. Accordingly, we compute the sum

$$\psi_{j_m} = \sum_{l \in \Lambda_{j_m}} \psi_{j_m,l} \tag{10}$$

and assign

$$\alpha_{j_m,l} = \psi_{j_m,l}/\psi_{j_m} \in [0,1], l \in \Lambda_{j_m} \tag{11}$$

with $\sum_{l \in \Lambda_{j_m}} \alpha_{j_m,l} = 1$. Based on Λ_{j_m} and $\{\alpha_{j_m,l}\}_{l \in \Lambda_{j_m}}$, we construct the categorical distribution $\text{Cat}(\Lambda_{j_m}, \{\alpha_{j_m,l}\}_{l \in \Lambda_{j_m}})$ with the outcome $l_{j_m}^*$ being the link index selected for the j_mth STA MLD. Namely, the probability mass function (PMF) of the categorical distribution $\text{Cat}(\Lambda_{j_m}, \{\alpha_{j_m,l}\}_{l \in \Lambda_{j_m}})$ can be expressed as

$$P(l_{j_m}^* = l) = \alpha_{j_m,l}, l \in \Lambda_{j_m}. \tag{12}$$

With the AP MLD selecting the $l_{j_m}^*$th link for the j_mth STA MLD, we add its index j_m to $\Phi_{l_{j_m}^*}$ and subtract its total number of bytes to be transmitted DL and UL $b_{j_m}^x$ from $r'_{l_{j_m}^*}$. Hence, $\Phi_{l_{j_m}^*}$ and $r'_{l_{j_m}^*}$ are updated as

$$\Phi_{l_{j_m}^*} \leftarrow \Phi_{l_{j_m}^*} \cup j_m \tag{13}$$

and

$$r'_{l_{j_m}^*} \leftarrow r'_{l_{j_m}^*} - b_{j_m}^x, \tag{14}$$

respectively.

Finally, after M iterations for addressing the M STA MLDs, the AP MLD determines a link selection $\{\Phi_l\}_{l=1}^L$.

C. Computational Complexity

With two processes, link quality assessment (Algorithm 1) and fairness-aware probabilistic link selection (Algorithm 2), *Equitas* determines a link selection $\{\Phi_l\}_{l=1}^L$ at the start of each time window. Below, we analyze its computational complexity in terms of the number of multiplications/divisions involved.

First, we look into Algorithm 1. To obtain the value of ML, it involves one multiplication. For each of the L links in each of the M STA MLDs, the computation of three eCDF values in (3), (4), and (5) involves three divisions, and the assessment of link quality in (6) involves two multiplications. Therefore, the computational complexity of Algorithm 1 is $\mathcal{O}(ML)$.

Then, we look into Algorithm 2. For each of the M STA MLDs, the computation of average weighted utility per byte in (7) involves one multiplication and one division. Moreover, for each of the $\mathcal{O}(M)$ STA MLDs which correspond to some index j_m with non-empty Λ_{j_m}, the assignment of probability $\alpha_{j_m,l}, l \in \Lambda_{j_m}$ in (11) involves $\mathcal{O}(L)$ divisions associated with the $\mathcal{O}(L)$ links belonging to Λ_{j_m}. Therefore, the computational complexity of Algorithm 2 is $\mathcal{O}(ML)$.

As a result, the computational complexity of *Equitas* is $\mathcal{O}(ML)$. With the polynomial computational complexity, *Equitas* is an efficient scheme to be deployed in the AP MLD.

V. SIMULATION

In this section, we evaluate the performance of *Equitas* in terms of throughput and fairness. Specifically, we compare the throughput and fairness performance of *Equitas*, the SLCI policy [12], and a random baseline method (reduced from *Equitas*), and we investigate the effect of different weight update choices on the fairness performance of *Equitas*. All evaluations are simulated with an MLO-enabled IEEE 802.11be Wi-Fi network under EMLSR operation in ns-3.

For the random baseline method, the AP MLD creates a random order of indices of STA MLDs to be addressed as $\hat{j}_1, \hat{j}_2, ..., \hat{j}_M \in \{1, 2, ..., M\}$. In the mth iteration, the AP MLD addresses the $\hat{j}_m$th STA MLD and obtains $\Lambda_{\hat{j}_m}$. If $\Lambda_{\hat{j}_m}$ is non-empty, then the AP MLD makes a uniformly random selection of the link index $l^*_{\hat{j}_m}$ from $\Lambda_{\hat{j}_m}$, and updates $\Phi_{l^*_{\hat{j}_m}}$ and $r'_{l^*_{\hat{j}_m}}$ accordingly.

Besides, we investigate how replacing (9) with each of the following weight update choices affects the fairness performance of *Equitas*:

- **A1**: $w_{j_m} \leftarrow w_{j_m} + 0.5$
- **M1**: $w_{j_m} \leftarrow 1.5w_{j_m}$
- **M2**: $w_{j_m} \leftarrow 2w_{j_m}$

While the A1 choice increments the weight by 0.5, the M1 and M2 choices multiply the weight by 1.5 and 2, respectively.

A. Parameter Settings

The Wi-Fi network is composed of an AP MLD fixed at origin $(0, 0)$ and a varying number of M mobile STA MLDs, which follow a random waypoint movement model with the maximum speed of 2 m/s and the pause duration of 1 second at a waypoint, with both DL and UL traffic on a $20\,\text{m} \times 20\,\text{m}$ 2D area. Each MLD has $L = 3$ interfaces at 2.4, 5, and 6 GHz frequency bands with respective channels of channel bandwidth 20, 40, and 80 MHz. The maximum byte limit of the channels $\{r_l\}_{l=1}^{L}$ is computed with the Shannon-Hartley theorem [15]. There are $T = 1000$ time windows, and each time window lasts for a duration of $\tau = 10.24$ ms. For brevity, we summarize Wi-Fi network parameter settings in Table I.

TABLE I
WI-FI NETWORK PARAMETER SETTINGS

Parameter	Value
Size of 2D area	$20\,\text{m} \times 20\,\text{m}$
(# AP MLD, # STA MLD)	(1, M)
STA MLD movement model	Random waypoint
Maximum STA MLD movement speed	2 m/s
STA MLD pause duration at a waypoint	1 second
# interface	$L = 3$
Frequency band	2.4, 5, 6 GHz
Channel bandwidth	20, 40, 80 MHz
Duration of a time window	$\tau = 10.24$ ms
# time window	$T = 1000$
DL/UL data rate for an STA MLD	20 Mbps
MAC protocol data unit (MPDU) payload size	700 bytes
(AP Tx power, STA Tx power)	(20 dBm, 15 dBm)
AP/STA noise figure	7 dB

For DL and UL respectively, the throughput is measured as the average network throughput over the $T = 1000$ time windows, and the fairness is measured as the Jain's fairness index [16] of the average throughput over the $T = 1000$ time windows from the M STA MLDs.

B. Simulation Results

First, we evaluate the throughput performance of the three methods (*Equitas*, SLCI [12], and Random) in terms of their achieved DL and UL average network throughput under different numbers of STA MLDs $M = \{10, 20, 30\}$, as shown in Fig. 3. It can be observed that *Equitas* outperforms the SLCI and Random methods for both DL and UL under various numbers of STA MLDs. Particularly, the superiority of *Equitas* over the SLCI and Random methods becomes more apparent under a larger number of STA MLDs. As the number of STA MLDs increases, the larger total offered load leads to a more saturated traffic, and the more congested environment results in a higher level of contention. To ameliorate the situation, the AP MLD needs to dynamically select a good-quality link for each STA MLD. Since the Random method does not take link quality into account and the SLCI method quantifies link quality with only channel busy percentage, both methods risk selecting a poorer-quality link for each STA MLD given the insufficient information. On the other hand, *Equitas* benefits from its link quality assessment process and is more likely to select a better-quality link for each STA MLD, thus reaching a higher average network throughput.

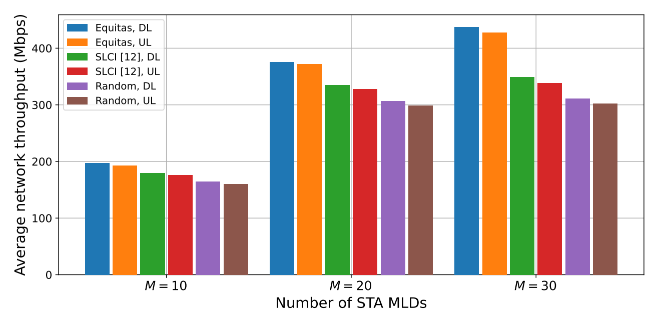

Fig. 3. DL and UL average network throughput achieved by different methods under different numbers of STA MLDs $M = \{10, 20, 30\}$

Next, we evaluate the fairness performance of the three methods (*Equitas*, SLCI [12], and Random) in terms of their achieved DL and UL Jain's fairness index under different numbers of STA MLDs $M = \{10, 20, 30\}$, as shown in Fig. 4. Similar to the throughput performance, *Equitas* outperforms the SLCI and Random methods for both DL and UL under various numbers of STA MLDs, and its superiority over both methods becomes more evident when the number of STA MLDs is larger. With an increased number of STA MLDs, it is more likely that some STA MLDs cannot be accommodated in the link selection for a time window due to the more intense congestion. In this case, these STA MLDs should be more favored for accommodation in the link selection for the next time window. With the objective of achieving weighted proportional fairness, *Equitas* carefully determines a link selection to ensure that each STA MLD can be fairly accommodated over the time windows, even under a larger number of STA MLDs. Eventually, as the number of STA MLDs increases, *Equitas* maintains a high Jain's fairness index with decent scalability, while the SLCI and Random methods experience a drastic performance drop due to their unawareness of fairness.

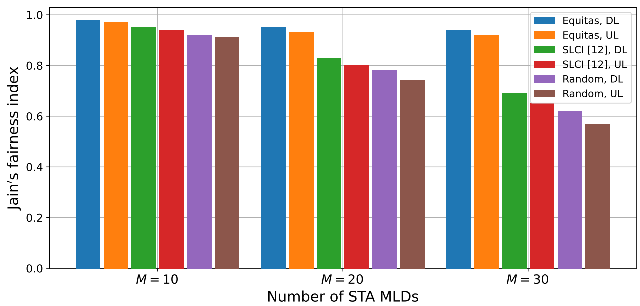

Fig. 4. DL and UL Jain's fairness index achieved by different methods under different numbers of STA MLDs $M = \{10, 20, 30\}$

Lastly, we investigate the effect of different weight update choices on the fairness performance of *Equitas*. As shown in Fig. 5, we compare the achieved DL and UL Jain's fairness index of *Equitas* under different weight update choices with the number of STA MLDs $M = 30$, where the more intense congestion occurs. With a comparable performance, the original weight update choice (9) slightly outperforms the others. This implies that the original weight update choice (9) is simple yet effective. Moreover, it is noteworthy that *Equitas* maintains a high Jain's fairness index under different weight update choices with stable robustness.

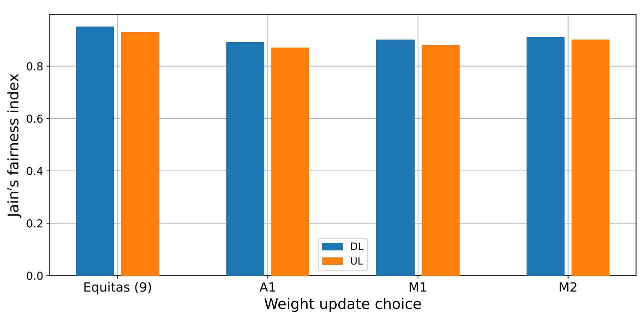

Fig. 5. DL and UL Jain's fairness index achieved by *Equitas* under different weight update choices with number of STAs $M = 30$

VI. Conclusion

In this paper, we propose *Equitas*, a fairness-aware dynamic link selection heuristic method for EMLSR operation. At the start of each time window, *Equitas* determines a link selection by taking two processes: link quality assessment and fairness-aware probabilistic link selection. In the link quality assessment process, the AP MLD assesses the link quality with measurements of SNR, total number of bytes that have been received DL and UL, and channel busy percentage. In the fairness-aware probabilistic link selection process, the AP MLD sorts the STA MLDs by average weighted utility per byte and constructs a categorical distribution with probability of selecting a link dependent on its assessed link quality. Considering link quality, *Equitas* highlights a polynomial computational complexity and acts as an efficient scheme to the multiple knapsack problem with the objective of achieving weighted proportional fairness, which balances between throughput and fairness, under the constraints of EMLSR operation. Simulation results demonstrate the efficacy of *Equitas* with respect to achieved average network throughput and Jain's fairness index for both DL and UL under different numbers of STA MLDs. In addition, we show that *Equitas* maintains a high Jain's fairness index for both DL and UL under different weight update choices with certain robustness.

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