Assessing a Private 5G SA and a Public 5G NSA Architecture for Networked Music Performances

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***Abstract*—Networked Music Performance (NMP) systems enable displaced musicians to play together. Recent advances in 5G technologies open novel possibilities for running NMPs over cellular wireless networks. However, tests on 5G support for NMPs are still limited to date, and typically restricted to specific use cases or architectures. In this paper we consider two 5G architectures, a private 5G standalone (SA) network with edge computing infrastructure, and a pre-commercial public 5G non-standalone (NSA) network. We analyze their capability to support NMPs in terms of four network metrics, namely end-to-end latency, packet error ratio, missed packets, and maximum number of consecutive missed packets. For our measurements we involved a jitter buffer of 10.66 ms. The results for the private 5G SA architecture show that the network was stable and capable of guaranteeing the latency and reliability requirements needed to ensure a realistic music interplay. Latency was constantly below 23 ms, whereas packet losses occurred with a probability of less than 0.01 on average. Conversely, the public 5G NSA architecture was insufficient to support NMPs, as the performance of the network in terms of latency and reliability were well above the perceptual thresholds that musicians can tolerate. These results suggest that public cellular 5G SA architectures with edge computing support are required for realistic real-time musical interactions.**

***Index Terms*—5G networks, networked music performances, Internet of Musical Things, latency, reliability.**

I. INTRODUCTION

The standardization of 5G mobile networks by the 3rd Generation Partnership Project (3GPP) has made it possible to overcome several issues that remained after completing the development of previous-generation 4G networks. 5G networks support higher-bandwidth data communications, and introduce numerologies to tune sub-carrier spacing and reduce the length of transmission slots. Higher numberologies enable faster transmission scheduling. Moreover, 5G standardized a flexible core network architecture, including native support for virtual network functions and edge-hosted computation, as well as lower latency in the radio access network (RAN) compared to 4G.

With the above capabilities, 5G provides the ideal networking substrate for novel use cases requiring ultra-reliable low-latency communication, enhanced mobile broadband or massive machine communications, as is the case for Internet of Things (IoT) deployments [1]. In particular, the extremely low-latency and high reliability targeted by 5G are crucial for Networked Music Performances (NMPs), where geographically displaced musicians play together over wired or wireless networks [2]–[5]. NMP systems (such as those reported in [6]–[12]) are a fundamental component of the Internet of Musical Things (IoMusT). This emerging sub-field of music technology research refers to the extension of the IoT paradigm to the musical domain [13]. IoMusT equipment has received a boost of attention during the lockdowns that followed the COVID-19 outbreak in 2020. Artists and musicians, in particular, have been using IoMusT devices to perform online rehearsals, teach music lessons, as well as NMPs themselves [14].

According to several studies [15]–[21], the end-to-end latency requirement in NMPs is very strict and amounts to 20–30 ms. Beyond these values, it becomes impossible to guarantees performance executions at the same conditions as traditional in-presence musical interactions. A delay of 20 to 30 ms corresponds to the time sound waves need to propagate in air to cover a distance of 8 to 10 m. Such distance constitutes the de-facto maximum displacement that can still be tolerated, while ensuring that performers do not lose tempo and synchronization in the absence of cues, such as the gestures of a conductor). On the other hand, the reliability of network transmissions is very important to provide a satisfactory quality of experience for the connected musicians [3]. Lost packets may result in a loss of the audio information or in a sub-optimal reconstruction of the audio signal by loss concealment methods [22], which cause playout outages and, ultimately, impair the perceived audio quality.

While the potentially very limited radio access delay and native support for virtualization of 5G networks represent a key factor for NMP support, 5G network coverage is not yet as widespread as 4G. In particular, existing 5G deployments are typically non-standalone (NSA), i.e., they offer 5G radio access backed by a 4G core network. While several solutions have been developed that allow the initial deployment of private and public 5G SA networks [23], only a few 5G architecture deployments have been investigated so far for the case of NMPs [24]–[27].

To bridge this gap, in this paper we consider two 5G architectures, a private 5G standalone (SA) network and a pre-commercial public 5G NSA network, and analyze their behavior when supporting NMPs. Some previous experiments

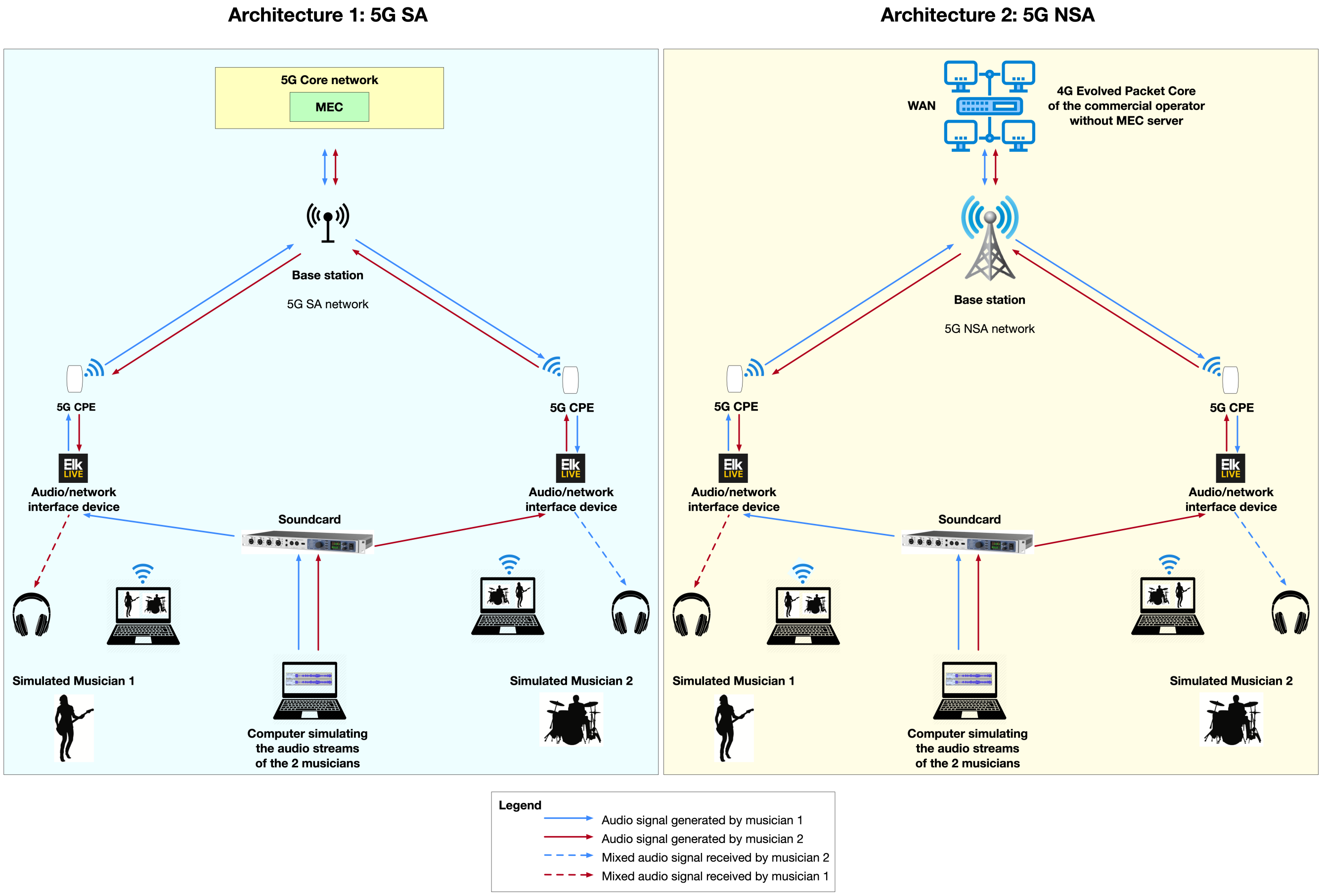

Fig. 1. Diagram and data flow of the two architectures deployed, the private 5G SA (left) and the pre-commercial public 5G NSA (right).

exist that consider the transmission of extremely low-latency audio and video over 5G links. However, these experiments typically consider dedicated setups with considerable reserved radio and core network resources [24], [28]. While these efforts prove the potential of 5G in support for NMPs, having dedicated setups does not point to the performance that a real commercial network may provide. In the same vein, other experiments with multiuser setups over pre-commercial networks [29] prove the feasibility of a specific setup but do not analyze the statistics of communications in detail, providing valuable but limited information for the design of embedded NMP devices.

Conversely, in this paper we focus on two typical 5G network architectures: a public pre-commercial 5G NSA network, and a private 5G SA network with Multi-access Edge Computing (MEC) infrastructure. We set up an NMP testbed in realistic radio access conditions (where all musical devices are closely co-located), collect performance metrics that help us assess the feasibility of each architecture for NMP, and perform a statistical analysis on our data. To our best knowledge, while the literature presents investigations of pre-commercial 5G-SA architectures (see e.g., [26]), no previous study has investigated the use of a 5G-NSA architecture for NMP applications. In a different vein, for the 5G-SA network we focused on the assessment of the sole wireless link, as the measurements can be easily transferred to a realistic NMP architecture involving a WAN by compounding them with those of the WAN. Moreover, the case of a single 5G cell serving different musician can be found in real-world scenarios, such as those concerning densely populated urban areas.

Nevertheless, our main aim with this study was not that of comparing the two architectures, but that of quantifying their performances across latency and reliability metrics and, as a consequence, understanding their limitations. Ultimately, we show that SA architectures and edge computing are key ingredients for future NMP scenarios.

II. EXPERIMENTAL SETUPS

An end-to-end network (private or public) is typically composed of three elements [30]:

1) *Core Network (CN)*: the central part of a network that provides services to users through the access network, and allows the transmission of IP packets to external networks such as the Internet.
2) *Radio Access Network (RAN)*: the network infrastructure that includes radio base stations and bridges the connection between mobile radio network devices and

the CN. To favor a smooth adoption of 5G technologies at least at the RAN side, 5G standards encompass two main configurations [31]. The so-called standalone (SA) configuration consists of the New Radio (NR) RAN connected to a natively 5G core network. Conversely, the non-standalone configuration, NSA, connects a 5G RAN to a 4G Evolved Packet Core (EPC): this setup is ideal for transitional phases, when operators progressively evolve their radio access infrastructure in order to offer better performance to their users, while still relying on a previous-generation core network, which is often sufficient to support existing wireless services, even in the presence of a faster RAN.

3) *User Equipment (UE)*: any device directly used by an end user to communicate. This includes mobile smartphone appliances, communication systems embedded in low-power edge devices, as well as massive IoT communication devices.

In the following we describe the above components in relation to the two 5G architectures we deployed for our experiments, which are schematically represented in Fig. 1. Both architectures were deployed in the city of L'Aquila, Italy.

A. Architecture 1: private 5G SA

For the private 5G SA architecture, we relied on the infrastructure of the ZTE Italia Innovation & Research Center (ZIRC), located in L'Aquila (Italy). In this setup, the base station was placed on the ceiling, roughly 3 m apart from two 5G UEs located on top of an office table (see Fig. 2, left). We measured an available bandwidth of 100 Mbit/s in downlink and 15 Mbit/s in uplink. Such bandwidths where selected to represent the configurations of current commercial operators, with the aim of understanding what limitations such kind of networks impose to NMP services. Notably, this configuration represents a significant difference with respect to our previous study reported in [27], where the bandwidths were much larger.

The two UEs acted, at the same time, as the sender and the receiver of digital audio packets. Each UE consisted of a Customer Premise Equipment (CPE, i.e., a ZTE MC801A1 5G/WiFi/Ethernet router) connected to an NMP device (namely, an Elk LIVE box [11]), and was connected to the other UE in a peer-to-peer fashion. Instead of involving human performers and live music, we arranged a setup that simulates synchronized audio traces that are part of the same piece. For this, we prepared an ad hoc software coded in the Pure Data real-time audio programming language [32], and two signals corresponding to the electric bass and drums lines as would be performed by two musicians playing together. The audio traces were played back simultaneously and routed from a laptop to a RME Fireface UFX II sound card, and from there to either of the two Elk LIVE boxes. Each box mixed the sound produced by one simulated performer with the sound received through the wireless network from the other UE. Headphones connected to each UE made it possible to hear the resulting mixed stream (see Fig. 1, left). Specific details related to the operations of the Elk LIVE boards (e.g., the control of a preliminary handshaking procedure) were enabled by two laptops, which only intervened in this initial phase. After that, the boards were connected in a peer-to-peer fashion.

Fig. 2. A picture of the simulation environment of the 5G SA architecture, showing the two Elk LIVE boxes, the two CPEs, the two headphones, the sound card, and the three laptops.

The NMP system employed in our study relies on a low-latency audio operating system and on ad-hoc hardware that translates analog audio signals into IP packets for network transport and performs the opposite operation when receiving IP-encapsulated audio data. The key elements of the system are a very stable packet pacing and timestamping at high precision, very low analog-to-digital, digital-to-analog, and packetization times. Moreover, the system enables logging features to track IP packet delivery delays, jitter, and packet losses. The NMP system outputs a protocol data unit (PDU) comprising 64 audio samples (each of 32 bits) for each of two audio channel (stereo). To optimize for latency, the system relies on the User Datagram Protocol (UDP) at the transport layer, with no retransmission scheme at the application layer. The total size of the PDU is 290 bytes, counting both audio channels. The device works with a sampling frequency of 48 kHz, and transmits packets at a rate of one packet every $64/(48 \cdot 10^3) \approx 1.33$ ms. Therefore, the minimum data rate required to transport all audio data seamlessly is approximately 2 Mbit/s (both over the uplink and the downlink segments). On-site measurements confirmed this bandwidth requirement. A constant jitter buffer of 10.66 ms was utilized to cope with late packets. This amount was selected to have a trade-off between latency and reliability. Given the high speed of analog-to-digital and digital-to-analog conversions (less than 1 ms). the main delay components in the NMPs (excluding the jitter buffer) are due to over-the-air transmissions, backhaul routing, and processing.

In our private 5G-SA network tests, the CN hardware was located in the same building as the base station, about 10 m apart, and connected via a fiber optic cable. Next to the base station, we installed a MEC server which acted as a TURN server, i.e., as a relay of the audio packets traffic between the peers.

B. Architecture 2: public 5G NSA

Fig. 1 (right) illustrates the pre-commercial public 5G NSA architecture, where the RAN operates in the n78 3GPP band. Besides the use of a different base station, we observe that there are two key differences with respect to the private 5G SA architecture: (i) we cannot count on any MEC server in this case; and (ii) the traffic is conveyed from the base station to the commercial core network of the operator via a wide-area network (WAN) widespread on the Italian territory. This results in higher transport delays than with the MEC server of the private 5G SA architecture. Moreover, the Italian telecommunication operator providing the public 5G network had to configure it ad hoc to deliver static IP addresses to the UEs, in order to enable a direct peer-to-peer communication between them.

In this case, the available bandwidth was measured as 300 Mbit/s in downlink and 27 Mbit/s in uplink. The distance between the UEs and the base station was about 50 m.

III. EXPERIMENTS

The evaluation procedure was common to both setups and consisted in operating the NMP system for 10 minutes, during which the UEs continuously transmitted audio packets to each other. This enabled a rich set of measurements related to the performance of the network during the NMP, thanks to the logging system located in each Elk LIVE box. We measured the four metrics of interest in our analysis (namely latency, packet error ratio, missed packets, as well as the maximum number of consecutive missed packets). We computed such metrics over time periods of ≈ 2.33 s. Due to this, each time period contains 1750 packets (each having 64 audio samples). For each recording, we discarded the first 15 seconds in order to remove extra delays or imperfect synchronization effects due to the initial handshaking of the devices. Finally this yielded the observation of ≈ 450.000 packets sent by each box, in each of the two investigated architectures.

We statistically quantify the above four metrics of interest by computing their mean, standard deviation, minimum and maximum, obtained by merging the log data recorded by each box. The results for the private 5G SA architecture are shown in Table I, whereas Table II shows the results for the public 5G NSA architecture. Fig. 3 (left) and Fig. 3 (right) show the evolution of the investigated metrics as recorded at one of the boxes in the 5G SA and NSA architectures, respectively. As it is possible to notice from Fig. 3 (right), a burst of below-average network performance conditions occurred after 6 minutes, leading to several lost or missed packets for 30 s, and to higher communication latency for about 1 minute. To assess the network performance under steady-state conditions, we also repeated our analysis on the measurements after filtering out such burst. The corresponding results are shown in the bottom section of Table II.

We searched for possible correlations between latency and the other three measures for both architectures. For this purpose we utilized Pearson's correlation tests. Concerning the private 5G SA architecture no significant correlations where identified. Conversely, for the public 5G NSA architecture significant correlations of medium strength were identified: for latency-packet error ratio, $r = 0.56$; for latency-missed packets, $r = 0.56$; for latency-max number of consecutive missed packets, $r = 0.66$; all were significant at $p < 0.001$. This was not the case without the burst, suggesting that the correlations previously obtained with the overall measurement were due to the burst itself.

TABLE I
RESULTS OF THE PRIVATE 5G SA ARCHITECTURE.

	Mean	**SD**	**Min**	**Max**
Latency (ms)	21.87	0.32	21.02	22.96
Packet error ratio	0.005	0.005	0	0.029
Missed packets	9.68	9.28	0	51
Max number of consecutive missed packets	2.43	4.19	0	47

For a fairer comparison of the two 5G architectures, we isolate the period from 3 to 6 minutes and plot the time series of the corresponding metrics in Fig. 4. These results show that the public 5G NSA architecture exhibits higher baseline delays than the private 5G SA one, reaching 32 ms against 22 ms for 5G SA deployment. In addition to this, we experienced a larger number of packet losses in the 5G NSA case, due to a mixture of packet errors at the RAN level and of losses related to network congestion, with one relevant spike at about 5 minutes and 20 seconds. These results support the convenience of edge server-mediated processing, mixing, and audio flow routing for NMP scenarios.

IV. DISCUSSION AND CONCLUSIONS

In this paper we aimed to quantitatively evaluate the state-of-the-art mobile wireless networks in the context of NMPs. We investigated two setups, a private 5G SA and a pre-commercial public 5G NSA. Our tests showed that the private 5G SA architecture guaranteed the latency and reliability requirements needed to ensure a realistic musical interplay. Yet, the presence of packet losses and bursts thereof would still require an efficient packet error concealment method. The measured end-to-end latency never topped 23 ms, and we observed that packet losses had a probability of less than 10^{-2}, on average, even though occasional bursts of up to 40 consecutive losses occurred in some cases.

Conversely, the 5G NSA architecture considered in our experiments proved insufficient to support NMPs. As it can be noticed from Table II, the performance of the network in terms of latency and reliability are well above the perceptual thresholds tolerable by musicians. The main reason behind this result is the large delay in end-to-end communications through the core network. In fact, such delay is observed not only in the presence of prolonged packet loss bursts, but also in normal operational conditions. The identified burst affecting the performance of the 5G NSA network is likely due to WAN congestion.

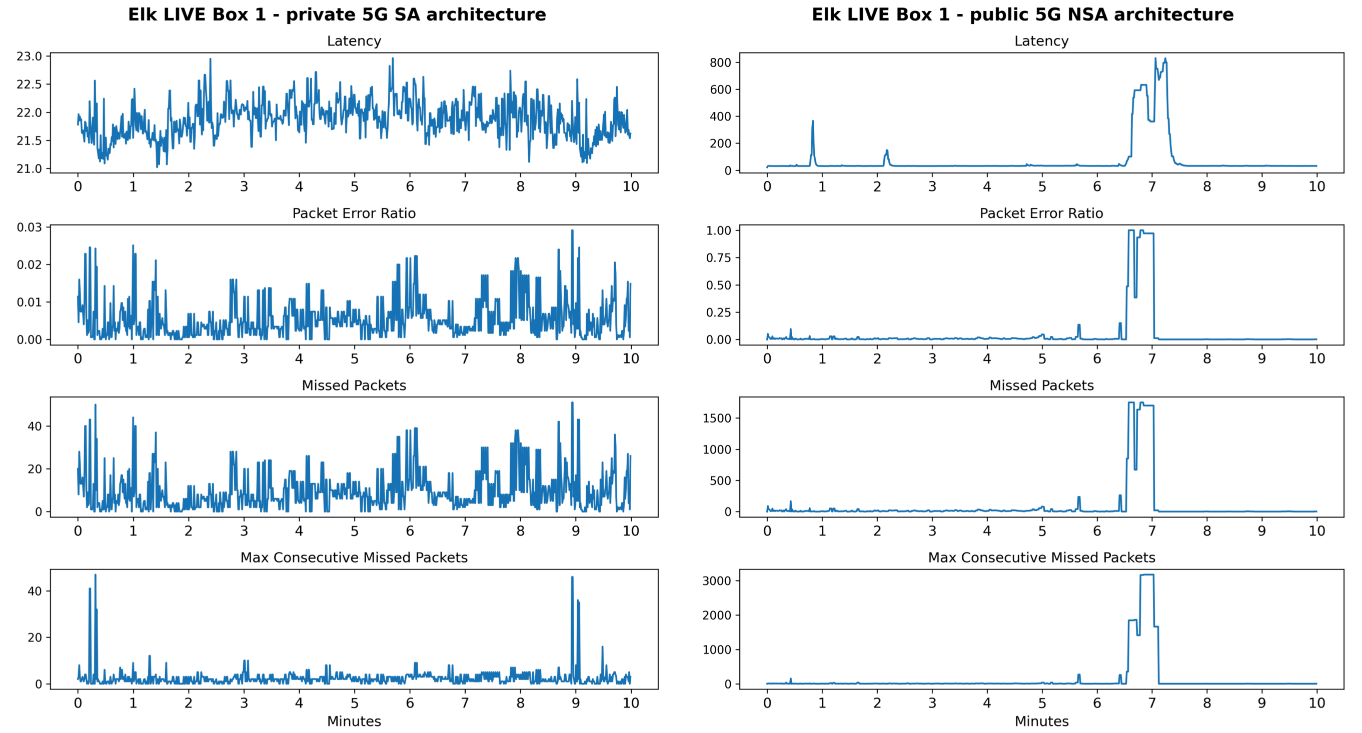

Fig. 3. Evolution of the four performance metrics over time (10 minutes), recorded at one of the two boxes, for the private 5G SA architecture (left) and the public 5G NSA architecture (right). Notice the different y-axis scale on the left and right panels.

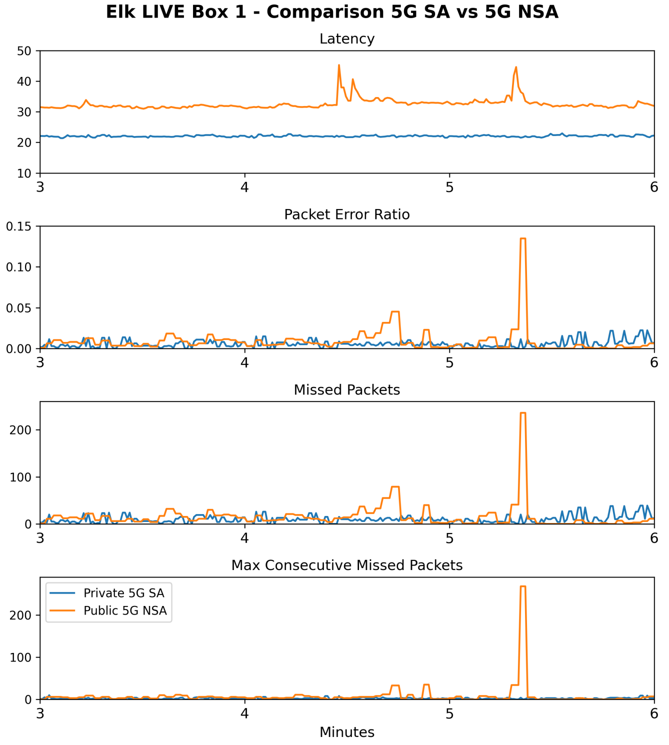

Fig. 4. Evolution of the four performance metrics over minutes 3 to 6, for the private 5G SA architecture (blue) and the public 5G NSA architecture (orange).

TABLE II
RESULTS OF THE PUBLIC 5G NSA ARCHITECTURE.

OVERALL MEASUREMENT				
	Mean	**SD**	**Min**	**Max**
Latency (ms)	74.26	146.74	22.01	830.95
Packet error ratio	0.049	0.19	0	1
Missed packets	87.01	346.15	0	1751
Max number of consecutive missed packets	136.22	566.5	0	3173
MEASUREMENT AFTER REMOVING THE BURST				
	Mean	**SD**	**Min**	**Max**
Latency (ms)	35.4	23.05	22.01	365.96
Packet error ratio	0.008	0.16	0	0.14
Missed packets	14.15	28.56	0	262
Max number of consecutive missed packets	7.62	28.1	0	268

In both architectures, packet losses and latency values also seem uncorrelated. This is in accordance with the observations in [26], obtained from a public 5G SA network deployment. The most likely reason is that packet losses and network delays have different root causes. For example, this implies that packet retransmissions at the radio link level do not cause statistically significant delay increases.

In our experiments, the 5G SA network deployment proved to be more suitable to NMP scenarios mainly because of two reasons: the availability of edge server facilities, and the detachment from a WAN, where resources are necessarily shared among multiple flows with different priorities. These ingredients are fundamental to realize real-time musical interactions. Because concentrating processing and audio routing functions on MEC infrastructure makes it possible to minimize transit through the core network of the operator, we argue that the availability of a close MEC server is a key ingredient of a successful 5G-enabled NMP scenario.

Our study is limited to a scenario with two NMP endpoints co-located in the same room and connected to the same base station. Moreover, measurement schedules constrained us to test our system for a total of 10 minutes. This time period covers the typical duration of up to three musical performance pieces, but remains short compared to longer performances (e.g., full concerts). In future work, we plan to conduct more extensive experiments, accounting for longer measurement periods, for the presence of additional boxes simulating the behavior of additional performers, as well as for background traffic patterns that are typical of different time periods throughout a typical day. Finally, we plan to conduct user studies to investigate the experience of musicians in interacting with the proposed systems.

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