Highly Reliable Communication Using Multipath Slices with Alternating Transmission

Italo Tiago da Cunha[1(✉)], Eduardo Castilho Rosa[2], Rodrigo Moreira[3], and Flávio de Oliveira Silva[4,5]

[1] Federal University of Jataí (UFJ), Jataí, GO, Brazil
italo@ufj.edu.br
[2] Goiano Federal Institute (IFGoiano), Catalão, GO, Brazil
eduardo.rosa@ifgoiano.edu.br
[3] Federal University of Viçosa (UFV), Rio Paranaíba, MG, Brazil
rodrigo@ufv.br
[4] Federal University of Uberlândia (UFU), Uberlândia, MG, Brazil
flavio@ufu.br
[5] Centro Algoritmi, University of Minho, Braga, Portugal
flavio@di.uminho.pt

Abstract. The development of mobile networks with network-slicing technologies has facilitated the delivery of increasingly customized applications to customers in various business verticals. Network slicing technology has made it possible to tailor applications to meet specific and rigorous requirements. However, Ultra-Reliable Low-Latency Communications (URLLC) remain challenging due to deploying network slices over an unreliable physical substrate. Traditionally, reliability has been enhanced through multipath, but this approach is limited to delivering URLLC. To address this issue, we propose and evaluate a method based on P4 that utilizes slices to enable reliability using the Alternating Transmission (AT) technique without Packet Duplication (PD). Our approach guarantees slice reliability while saving bandwidth compared to existing state-of-the-art methods.

1 Introduction

Mobile networks significantly facilitate the world's digital transformation by revolutionizing the performance of everyday tasks [1]. 5G technology has enabled innovations such as real-time video transmission, integration with cloud computing, and compatibility with the Internet of Things (IoT). These advancements have enabled the successful design and deployment of various technologies, including technology-enhanced clothing, health monitors, autonomous vehicles, smart cities, and Industry 4.0 [1].

Towards digital transformation, Network Slices (NS) has received attention and efforts in developing and standardizing the mobile network 5G. NS provides deployment of isolated logical networks, self-managed with heterogeneous requirements over a general purpose network [2,3]. NS enables on-demand personalized services in networks with limited resources, enabling optimal utilization in static and mobile environments [4]. That is, NS allows several customized services on demand to be served by

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the same physical network, in which resources can be dynamically allocated through logical slices according to Quality of Service (QoS) requirements.

Improving the dependability of connections across a network that is likely to experience issues is a significant challenge for new network architectures. These systems are frequently utilized in critical applications, such as smart grids, industrial Internet, remote surgeries, intelligent transportation systems, vehicle communications, high-speed trains, drones, and industrial robots. There is no universal standard for consuming these applications due to their unique characteristics [3,5].

Recent advances in literature focused on tackling the challenge of ultra-reliable network slicing by utilizing PD in Multi-Connectivity (MC) scenario [6]. These efforts do not rely on alternating transmission. This study presents a novel, highly reliable communication approach using multiple slices bringing together AT with multipath support. Using data-plane programmability, we prototype our approach using Mininet and a programmable P4-based software switch (*bmv2*) [7,8]. This prototype uses a dispatcher supporting multipath together AT between peers. In this work, multipath support means more than two paths between the communicating peers. The AT capacity uses the multiple slices to provide reliability by optimizing bandwidth consumption.

The main contribution of this work is to use the NS concept to increase reliability by using multipath support with AT. Our work avoids the downsides of PD with an optimized bandwidth consumption that increases reliability by increasing the number of NS.

The remainder of this work is organized as follows: Sect. 2 presents a short state-of-art survey and related work to our rationale. Section 3 describes the proposed packet multipath alternating transmission and usage scenarios. Section 4 presents the experimental scenario we used to evaluate our approach and discuss experimental results. Finally, in Sect. 5, we conclude the paper while highlighting the future research directions.

2 Related Work

This section discusses related studies aimed at deploying ultra-reliable network slicing. Finally, we contrast our work in Table 1 by highlighting important features and their differences.

To achieve high reliability and low latency, Islambouli et al. 2019 [9] make use of more than one network interface, network, and path per User Entity or, User Equipment - UE, for sending packets, with emphasis on duplicates of fragments of packets. In this scenario, there is not only an over-allocation of resources, but there can also be a considerable consumption of resources, such as batteries and data.

The work of Mahmood et al. 2019 [10], provides, according to the authors, a complete analysis of MC. In particular, the improvement of reliability with MC, measured in terms of interruption probability gain, which is obtained analytically. In addition, the operational cost of the MC in terms of resource utilization is also analyzed. Overall, [10] emphasizes that the price for increased reliability with MC is almost double that of single connectivity regarding resources and additional signaling overhead. However, it was considered that resource efficiency is not the main performance indicator for many applications that require high reliability. However, this arouses a strong motivation to investigate more resource-efficient MC schemes. This time, the present work aims to optimize resources to provide reliability, as initially shown in [11].

According to Gebert and Wich 2020 [12], they used *survival time* to devise a new communication scheme "AT", which enables the alternate sending of packets, either through DC or carrier aggregation. It should be noted that both in the alternating transmission of packets via DC and carrier aggregation, there is no duplication of packets and that the work does not address URLLC and NS. And through the results obtained, it may be interesting to apply AT in the context of URLLC, combined with multipath slices - what we did here.

Something interesting at Centenaro et al. 2020 [13] is that they address DC in downlink by proposing two mechanisms that prevent unnecessary duplicate transmissions to optimize the spectrum. It should also be noted that the mechanisms seek to provide transmission redundancy only at the end of a communication.

To provide reliability, Shahriar et al. 2020 [14] propose the incorporation of two techniques to reduce the resources of backup: (i) bandwidth elasticity, i.e., the adjustment of the amount of bandwidth guaranteed in case of failures to a minimum value; and (ii) provisioning of multiple alternate paths - restricted to the EON scope. Thus, the simulated work presents interesting contributions, especially in formalism, but it does not understand E2E communication. Based on this, the present research will expand and implement this in E2E communication via multipath to increase reliability.

Concerning the simulated work of Sweidan et al. 2020 [15], which is an extension of the work of Islambouli et al. 2019 [9], the authors discuss a more general and practical network model that serves multiple applications to identify specific paths in the network as part of a dedicated slice that meets stringent performance requirements. In a more general scope, the objective is to maximize the number of flows allowed by applications, considering different requirements, both in terms of delay and reliability, inherent to ongoing URLLC applications. Differently from the work proposed here, [15] did not use slices containing replicas of packages and even elasticity in the referred ones. These points are essential to guarantee reliability and low latency in E2E communication - even more so if it crosses CN.

For short, the works of Mishra et al. [16,17] and Kar et al. 2023 [18], via Simu5G develop a novel NR-DC architecture, a multi-connectivity with Packet duplication via Simu5G and Reduces frequent handovers and allows high UE mobility with no additional complexity, respectively.

Showing the relevance of MC, Susloparov et al. 2022 [19] considered a scenario in which AR/VR traffic is served in a 5G system that supports MC. Another research from Paropkari and Beard 2023 [20] presents a technique that duplicates enough packets across multiple connections to meet the outage criteria.

Majamaa et al. 2023 [21] confirm that packet duplication (PD) through multi-connectivity is a promising solution to ensure reliable communication in such networks. With this in mind, they propose a dynamic PD activation scheme for Non-Terrestrial Networks (NTNs) based on hybrid automatic repeat request feedback.

Elias et al. 2023 [22] analyzes the problem of admission control and resource allocation in MC scenarios, considering different requirements and 5G NR features. To solve these problems, they developed an optimization framework that decides which users to admit in the system, whether to activate multiple connections to satisfy user requirements and how to allocate radio resources.

Kamboj et al. 2023 [23] punctuated that software-defined multipath routing is a viable approach to fulfill such QoS requirements by improving the data delivery performance through multipath. Opportunity to improve the data delivery performance through multipath to achieve QoS. Another research that caught our attention came from Großmann and Homeyer 2023 [24], which presented a solution based on P4 to duplicate packets to send them to their destination via multiple routes. This differs from what we propose in the number of paths that can be used and the Alternating Transmission technique that we use.

Interestingly, the idea of incoming packets in an MC way is extended to wireless technology. Levitsky et al. 2022 [25] confirm that when they wrote that Multi-link Operation (MLO) is a key feature of Wi-Fi 7, which is currently under development. MLO improves throughput and latency by allowing two devices to establish multiple links between them. The maximal gains are achieved when the links do not interfere, and the devices can use them independently. And we know, as shown in the Evaluation section, that this is true in the context of what we're proposing.

Alsakati et al. 2023 [26] evaluated the performance of MLO, using different policies, in serving Augmented Reality (AR) applications compared to Single-Link (SL). They support the idea that AR applications require high throughput, low latency, and high reliability to ensure a high-quality user experience. Related to the idea of MLO, Ali and Bellalta 2023 [27] proposed a collaborative ML approach to training models across multiple distributed agents without exchanging data to learn the best MLO-Link Allocation (LA) collaboratively, what can be appreciated to the adoption of new paths.

Carrascosa-Zamacois et al. 2023 [28] presented the first work studying the performance of MLO using real spectrum occupancy measurements. All this work related to MLO reinforces that the idea of alternating transmission of packets in a multipath way - guaranteeing reliability- is a promising area of research relevant to our work.

We summarize our brief literature review in Table 1. The rationale behind this table relies on the contrast we employed, considering some features. The column "DC/MC" means: Dual Connectivity and/or Multi-Connectivity. It's important to highlight that the multipath capacity means more than two paths between the communicating peers in the work.

Table 1. Short State-of-the-Art Survey.

Approach	Addresses 5G/B5G	DC/MC	Reliability	Multipath Support	Alternating Transmission
Islambouli *et* al. 2019 [9]	●	●	●	●	○
Mahmood *et* al. 2019 [10]	●	●	●	○	○
Gebert; Wich 2020 [12]	●	●	○	○	●
Centenaro *et* al. 2020 [13]	●	●	●	○	○
Shahriar *et* al. 2020 [14]	●	●	●	●	○
Sweidan *et* al. 2020 [15]	●	●	●	●	○
Mishra *et* al. 2021 [16]	●	●	●	○	○
Mishra *et* al. 2022 [17]	●	●	●	○	○
Levitsky *et* al. 2022 [25]	○	●	○	○	○
Susploparov *et* al. 2022 [19]	●	●	●	○	○
Paropkari; Beard 2023 [20]	●	●	○	○	○
Kar *et* al. 2023 [18]	●	●	●	○	○
Elias *et* al. 2023 [22]	●	●	●	○	○
Ali; Bellalta 2023 [27]	○	●	●	○	○
Alsakati *et* al. 2023 [26]	○	●	●	○	○
Carrascosa-Zamacois *et* al. 2023 [28]	○	●	○	○	○
Majamaa *et* al. 2023 [21]	●	●	●	○	○
Kamboj *et* al. 2023 [23]	●	●	○	●	●
Großmann; Homeyer 2023 [24]	○	●	●	○	○
Our Work	●	●	●	●	●

3 Multipath Slices with Alternating Transmission

This section details the reliability of using multiple NS to provide multipath and AT. First, we assumed that a network interface does not always send packets because it depends on the upper layer (application layer) for this to occur. Thus, there is a small timeframe in which the “link” medium is idle. This idle time is presented in Fig. 1 by time distance between two packets. Figure 1 also abstracts three slices with distinct paths between two communicating peers. If the packet within the transmission uses different slices, the picture represents AT without PD. Thus, we have no reliability in the event of failure.

As shown in Fig. 1, the sender transmits packets in multipath mode to the destination, which may occur through three different slices. No guarantee mechanism is available for the retransmission of a packet in the event of failure of any of the slices, which is the responsibility of higher layers and most likely requires a retransmission request from the recipient for this to occur. This causes a delay in the acknowledgment of packets, as they may have been corrupted or even lost. Therefore, it compromises real-time applications not only in terms of reliability but also in terms of delay.

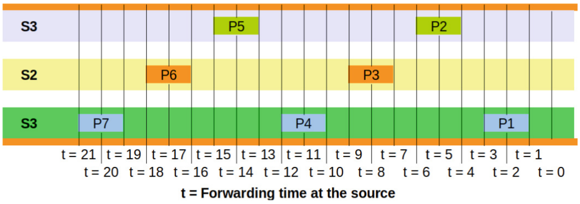

Fig. 1. Scenario of packets forwarding with no reliability using Multipath Slices with AT.

The rationale behind our method is to fit duplicates in this time interval when slices are idle, as shown in Fig. 2. That is, the copy of a packet that has just been passed through one slice is merged into another. In this way, slice bandwidth usage will be optimized, and there will be a significant increase in reliability, which is essential for URLLC applications.

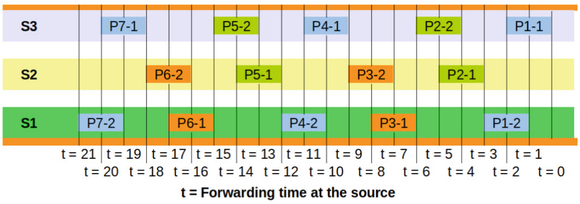

Fig. 2. Approach to get reliability via Multipath Slices using three slices with AT.

Figures 2 and 3 illustrate the behavior of our method in an ideal scenario with no packet loss and three and four active slices, respectively. Idle slices are used to send both original and redundant packets in an interleaved manner, thus ensuring the reliability of the communication. Notably, using PD is not indistinct, flooding all slices with replicas. As shown in Figs. 2 and 3, the PD occurs in a controlled way with a single copy alternating the transmissions between the available slices during communication.

From the analysis of Fig. 3, it can be observed that using our technique of alternating packet forwarding between slices, the number of duplicates in the network as a whole dropped to 50%.

Figure 4 shows the proposed approach for a failure scenario. According to Fig. 4, communication is served by three distinct slices in which duplicates of packets that have just been transmitted are interspersed. For example, Packet 2 “P2-1” was initially forwarded by the sender through Slice S2 at time instant t3 and, being an instant of time later, forwarded a copy of it through Slice S3 “P2-2”. This optimizes the use of slices and increases the reliability. If there is a loss or corruption of a packet, communication will be maintained without the need for retransmission.

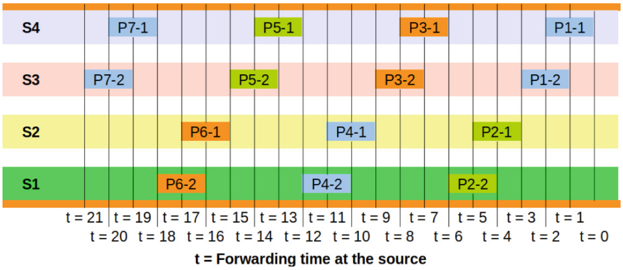

Fig. 3. Approach to get reliability via Multipath Slices using four slices with AT.

Alternatively, multipath slices can handle and divide traffic loads among other slices. As shown in Fig. 4, these slices are already active and inserted in the communication without the need for additional time to instantiate a new slice [14, 29, 30].

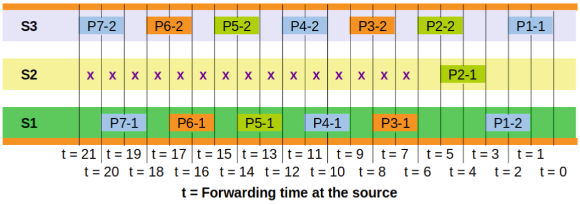

Fig. 4. Fail in slice 2 and communication working without loss or delay.

According to Fig. 4, at time frame 6, Slice S2 no longer forwards packets, either because of intermittent or permanent failure. However, communication is not disrupted since slices S1 and S3 are still active, absorbing the traffic load of the one that failed, the packets (P5-1) and (P3-2, P6-2), respectively. It should be noted that such an approach changes the sender slice for some packets, as happened with P4-1, which in Fig. 2 arrived through Slice 3, and now, through Slice 1 (Fig. 4).

NS support is a standard 5G/B5G network. Our method explores the native capacity of these networks to provide reliable communication. So, instead of considering that each slice offers different capabilities according to the application on top, the approach here is to use multiple slices deployed in multiple paths with alternating transmission to provide to the User Equipments (UEs) a highly reliable scenario natively. We argue that a single NS will not support applications that require highly reliable communication.

4 Experimental Evaluation

In this section, we describe the experimental setup and the preliminary results. We conducted two experiments based on a mininet to simulate a multi-slice environment.

The topology of both experiments consisted of multi-homed nodes interconnected with BMv2 [31] software switch instances.

We conducted experiments to answer the following questions: (1) Can communication between two communicants be maintained through distinct slices? (2) In the worst-case scenario, when a slice is compromised and "stops working," what impact does this have on the proposed topology?

4.1 Experiment 1

This experiment evaluated the effect of link failure on the End-to-End (E2E) throughput when using our dispatcher, in contrast to the traditional approach based on single-channel communication. This experimental scenario was similar to the Dual Connectivity (DC) with the PD rationale. As shown in Fig. 5, the end hosts are connected through two slices, each instantiated as an overlay tunnel on top of switches sw1, sw2, and sw4.

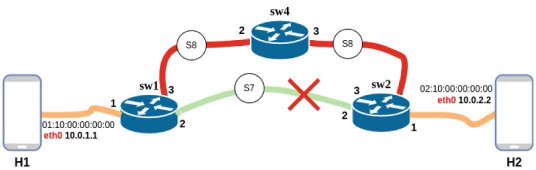

Fig. 5. Experimental scenario to use Multipath Slices in experiment 1.

We used the Python Scapy library to send 2000 packets from H1 to H2. The packets are sent continually with zero interpacket time. Thus, the maximum rate achieved was based on the speed at which the script library could send packets over the virtual interface. To simulate a link failure, we disabled the output face in switch 1 when the packet 1000th was sent.

The unexpected behavior of throughput up to 20 s in the simulation is due to the nondeterministic latency of `bmv2`, which is normal for software switches. However, as shown in Fig. 6, the throughput stabilizes from 20 s of simulation onward, and we can observe that the throughput is similar in both the multi-slice and traditional approaches. This behavior is expected in scenarios where link failures do not occur.

However, just after the second slice failure, we can see that the throughput goes to zero in the traditional method, whereas in our multi-slice approach, it is possible to maintain communication with 50% of the initial throughput. This is because, in our approach, we intelligently split the traffic between multiple slices to ensure reliability. We must note that the loss will not affect the destination because the user received another copy of the data.

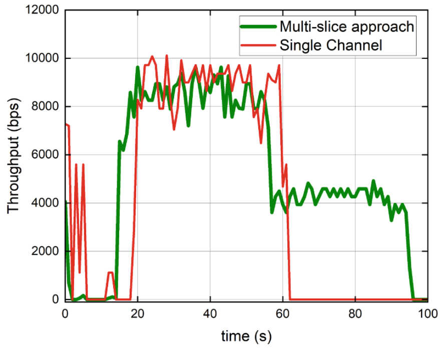

Fig. 6. Throughput when using a multi-slice approach.

4.2 Experiment 2

In the second experiment, we worked on three active slices, S8, S7, and S5, in a scenario with four switches and two hosts, as illustrated in Fig. 7. It should be noted that this scenario did not result in packet loss or even path interruption.

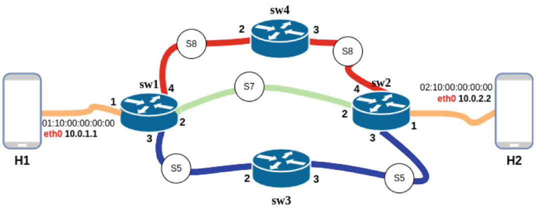

Fig. 7. Experimental scenario to use multipath slices.

As shown in Fig. 7, with three functional slices, the traffic in all of them was 66,66% of the total traffic for a single connection or in the PD scenario. In other words, a significant gain in bandwidth and, consequently, in reliability, especially cause, is not necessary to initialize a new slice in case of failure. Table 2 summarizes and extrapolates the results of Experiment 2 by considering four different slices.

Our method increased the reliability while reducing bandwidth wasting compared with naive PD. The best results were obtained when we used four slices for incoming packets, as shown in Table 2. In other words, the bandwidth consumption decreases by increasing the number of paths ("slices"). Therefore, we can aggregate more paths with smaller bandwidths to provide elasticity.

Table 2. Reliability and number of packets crossing the network

	Source Transmission		Achieved Reliabiliy	Per Flow	
# of packets generated by the simulation	**Using**	**# of Packets**		**Bandwidth Consumption**	**# of Packets**
1200	Single		○	100%	1200
3000	Connectivity		○	100%	3000
1200	Packet		●	100%	1200
3200	Duplication		●	100%	3000
1200	3 Slices		●	66.6%	800
3000	(Our Method)		●	66.6%	2000
1200	4 Slices		●	50%	600
3000	(Our Method)		●	50%	1500

5 Concluding Remarks

In this paper, we proposed and evaluated a new method for ultra-reliable network slicing by leveraging idle slices and network time slots. Existing approaches do not consider alternating transmissions in communication that involves more than two paths. On the other hand, our method can forward traffic with some redundant packets through multiple slices interleaved. Our solution enables new slices to be predesigned, supporting connectivity reliability when there is a problem between the communicants.

We introduced and assessed a mechanism that offers enhanced network-slicing dependability. Our evaluations demonstrated that, as the number of slices increased, the level of reliability also increased significantly.

In future work, we will refine our methods to ensure reliability in asymmetric network slices with different bandwidth allocations. Our findings provide fresh perspectives on achieving ultra-reliability in NS while efficiently utilizing unused resources from other slices.

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References

1. O'Connell, E., Moore, D., Newe, T.: Challenges associated with implementing 5G in manufacturing. Telecom **1**(1), 48–67 (2020)
2. Moreira, R., Rosa, P.F., Aguiar, R.L.A., Silva, F.O.: NASOR: a network slicing approach for multiple autonomous systems. Comput. Commun. **179**, 131–144 (2021)
3. Martins, J.S.B., et al.: Enhancing network slicing architectures with machine learning, security, sustainability and experimental networks integration. IEEE Access **11**, 69144–69163 (2023)
4. Chang, C.-Y., et al.: Performance isolation for network slices in industry 4.0: the 5Growth approach. IEEE Access **9**, 166990–167003 (2021)

5. Liu, Y., Clerckx, B., Popovski, P.: Network slicing for eMBB, URLLC, and mMTC: an uplink rate-splitting multiple access approach. IEEE Trans. Wireless Commun. **23**, 2140–2152 (2023)
6. Silva, M., Santos, J., Curado, M.: The path towards virtualized wireless communications: a survey and research challenges. J. Netw. Syst. Manage. **32**, 12 (2023)
7. Bosshart, P., et al.: P4: programming protocol-independent packet processors. ACM SIGCOMM Comput. Commun. Rev. **44**, 87–95 (2014)
8. Lantz, B., O'Connor, B.: A mininet-based virtual testbed for distributed SDN development. ACM SIGCOMM Comput. Commun. Rev. **45**, 365–366 (2015)
9. Islambouli, R., Sweidan, Z., Sharafeddine, S.: Dynamic multipath resource management for ultra reliable low latency services. In: 2019 IEEE Symposium on Computers and Communications (ISCC), pp. 987–992, June 2019. ISSN 2642-7389
10. Mahmood, N.H., Karimi, A., Berardinelli, G., Pedersen, K.I., Laselva, D.: On the resource utilization of multi-connectivity transmission for URLLC services in 5G new radio. In: 2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW), pp. 1–6, April 2019
11. Cunha, I., Rosa, E., Silva, F.: Comunicação Fim-a-Fim Altamente Confiável e de Baixa Latência entre UEs Móveis no Contexto de 5G/B5G via Multipath Slices Elásticas. In: Anais do XIII Workshop de Pesquisa Experimental da Internet do Futuro, Porto Alegre, RS, Brasil, pp. 41–46. SBC (2022). ISSN 2595-2692. Event-place: Fortaleza/CE
12. Gebert, J., Wich, A.: Alternating transmission of packets in dual connectivity for periodic deterministic communication utilising survival time. In: 2020 European Conference on Networks and Communications (EuCNC), June 2020. ISSN 2575-4912
13. Centenaro, M., Laselva, D., Steiner, J., Pedersen, K., Mogensen, P.: Resource-efficient dual connectivity for ultra-reliable low-latency communication. In: 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), May 2020. ISSN 2577-2465
14. Shahriar, N., et al.: Reliable slicing of 5G transport networks with bandwidth squeezing and multi-path provisioning. IEEE Trans. Netw. Serv. Manag. **17**, 1418–1431 (2020)
15. Sweidan, Z., Islambouli, R., Sharafeddine, S.: Optimized flow assignment for applications with strict reliability and latency constraints using path diversity. J. Comput. Sci. **44**, 101163 (2020)
16. Mishra, P., Kar, S., Bollapragada, V., Wang, K.-C.: Multi-connectivity using NR-DC for high throughput and ultra-reliable low latency communication in 5G networks. In: 2021 IEEE 4th 5G World Forum (5GWF), pp. 36–40, October 2021
17. Mishra, P., Kar, S., Wang, K.-C.: Performance evaluation of 5G multi-connectivity with packet duplication for reliable low latency communication in mobility scenarios. In: 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), pp. 1–6, June 2022. ISSN 2577-2465
18. Kar, S., Mishra, P., Wang, K.-C.: A novel single grant-based uplink scheme for high throughput and reliable low latency communication. In: 2023 19th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), pp. 169–174, June 2023. ISSN 2160-4894
19. Susloparov, M., Krasilov, A., Khorov, E.: Providing high capacity for AR/VR traffic in 5G systems with multi-connectivity. In: 2022 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), pp. 385–390, June 2022
20. Paropkari, R.A., Beard, C.: Multi-connectivity-based adaptive fractional packet duplication in cellular networks. Signals **4**(1), 251–273 (2023)
21. Majamaa, M., Martikainen, H., Puttonen, J., Hämäläinen, T.: On enhancing reliability in B5G NTNs with packet duplication via multi-connectivity. In: 2023 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE), pp. 154–158, September 2023. ISSN 2380-7636

22. Elias, J., Martignon, F., Paris, S.: Multi-connectivity in 5G new radio: optimal resource allocation for split bearer and data duplication. Comput. Commun. **204**, 52–65 (2023)
23. Kamboj, P., Pal, S., Bera, S., Misra, S.: QoS-aware multipath routing in software-defined networks. IEEE Trans. Netw. Sci. Eng. **10**, 723–732 (2023)
24. Großmann, M., Homeyer, T.: Emulation of multipath transmissions in P4 networks with Kathará. In: KuVS Fachgespräch - Würzburg Workshop on Modeling, Analysis and Simulation of Next-Generation Communication Networks 2023 (WueWoWAS 2023), pp. 1–4. Universität Würzburg (2023)
25. Levitsky, I., Okatev, Y., Khorov, E.: Feasibility of simultaneous transmit and receive in Wi-Fi 7 multi-link devices: demo. In: Proceedings of the Twenty-Third International Symposium on Theory, Algorithmic Foundations, and Protocol Design for Mobile Networks and Mobile Computing, MobiHoc 2022, New York, NY, USA, pp. 293–294. Association for Computing Machinery, October 2022
26. Alsakati, M., Pettersson, C., Max, S., Moothedath, V.N., Gross, J.: Performance of 802.11be Wi-Fi 7 with multi-link operation on AR applications. In: 2023 IEEE Wireless Communications and Networking Conference (WCNC), pp. 1–6, March 2023. ISSN 1558-2612
27. Ali, R., Bellalta, B.: A federated reinforcement learning framework for link activation in multi-link Wi-Fi networks. In: 2023 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), pp. 360–365, July 2023
28. Carrascosa-Zamacois, M., Geraci, G., Knightly, E., Bellalta, B.: Wi-Fi multi-link operation: an experimental study of latency and throughput. IEEE/ACM Trans. Netw. **32**, 308–322 (2023)
29. Zhang, W., Lei, W., Zhang, S.: A multipath transport scheme for real-time multimedia services based on software-defined networking and segment routing. IEEE Access **8**, 93962–93977 (2020)
30. Court, A., Alamleh, H.: Multi-path data transmission to protect data in transit. In: 2023 IEEE International Conference on Consumer Electronics (ICCE), pp. 1–6, January 2023. ISSN 2158-4001
31. Bas, A., Fingerhut, A., Sivaraman, A.: The behavioral model (BMv2), January 2024. Original-date: 2015-01-26T21:43:23Z