A Method for Mathematical Modeling of Traffic Distribution in Multi-link Devices*

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Abstract

This paper presents a mathematical model of traffic distribution in multi-link devices, which formalizes the data transmission control process as a controlled queuing system. The proposed approach solves the problem of the lack of a unified basis for describing access policies, transforming the task from testing disparate heuristics into a rigorous mathematical formalization. The planning process is reduced to a one-to-one mapping of the system state to a vector of control actions. The introduction of a link compatibility matrix and constraint equations allows physically invalid transmission configurations to be eliminated at the algorithmic level. This approach establishes an analytical relationship between control parameters and expected metrics, enabling the estimation of throughput, delays, and the probability of violating time constraints prior to actual transmission. The developed framework provides a theoretical basis for the quantitative comparison of various distribution mechanisms and creates an environment for the design of adaptive access control algorithms.

Keywords

wireless networks, multi-link operations, traffic distribution, queuing systems, access control[1]

1. Introduction

The introduction of the IEEE 802.11be standard [1] is driven by the increase in traffic volume and the need to support services that require not only high speed [2], but also low latency [3].

Among the innovations of the new standard is the introduction of the Multi-Link Operation (MLO) concept, which allows devices to aggregate multiple interfaces across different links [4]. Although this provides an expansion of the frequency resource, the overall network performance still depends on mechanisms for accessing the medium and distributing traffic among available radio interfaces [5].

Currently, various traffic distribution policies have already been implemented by both wireless equipment manufacturers and research projects that use their own priorities [6]. Accordingly, the use of certain mechanisms for balancing and distributing traffic among links can yield radically different results [7]. For example, it has been proven that under asymmetric channel utilization, an inefficient distribution policy in an MLO can lead to delays that significantly exceed those in single-link mode [8].

In this regard, a scientific and practical problem arises, which consists in the justified selection and adaptation of a traffic distribution policy among links for given network operating conditions.

Since the use of different policies under identical conditions yields varying transmission quality metrics, there is an objective need to develop a model that will allow for the quantitative assessment of the effectiveness of a given policy under specified MLO conditions and constraints.

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2. Related works

Among studies of traffic distribution methods in IEEE 802.11be networks, the use of machine learning adaptive algorithms [9] and deterministic heuristics can be highlighted. To increase throughput, reinforcement learning-based multi-agent algorithms are proposed. In particular, a parallel transfer learning algorithm [8] and a recurrent algorithm for dynamic traffic distribution [9] are applied.

An alternative approach involves using a mechanism to bind traffic identifiers to links [4]. Both fixed schemes, where a specific type of traffic is isolated on a specific interface, and dynamic balancing strategies for links with the lowest load [5] are being investigated. In experimental evaluations of MLO [10], fully independent access on each link (I-EDCA) or the heuristic of sending a packet to the first available link is often used [11]. On the other hand, in open-source implementations of wireless stacks (e.g., the Linux kernel network [12]) deterministic packet-level flow splitting based on a cyclic principle is used.

Therefore, given the large number of proposed traffic distribution algorithms in MLO, there is a need to develop a unified model that will allow describing any policy in standardized terms of its input data, decision-making rules, and resulting metrics.

The aim of this article is to construct a unified mathematical model of traffic distribution in a multi-link device (MLD), which formalizes the process of data transmission control at the Upper MAC (U-MAC) level as a decision-making problem in a queuing system to create a basis for comparing different control policies.

3. Methodology

In the context of this work, multi-link device (MLD) is considered as a queuing system with controlled packet distribution among several links operating in a stochastic environment.

Control of this distribution is carried out at the U-MAC level as the sole decision-making point, while each link has its own access procedures and its own process for accessing the medium to obtain transmission opportunities.

Let us fix the time stamp t as the start of the scheduling cycle, during which the U-MAC [13] (Figure 1) has the current state of the links and queues and generates a control action for the next interval.

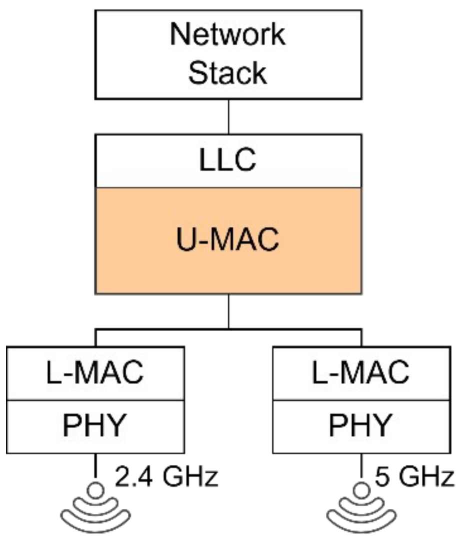

Figure 1: Multi-link device (MLD).

Let MLD operate in a frequency domain represented by a set of active links $L = 1, 2, \ldots, N$ that have successfully completed the connection establishment procedure and are ready to transmit data [1]. This allows us to exclude unavailable or unconfigured interfaces from the decision space.

The incoming data stream is described by a set of streams with transmission queues $F = f_1, f_2, \ldots, K$. Each of these $f_k \in F$ is characterized by a sequence of requirements (1):

$$\psi_k = \{P_k, D_k^{max}, \tau_k\}, \tag{1}$$

where P_k is the flow priority, according to the EDCA traffic classification: VO, VI, BE, BK; D_k^{max} is the maximum permissible delay; τ_k is the traffic type, e.g.,$\tau_k \in \{\text{RTA}, \text{Elastic}\}$ [14], which determines the need to comply with D_k^{max}.

Let us denote the system state vector as $S(t)$. At any given moment t, it is defined as a combination of the transmission medium state and the transmission queue state (2):

$$S(t) = \langle X_{links}(t), Q_{traffic}(t) \rangle. \tag{2}$$

Note that in this case, $S(t)$ is considered observable at the beginning of each cycle t, i. e., link metrics are obtained from PHY/MAC measurement data and transmission statistics, while the state of the queues is directly accessible to U-MAC.

The state of each link $l \in L$ is described by a column vector of normalized metrics $x_l(t) \in \mathbb{R}^{4\times 1}$ (3). These metrics are obtained directly from measurements at the physical and MAC levels [15], which ensures end-to-end modeling and a connection to the actual channel physics:

$$x_l(t) = \begin{bmatrix} \mu_l^{occ}(t) \\ \mu_l^{\text{int}}(t) \\ \mu_l^{qual}(t) \\ \delta_l^{restr}(t) \end{bmatrix}, \tag{3}$$

where $\mu_l^{occ}(t)$ is a resource availability metric (indicates channel occupancy); $\mu_l^{\text{int}}(t)$ is a robustness metric; $\mu_l^{qual}(t)$ is a signal quality metric (SNR/MCS); $\delta_l^{restr}(t)$ is a binary constraint indicator (e.g., due to an NSTR conflict).

This means that the overall status of all channels can be represented as a matrix $4 \times N$ (4):

$$X_{links}(t) = [x_1(t), x_2(t), \ldots, x_N(t)]. \tag{4}$$

Additionally, to make an effective decision, the system must consider the state of the queues, which is determined based on the traffic state vector for a set of flows F (5):

$$Q_{traffic}(t) = [q_1(t), \ldots, q_K(t)]^T, \tag{5}$$

where the state of an individual flow $q_k(t)$ is determined by the pair: $L_k(t)$ is the current queue length of the flow k and $T_k^{rem}(t)$ is the remaining time until the delay requirements are violated.

This state subspace effectively reflects the balance between quality of service and delivery urgency. The parameter $L_k(t)$ characterizes the amount of data in the transmission queue, and the parameter $T_k^{rem}(t)$ characterizes the time pressure, where the smaller the value of T^{rem}, the narrower the permissible waiting space in the queue and the higher the risk of deadline violation. In this case, the parameter $T_k^{rem}(t)$ is determined depending on the traffic type τ_k (6):

$$T_k^{rem}(t) = \begin{cases} D_k^{max} - (t - t_k^{arrival}), & \text{if } \tau_k = \text{RTA} \\ \infty, & \text{if } \tau_k = \text{Elastic} \end{cases}. \tag{6}$$

To configure transmission, the U-MAC scheduler must make a decision based on data regarding the traffic distribution scheme across interfaces [16], the amount of data to be transmitted, and the TXOP duration:

1) To determine the distribution scheme, let's introduce a binary assignment matrix $X(t)$ [17] of dimension $K \times N$ (where $K=|F|$ is the number of active flows, $N=|L|$ is the number of active links (7):

$$X(t)=\begin{pmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,N} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ x_{K,1} & x_{K,2} & \cdots & x_{K,N} \end{pmatrix}, x_{k,l} \in \{0,1\}. \quad (7)$$

Here, the element $x_{k,l}=1$ indicates that packets from the k stream are included in the transmission plan for the l link in the current cycle. The value $x_{k,l}=0$ means that the stream is not served by this link [18]. The row k indicates which links are involved in serving the k-th stream.

The ratio $\sum_{l=1}^{N} x_{k,l} > 1$ means that when links are aggregated, traffic is distributed among them in parallel. The column l indicates that streams are served on the l-th link during the current TXOP.

2) To determine the amount of data to be transmitted, we introduce the load distribution matrix $B(t) \in R_{\geq 0}^{K \times N}$ whose elements $b_{k,l}$ determine the amount of information scheduled to be transmitted from the queue of the k-th flow over the l-th link (8):

$$B(t)=\begin{pmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,N} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ b_{K,1} & b_{K,2} & \cdots & b_{K,N} \end{pmatrix}, \quad (8)$$

where the sum of the row $\sum_{l} b_{k,l}$ determines how much the queue $L_k(t)$ will decrease after the transmission cycle is complete.

The sum of the column $B_l^{agg} = \sum_{k} b_{k,l}$ determines the payload size in the physical layer frame on the l link. The relationship between the matrices X and B can be represented as $b_{k,l} > 0 \Rightarrow x_{k,l} = 1$, i.e., if the flow is not assigned to a link ($x_{k,l}=0$), then the amount of transmitted data is identically zero ($b_{k,l}=0$).

3) To calculate the reserved TXOP time, let's introduce the time vector (9):

$$\tau(t)=[\tau_1, \tau_2, \ldots, \tau_N]^T, \quad (9)$$

where τ_l is the transmission duration on the l-th link in microseconds.

Thus, the scheduler's decision at time t can be represented as a set of matrices and vectors (10), which allows any allocation policy to be interpreted as an algorithm for filling these matrices

$$A(t)=\langle X(t), B(t), \tau(t) \rangle. \quad (10)$$

In order for this plan to be physically realizable without violating the standard, it must lie within the set of feasible solutions $S_{feasible}$. The constraints on the solution space are determined by the MLD architecture and the MLO mode:

1) The key limiting factor in multi-link systems is internal interference. Information about such hardware limitations, which is encoded in the state vector described above via the indicator δ_l^{restr}, is aggregated at the system level into the link compatibility matrix $C \in 0{,}1^{N \times N}$. The matrix C is symmetric ($c_{i,j} = c_{j,i}$) and is determined during the connection establishment phase. The element $c_{i,j}$ determines the possibility of simultaneous independent operation of the link pair i and j:

- $c_{i,j} = 1$ for a simultaneous transmit and receive (STR) pair;
- transmission on i does not interfere with reception on j;
- $c_{i,j} = 0$ for a non-simultaneous transmit and receive (NSTR) pair;
- simultaneous bidirectional activity is prohibited.

Accordingly, for any pair of active links i, j involved in transmission ($x_{\cdot,i} \cdot x_{\cdot,j} = 1$) and constituting an NSTR pair ($c_{i,j} = 0$), the equality of transmit opportunity (TXOP) duration (11) must hold so that the transmission phase and acknowledgment wait phase on both links coincide in time.

$$\forall i, j \in L : (x_{\cdot,i} \cdot x_{\cdot,j} = 1) \wedge (c_{i,j} = 0) \rightarrow \tau_i = \tau_j. \quad (11)$$

2) The physical feasibility of the solution requires that the scheduled time τ_l [19] be sufficient for transmitting the planned data volume. For this, the minimum required time t_l^{req} for transmitting the payload on the link l is calculated as (12):

$$t_l^{req} = \frac{\sum_{k=1}^{K} b_{k,l}}{R_l(\mu_l^{qual})} + T_{phy\_overhead}, \quad (12)$$

where R_l is the physical transmission rate, determined based on the signal-to-interference-plus-coding ratio (SINR/MCS) from the state vector x_l, and $T_{phy\_overhead}$ is the standard time overhead for the preamble and headers. In the case of NSTR synchronization, the total TXOP duration τ_{sync} is determined by the slowest link (13):

$$\tau_{sync} = \max_{\{l | \text{active NSTR}\}} (t_l^{req}). \quad (13)$$

This results in overhead costs for synchronization. For each link l in the NSTR group, the amount of overhead $\Delta\tau_l$ is (14):

$$\Delta\tau_l = \tau_{sync} - t_l^{req} \geq 0. \quad (14)$$

3) If a subset of links $L_{EMLSR} \subset L$ operates in enhanced multi-link single-radio (EMLSR) mode, then at any given moment, transmission is possible only over one of them due to the presence of only one interface. This is formalized as the mutual exclusion constraint (15):

$$\sum_{l \in L_{EMLSR}} I\left(\sum_{k=1}^{K} x_{k,l} > 0\right) \leq 1. \quad (15)$$

4) The IEEE 802.11 standard imposes constraints on the complexity of aggregating frames; specifically, there is a limit on the number of different traffic identifiers (TIDs) that can be combined

into a single A-MPDU (typically $N_{TID}^{max}=8$). This imposes restrictions on the columns of the mapping matrix X (16):

$$\forall l \in L: \sum_{k=1}^{K} x_{k,l} \le N_{TID}^{max}. \tag{16}$$

Given a formalized state vector $S(t)$ and valid boundaries $S_{feasible}$, the traffic control problem in MLD can be reduced to a rule that maps each situation to a specific control action [20]. Here, the traffic distribution policy π is defined as a function that transforms information about the current system state and a set of internal settings into a control vector (17):

$$\pi : S \times \Omega \rightarrow S_{feasible}, \tag{17}$$

where Ω is the policy configuration parameter space.

For further comparison, we will present the distribution policy directly as a universal structure consisting of the following components:

- input data that form the state vector reflecting the dynamics of the environment and traffic requirements $S(t)=\langle X_{links}(t), Q_{traffic}(t)\rangle$;
- policy parameters ($\Theta \in \Omega$) as a set of settings or weighting coefficients that determine the algorithm's behavior;
- a decision-making rule [21] as an algorithmic core that transforms the system state and policy parameters into a control action [22].

The structure of the allocation policy can then be described as (18):

$$A(t)=\pi(S(t);\Theta). \tag{18}$$

This allows us to formulate the network tuning problem as the search for a vector Θ that provides the best performance metrics for a fixed rule structure π.

Since MLD operates under conditions of uncertainty, and some algorithms involve random selection of actions, it is appropriate to extend the definition of a policy as a conditional probability distribution over the space of feasible solutions (19):

$$\pi(A|S;\Theta)=P(A(t)=A / S(t)=S). \tag{19}$$

In this case, a specific decision $A(t)$ in each cycle is selected by sampling from this distribution (20):

$$A(t) \sim \pi(\cdot|S(t);\Theta). \tag{20}$$

The key task of the model is to predict the consequences of the control decision $A(t)=\langle X, B, \tau \rangle$ on the system state.

Since the wireless channel is a stochastic environment, exact metric values cannot be guaranteed; however, their estimates and risks can be derived based on the state vector $S(t)$.

To ensure the accuracy of the calculations, we introduce the concept of the current planning cycle duration T_{cycle}.

Since transmission occurs in parallel across different links and completes at different times (or is synchronized under NSTR), the cycle duration is determined by the maximum duration of the reserved TXOP among all active links (21):

$$T_{cycle}=\max_{l \in L}(\tau_l)+T_{ack}, \tag{21}$$

where T_{ack} is the time to receive an acknowledgment.

The nominal physical layer rate may differ from the actual throughput due to transmission errors. Let $p_l(\mu_l^{qual})$ be the probability of an error during reception on the link l, which is a function of the signal quality metric. Then the mathematical expectation of the volume of successfully transmitted data for the flow k on the link l is (22):

$$E[Data_{k,l}] = b_{k,l} \cdot (1 - p_l(\mu_l^{qual})). \quad (22)$$

And the total expected throughput for the stream k in the current cycle is defined as (23):

$$TH_k(A,S) = \frac{1}{T_{cycle}} \sum_{l \in L} x_{k,l} \cdot b_{k,l} \cdot (1 - p_l(\mu_l^{qual})). \quad (23)$$

4. Results

To illustrate this estimate, we will use a system with two links: $R_1 = 5$ MB/s (L1) and $R_2 = 0.5$ MB/s (L2). The estimate is performed for four load matrix formation strategies B with queue sizes L_k ranging from 1 to 20 KB.

The first strategy [5] directs the entire queue size exclusively to the first link ($b_1 = L_k, b_2 = 0$).

The second strategy directs traffic only to the second link ($b_1 = 0, b_2 = L_k$).

The third strategy (stochastic distribution) simulates unpredictable behavior by sending data in a random proportion $b_1 = L_k \cdot p$ and $b_2 = L_k \cdot (1 - p)$, where p is a pseudorandom variable in the range from 0.1 to 0.9.

The fourth strategy (proportional distribution) divides the data strictly in proportion to the physical interface speeds ($b_1 = L_k \cdot \frac{R_1}{R_1 + R_2}, b_2 = L_k \cdot \frac{R_2}{R_1 + R_2}$), ensuring simultaneous completion of transmission $\tau_1 = \tau_2$. The corresponding throughput estimation graph is presented for the STR mode at Figure 2 and for NSTR at 3.

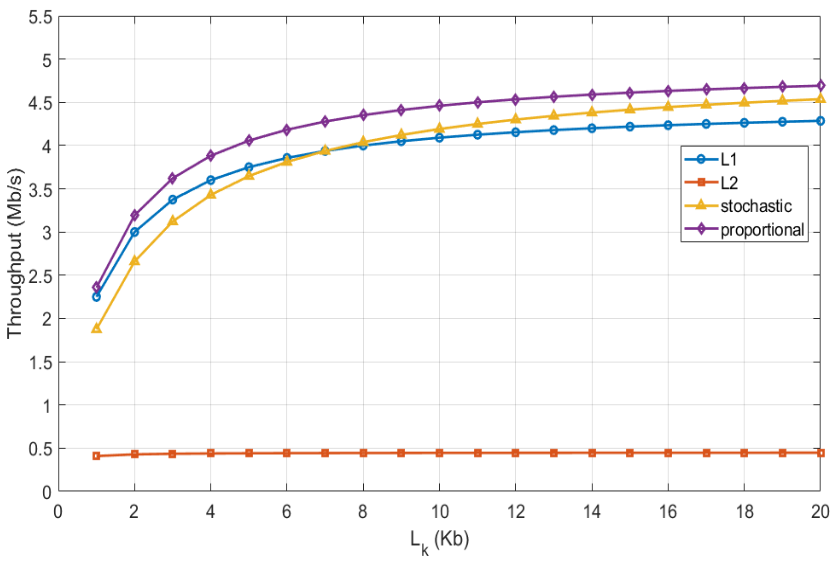

Figure 2: Throughput estimation for STR.

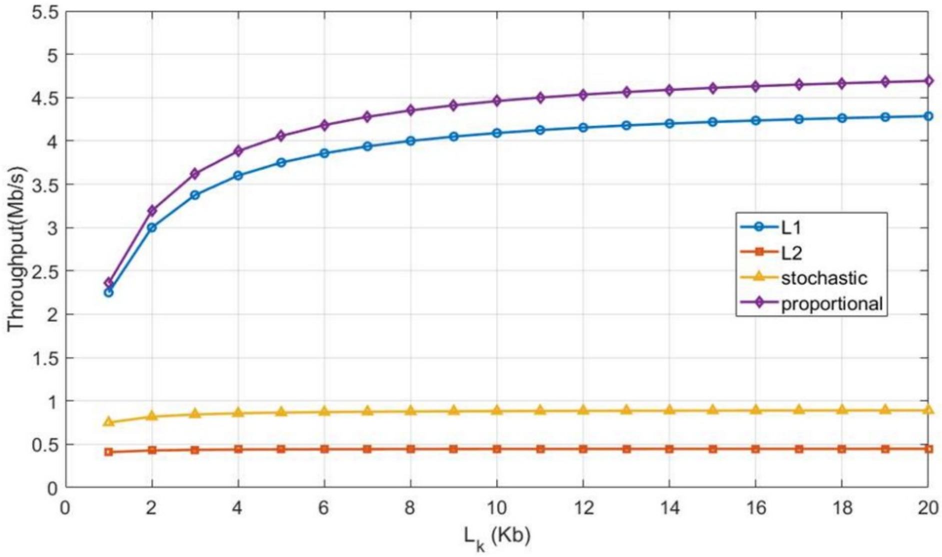

Figure 3: Throughput estimation for NSTR.

To further calculate the probability of deadline violations, it is necessary to estimate the expected packet service delay, which consists of queueing time, access time, and transmission time.

Access time (T_{acc}) is a random variable that depends on competition for the medium [23]. Using the availability metric μ_l^{occ}, the average access waiting time for the link l will be (24):

$$E[T_{acc,l}] \approx \frac{CW_{min}}{2} \cdot \sigma \cdot \frac{1}{\mu_l^{occ}}, \tag{24}$$

where σ is the slot duration. This expression is an approximate estimate for random-access systems; the factor models the increase in retransmissions and collisions under high load.

The queue length at the start of the next cycle $L_k(t+1)$ is predicted based on the balance between the arrival of new data (at a rate of λ_k) and successful transmission. It is important to note that data that was transmitted with an error (p_l) remains in the queue for retransmission (25):

$$L_k(t+1) = max\left(0, L_k(t) - \sum_{l \in L} b_{k,l} \cdot (1 - p_l(\mu_l^{qual}))\right) + \lambda_k \cdot T_{cycle}. \tag{25}$$

The average delay is determined according to Little's law [18], where the expected delay for a flow k is inversely proportional to the effective service rate [20] (26):

$$\bar{D}_k(A,S) \approx \frac{L_k(t)}{TH_k(A,S)} + \min_{l: x_{k,l}=1} (E[T_{acc,l}]). \tag{26}$$

The results of calculations based on the derived expression are presented in graphs for the STR mode at Figure 4 and the NSTR mode at Figure 5. which demonstrate the total packet dwell time in the previously described system.

The evaluation was performed for the four load matrix formation strategies described above B with additional consideration of the average waiting time for access to the medium.

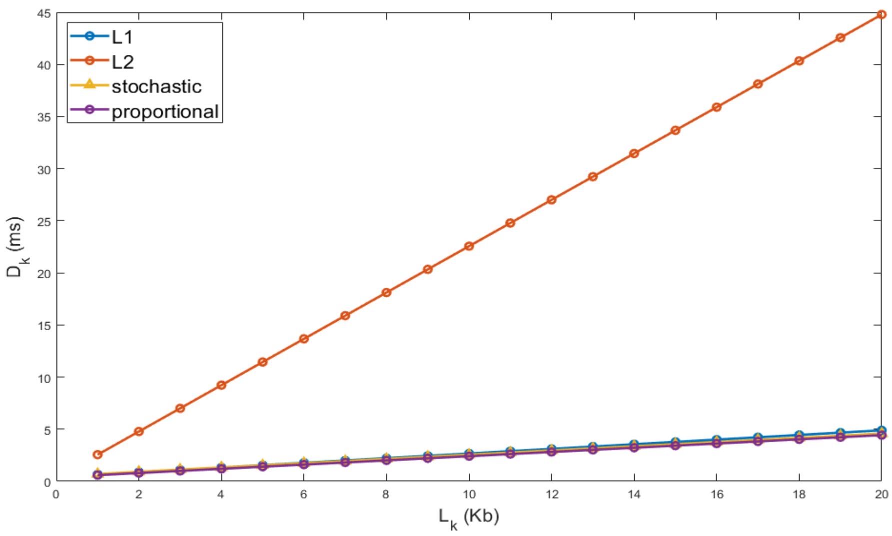

Figure 4: Average delay for STR.

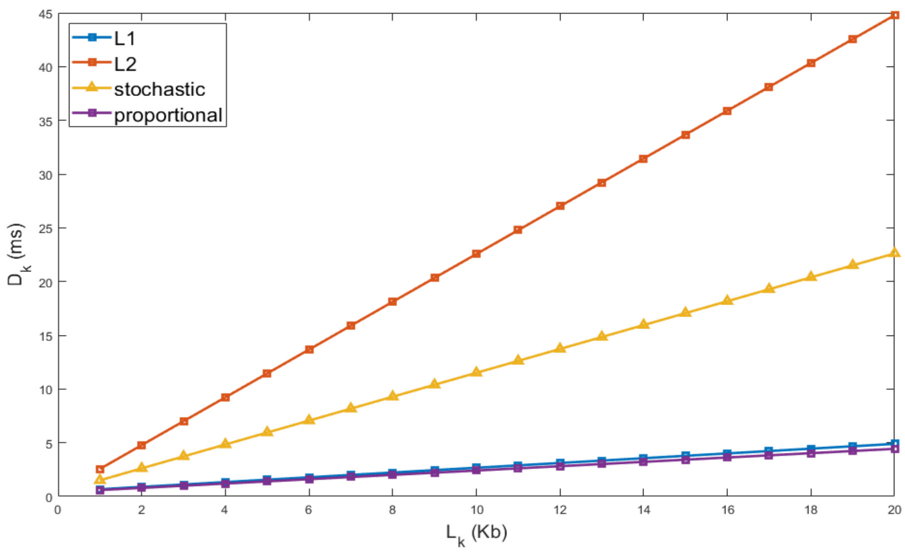

Figure 5: Average delay for NSTR.

The risk of missing a deadline arises if the service rate is insufficient to transmit the available data volume within the allotted time. We approximate the service time distribution using an exponential distribution [23]. Then, the probability of failure is estimated as a function of the ratio of available time to required time (27):

$$P_{fail,k}(A) \approx \exp\left(-\frac{T_k^{rem}}{E[T_{drain}]}\right) = \exp\left(-\frac{T_k^{rem} \cdot TH_k(A,S)}{L_k(t)}\right) \tag{27}$$

where: T_k^{rem} is the remaining time until the deadline (available time resource); $L_k(t)$ is the current queue size (in bits); $TH_k(A,S)$ is the expected throughput (in bits/s), defined above.

Visualizations of the obtained values of the probability of violating time constraints are presented in graphs for the STR modes at Figure 6 and the NSTR mode at Figure 7.

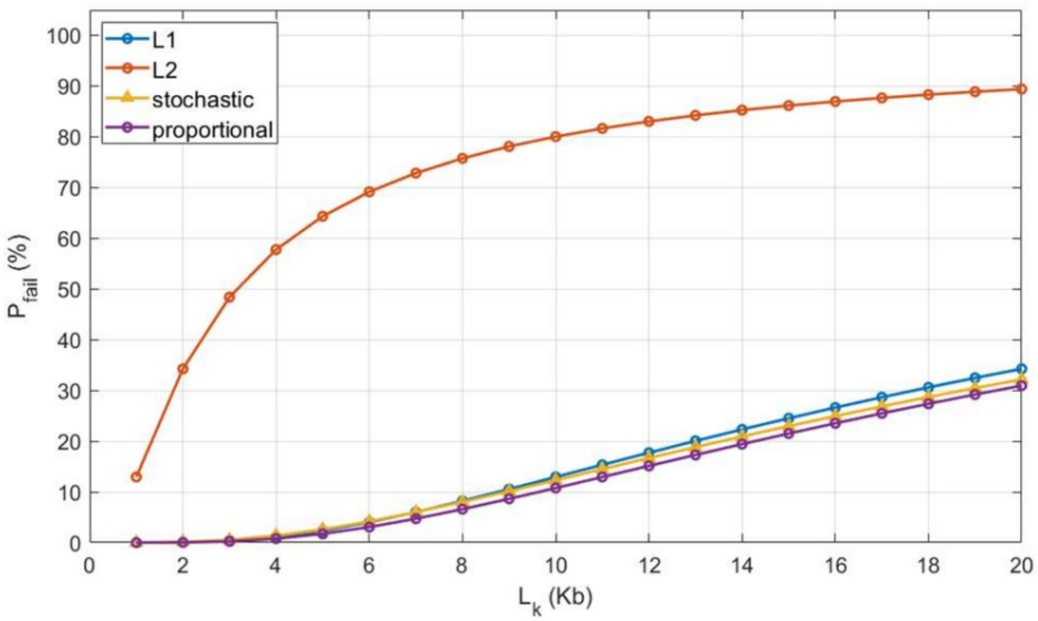

Figure 6: Probability of missing the deadline for STR.

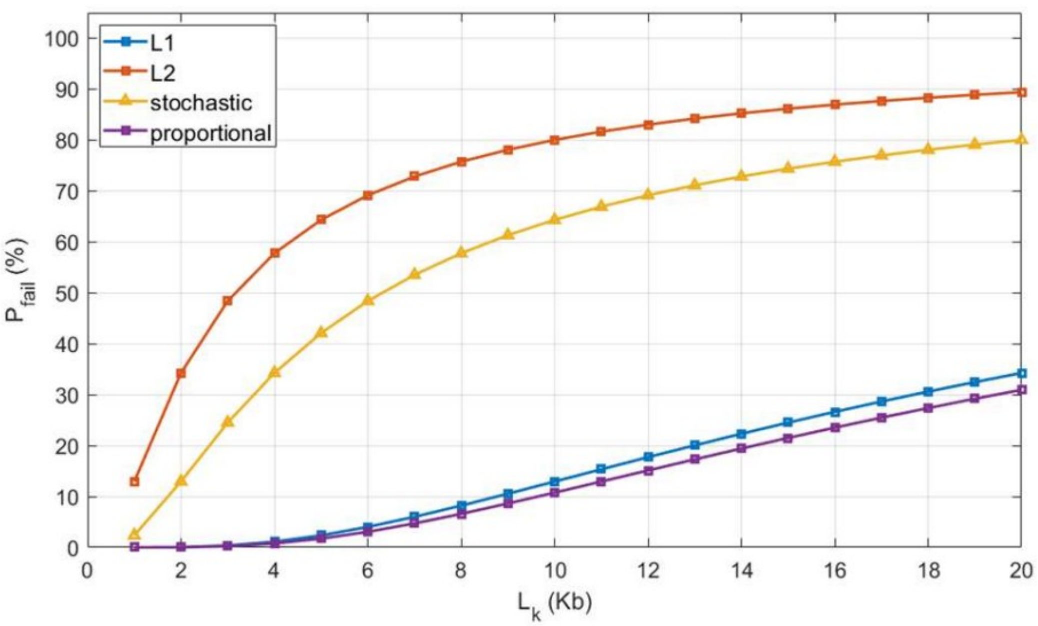

Figure 7: Probability of missing the deadline for NSTR.

This expression demonstrates how reliability depends on the decision made: an increase in the allocated resource (growth of TH_k) leads to a faster decrease in the exponent, reducing the probability of failure ($P_{fail} \to 0$), while an increase in the queue (growth of L_k) reduces the denominator in the fraction, bringing the probability of failure closer to one ($P_{fail} \to 1$).

5. Discussion

The implementation of MLO technology allows devices to use multiple radio interfaces simultaneously; however, due to the physical limitations of devices using this technology, performance critically depends on traffic allocation policies.

Currently, most of these policies are based on disparate deterministic heuristics, which, under conditions of asymmetric link load, can lead to different results depending on the state and mechanisms of access to the network.

Therefore, there is an objective problem of the lack of a unified method for describing and comparing traffic distribution policies.

This article examines an approach to solving the problem of traffic distribution in a multi-link network, where the decision-making process is reduced to determining a control action based on the current state of the system. This makes it possible to describe the distribution policy as an algorithm with specified parameters and an output.

The proposed approach can be applied in practice to mechanisms for adaptive traffic distribution planning across links, automatic network configuration, or as a testing environment for algorithms [24, 25] without the need to use actual hardware.

The essence of the proposed methodology lies in calculating the probability of frame delivery delay using statistical modeling [26], which allows for a quantitative assessment [27] of the reliability of any traffic distribution policy. This metric is derived based on the expected transmission rate, which is obtained by combining link parameters and the current state of queues into a single system [28].

To ensure the methodology aligns with the actual capabilities of the equipment, we use a compatibility matrix for filtering [29] that restricts impossible configurations in accordance with the IEEE 802.11 be standard.

That is, this methodology, in the form of a system of equations, allows us to numerically determine whether the selected distribution policy is physically capable of ensuring frame delivery by the deadline including the risk management [30].

6. Conclusion

The simulation results show that the effectiveness of traffic distribution policies is determined not by the number of links, but by the alignment between the load, the links' characteristics, and the state of the environment.

The application of our methodology demonstrates this mechanism. By integrating the physical parameters of the links (in this case, their asymmetry) into the delay formulas, we found that adding an additional, but slower, link creates a "bottleneck" effect.

Instead of the expected increase in throughput, the total queue length increases due to the relatively slow link, causing the overall MLO performance to drop to the level that would be achieved by transmitting only through the single fastest channel.

An evaluation of the results comparing the four strategies revealed clear quantitative differences in their effectiveness. As the volume of data in the queue increases, stochastic distribution leads to a sharp exponential jump in delays, bringing the probability of missing the time deadline close to a critical 80–90%.

In contrast, the use of proportional distribution, which ties the volume of directed traffic to the speed of an individual link, mitigates this risk and keeps the failure rate at 30% in both STR and NSTR modes.

The proposed methodology allows for an informed choice of traffic distribution policies by pre-assessing their consequences. The method's ability to calculate the probability of failure based on an exponential service time distribution provides users with numerical thresholds for switching distribution policies.

In other words, implementing this method can enable the testing and configuration of U-MAC-level schedulers for MLO devices.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

1. IEEE 802.11 Working Group. IEEE P802.11be/D3.0: Draft Standard for Information technology —Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 8: Enhancements for extremely high throughput (EHT), IEEE, 2023.
2. C. Chen, X. Chen, D. Das, D. Akhmetov, and C. Cordeiro, Overview and Performance Evaluation of Wi-Fi 7, IEEE Communications Standards Magazine, 6(2), (2022) 12-18. doi: 10.1109/MCOMSTD.0001.2100082.
3. C. Deng, X. Fang, X. Han, X. Wang, L. Yan, R. He, Y. Long, and Y. Guo, IEEE 802.11be Wi-Fi 7: New Challenges and Opportunities, IEEE Communications Surveys & Tutorials, 22(4), (2020) 2136-2166. doi: 10.1109/comst.2020.3012715.
4. Á. López-Raventós, and B. Bellalta, Multi-link operation in IEEE 802.11be WLANs, IEEE Wireless Communications, 29(4), (2022) 94-100. doi: 10.1109/MWC.006.2100404.
5. Á. López-Raventós, and B. Bellalta, Dynamic Traffic Allocation in IEEE 802.11be Multi-Link WLANs, IEEE Wireless Communications Letters, 11(7), (2022) 1404-1408. doi: 10.1109/LWC.2022.3171442.
6. J. Zhang, Q. Tan, Y. Gao, X. Sun, and W. Zhan, WiFi 7 with Different Multi-Link Channel Access Schemes: Modeling, Fairness, and Optimization, IEEE Transactions on Communications, 72(10), (2024) 6225-6236. doi: 10.1109/TCOMM.2024.3400278.
7. W. Murti, and J.-H. Yun, Multilink Operation in IEEE 802.11be Wireless LANs: Backoff Overflow Problem and Solutions, Sensors, 22(9), (2022) 3501. doi: 10.3390/s22093501.
8. M. Carrascosa-Zamacois, G. Geraci, E. Knightly, and B. Bellalta, Wi-Fi Multi-Link Operation: An Experimental Study of Latency and Throughput, IEEE/ACM Transactions on Networking, 32(1), (2024) 308-322. doi: 10.1109/TNET.2023.3283154.
9. M. Han, Z. Chen, and X. Sun, Bandit-Based Multiple Access Approach for Multi-Link Operation in Heterogeneous Dynamic Networks, IEEE Open Journal of the Communications Society, 6, (2025) 1423-1437. doi: 10.1109/OJCOMS.2025.3535619.
10. P. E. Iturria-Rivera, M. Chenier, B. Herscovici, B. Kantarci, and M. Erol-Kantarci, Channel Selection for Wi-Fi 7 Multi-Link Operation via Optimistic-Weighted VDN and Parallel Transfer Reinforcement Learning, IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), (2023) 1–6. doi: 10.1109/PIMRC56721.2023.10293832.
11. P. E. Iturria-Rivera, M. Chenier, B. Herscovici, B. Kantarci, and M. Erol-Kantarci, RL meets Multi-Link Operation in IEEE 802.11be: Multi-Headed Recurrent Soft-Actor Critic-based Traffic Allocation, ICC IEEE International Conference on Communications, (2023) 4001-4006. doi: 10.1109/ICC45041.2023.10279008.
12. Linux Wireless mac80211 – Linux kernel 802.11 wireless stack, The Linux Kernel Organization, (2024). https://wireless.wiki.kernel.org/en/developers/documentation/mac80211.
13. D. Ergenç, and F. Dressler, An Open Source Implementation of Wi-Fi 7 Multi-Link Operation in OMNeT++, 20th IEEE/IFIP Wireless On-Demand Network Systems Conf., (2025) 131-134.
14. N. Dawar, K. N. Nguyen, A. Sehgal, Y. Zhu, B. Loong Ng, and J. Choi, Enhancing Wi-Fi 7: Traffic Flow Intelligence and Multi-Link Operation for Optimal Efficiency, IEEE Access, (2024). doi: 10.1109/ACCESS.2025.3557435.
15. G. Onalan, M. H. Kurtoglu, and E. Soyak, Passive Side-Channel Interference Estimation for WiFi Networks, IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), (2021) 1-6. doi: 10.1109/PIMRC50174.2021.9569396.
16. L. Zhang, H. Yin, S. Roy, L. Cao, X. Gao, and V. Sathya, IEEE 802.11be Network Throughput Optimization with Multi-Link Operation and AP Coordination, Networking and Internet Architecture, (2023). doi: 10.48550/arXiv.2312.00345.

17. A. Abdalhafid, S. K. Subramaniam, Z. A. Zukarnain, and F. H. Ayob, Multi-Link Operation in IEEE802.11be Extremely High Throughput: A Survey, IEEE Access, 12, (2024) 44349-44371. doi: 10.1109/ACCESS.2024.3378997.
18. M. Carrascosa-Zamacois, G. Geraci, L. Galati-Giordano, A. Jonsson, and B. Bellalta, Understanding Multi-link Operation in Wi-Fi 7: Performance, Anomalies, and Solutions, IEEE Commun. Magazine, 61(4), (2023) 136-142. doi: 10.1109/PIMRC56721.2023.10293865.
19. K. Hong, J. P. Kim, M.-S. Kim, and S. Lee, Channel measurement-based access point selection in IEEE 802.11 WLANs, Pervasive and Mobile Computing, 29, (2016) 1-16. doi: 10.1016/j.pmcj.2015.10.018.
20. G. Cena, M. Rosani, and S. Scanzio, Packet Steering Mechanisms for MLO in Wi-Fi 7. IEEE 29th International Conference on Emerging Technologies and Factory Automation (ETFA), (2024) 1-4. doi: 10.1109/ETFA61755.2024.10710726.
21. S. Khlamov, V. Savanevych, Yu. Netrebin, and T. Trunova, AI-based decision-making process in pipeline for astronomical data mining, CEUR Workshop Proceedings, 4048, (2025) 172-186. https://ceur-ws.org/Vol-4048/paper14.pdf.
22. Y. Romanenkov, V. Mukhin, V. Kosenko, D. Revenko, O. Lobach, N. Kosenko, and A. Yakovleva, Criterion for Ranking Interval Alternatives in a Decision-Making Task, International Journal of Modern Education and Computer Science (IJMECS), 16(2), (2024) 72-82. doi: 10.5815/ijmecs.2024.02.06.
23. B. Bellalta, M. Carrascosa L. Galati-Giordano, and G. Geraci, Delay Analysis of IEEE 802.11be Multi-Link Operation Under Finite Load, IEEE Wireless Communications Letters, 12(4), (2023) 595-599. doi: 10.1109/LWC.2023.3235001.
24. S. Khlamov, M. Mendielieva, O. Vovk, and Zh. Deineko, Comparative analysis of JMeter and Postman for API-based performance testing, CEUR Workshop Proceedings, 4048, (2025) 426-440. https://ceur-ws.org/Vol-4048/paper34.pdf.
25. M. Rosani, G. Cena, D. Cavalcanti, V. Frascolla, G. Marchetto, and S. Scanzio, A Software Platform for Testing Multi-Link Operation in Industrial Wi-Fi Networks, IEEE 20th WFCS, (2024) 1-8. doi: 10.48550/arXiv.2411.12077.
26. V. O. Shvedun, and S. V. Khlamov, Statistical modeling for determination of perspective number of advertising legislation violations, Actual Problems of Economics, 184(10), (2016), 389-396.
27. I. Ruban, H. Horenskyi, Yu. Romanenkov, and D. Revenko, Models of adaptive integration of weighted interval data in tasks of predictive expert assessment, Eastern-European Journal of Enterprise Technologies, 5(4-119), (2022) 6-15. doi: 10.15587/1729-4061.2022.265782.
28. S. Bielievtsov, I. Ruban, K. Smelyakov, and D. Sumtsov, Network technology for transmission of visual information, CEUR Workshop Proceedings, 2318, (2018) 160-175. https://ceur-ws.org/Vol-2318/paper14.pdf.
29. S. Khlamov, V. Savanevych, V. Vlasenko, O. Briukhovetskyi, T. Trunova, I. Levykin, V. Shvedun, and I. Tabakova, Development of the matched filtration of a blurred digital image using its typical form, Eastern-European Journal of Enterprise Technologies, 1(9-121), (2023) 62-71. doi: 10.15587/1729-4061.2023.273674.
30. V. Martovytskyi, V. Argunov, I. Ruban, and Y. Romanenkov, Developing a risk management approach based on reinforcement training in the formation of an investment portfolio, Eastern-European Journal of Enterprise Technologies, 2(3-122), (2023) 106-116. doi: 10.15587/1729-4061.2023.277997.