The Internet of Musical Things Meets Satellites: Evaluating Starlink Support for Networked Music Performances in Rural Areas

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***Abstract*—Low Earth Orbit (LEO) satellite constellations offer a viable alternative to traditional fixed and wireless technologies, ensuring comparable speeds and latency even in rural areas. One of the applications that can be served by such types of satellite-based Internet access is represented by networked music performance (NMP) systems, which connect remote musicians and enable them to play together. Such systems are particularly relevant to communities located in rural areas, as they might lack access to local music education services, or may encounter difficulties in traveling to meet in presence for playing together. The integration of NMP system with LEO satellites could offer a viable alternative to in-person collaborative music activities, allowing musical stakeholders to reduce the costs for travel and the times to commute, with the benefit of zeroing pollution. However, thus far the use of NMP systems over satellite connections has been largely overlooked by the research community. To bridge this gap, we evaluate the performance of two Starlink-based communication infrastructures in supporting an NMP between two Italian cities, Trento and Verona. The first infrastructure connected two rural areas in the respective cities via two satellite links, one per terminal. The second connected one rural area in Trento to a neighborhood of Verona, respectively via a satellite link and a wired terrestrial network. Our findings clearly indicate that the performance of the current Starlink service in the tested geographical areas does not adhere to the strict latency and reliability requirements of NMPs. This calls for further research in this scarcely investigated domain at the frontiers of 6G networks.**

***Index Terms*—Internet of Musical Things, Satellites, low-earth-orbit, networked music performance**

I. Introduction

Internet access technologies and protocols continuously advance to meet the growing demand for faster and more reliable connectivity. Innovations in these areas are driven by the need to support an increasing number of devices and users, as well as to accommodate the ever-expanding data consumption [1]. As a result, we are witnessing continuous improvements both in the infrastructure that delivers Internet services and in the protocols that govern data exchange [2]. In densely populated areas, deploying wired connections such as optical fibers can be feasible and cost-effective. However, wiring efforts are usually much rarer in rural or mountain regions, where uncertain returns of investment do not justify infrastructure development costs. In these conditions, wireless networks often offer a viable alternative for Internet access, one prominent option being represented by satellite links.

Traditional satellite communications utilize geostationary satellites positioned at an orbit of about $36\,000\,\mathrm{km}$ [3], [4]. While these satellites can cover extensive areas of the Earth, offering connectivity to thousands of customers, this coverage comes with a latency of several hundred milliseconds due to their high altitude (the minimum latency is approximately 600 ms, with data transfer rates of up to 100 Mbps [5]). A different, more recent approach is cover the Earth with very large constellations of low earth orbit (LEO) satellite. These mega-constellations orbit the Earth at an altitude of about $600\,\mathrm{km}$), decreasing the radio link latency by about 60 times. In these conditions, satellite-based Internet access offers comparable performance to traditional fixed and wireless technologies, especially in terms of data rate and latency [6].

One of the applications that can be served by satellite-based Internet access is represented by networked music performance (NMP) systems [7]–[9]. These systems connect geographically displaced musicians and enable them to play together over a wired, wireless or hybrid network. Making this kind of service possible in rural areas would bring enormous benefits to rural communities when it comes to musical activities. For instance, rural areas might lack access to local music education services, such as those offered by conservatories of music, music schools, or even private music teachers. Moreover, for people interested in learning or playing music, it could be difficult to move due to long distances to be traversed, bad weather conditions, or both. Therefore, the integration of NMP system with LEO satellites could offer a viable alternative that would allow musical stakeholders to reduce the commuting costs and times. This also carries benefits for the environment, because avoiding the need for travels entails zeroing the corresponding pollution [10].

However, thus far the usage of NMP systems over satellites

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has been largely overlooked by the research community. To bridge this gap, in this paper we evaluate the performance of two Starlink-based communication infrastructures in supporting an NMP between two Italian cities, Trento and Verona. The first infrastructure connected two rural areas in the respective cities via a satellite-to-satellite communication. The second connected one rural area in Trento to a neighborhood of Verona, respectively via a satellite link and a wired terrestrial network.

This endeavor falls in the remits of research about the emerging Internet of Musical Things (IoMusT) field, an extension of the Internet of Things paradigm to the musical domain [11]. To the best of the authors' knowledge, this is the first study investigating how to use LEO satellites in IoMusT settings, and specifically how to integrate the Starlink service with an NMP system. Notably, our study also represents a first step towards the usage of sixth-generation cellular networks (6G) in the IoMusT, for which the integration of non-terrestrial networks (NTNs) is expected [12], especially to serve rural areas [13]. Moreover, the tackled research direction aims to foster music culture and music education diffusion, contributing to the positive social impact expected by 6G [14].

II. Related Work

A. NMP over wireless networks

NMPs represent a very challenging application for networking systems. This is due to the stringent requirements on latency and reliability [15]. Several studies have consistently confirmed that to play together synchronously, musicians need to exchange their musical signals with a maximum latency of 25 to $30\,\mathrm{ms}$ [7]. Moreover, jitter (i.e., the latency variation), should be minimal and constant. At the same time, it is crucial that the quality of the transmitted audio content is satisfactory to musicians. This translates in having a reliable communication channel (especially devoid of long packet loss bursts), that are detrimental to the listening and playing experience.

Most of research in the NMP area has been conducted on the usage of wired networks to support the exchange of audio signals. Recently, the advent of 5G networks has fostered NMPs over a wireless link [16], [17]. The attention of researchers in this space, has mostly focused on the assessment of 5G performance in supporting of NMPs. Examples can be found in [18]–[20]. A recent research line integrates 5G architectures with NMP systems enhanced with spatial audio systems, in order to provide musicians with immersive and more realistic sonic experiences [21].

In a different vein, previous attempts to integrate data provided by satellites in NMP systems have focused on the use of the global positioning system (GPS) as an approach to generate a globally shared synchronized time signal, which would serve as a global conductor within an NMP [22]. Such an approach has been used in different systems [19] and studies [23]–[25].

B. Evaluation of Starlink performance

Starlink currently advertises its priority service plan as targeting latencies of 25 to $60\,\mathrm{ms}$, downlink data rates of 40 to $220\,\mathrm{Mbit/s}$, and uplink rates of 8 to $25\,\mathrm{Mbit/s}$ for the priority plan. The standard plan used in this paper features slightly lower data rates (25 to $80\,\mathrm{Mbit/s}$ in downlink and 5 to $10\,\mathrm{Mbit/s}$ in uplink) and the same latency as the priority plan.[1] To date, a few studies have investigated the performance of Starlink in practical conditions. The study in [6], conducted in Western Europe in 2022, revealed that the minimum latency of Starlink is in the order of $20\,\mathrm{ms}$ for close destinations (as publicly advertised), and that it may increase to a few hundreds of milliseconds under high traffic load. In addition, the study showed that packet losses occurred more frequently and only affected a few consecutive packets when the link was loaded. Conversely, fewer packet losses occurred under light link loading, but such losses entailed longer bursts.

The authors of [26] measured consistent instances of periodic throughput reductions occurring every $15\,\mathrm{s}$, which corresponded to frequency reallocation and beam switching. In [27], the performance bottlenecks were examined, revealing that packet loss, throughput, and latency are adversely impacted by poor weather conditions, inter-satellite handovers, and the commmon bent-pipe architecture. The study reported in [28] explored the use of Starlink for real-time multimedia services, demonstrating that with appropriate system configurations, Starlink can support video-on-demand and live streaming. However, service quality deteriorated when Starlink was used for interactive video conferencing during adverse weather conditions.

III. Experiment 1: Two musicians connected via satellite links

The aim of this experiment was to assess the performance of a communication architecture including two NMP nodes in rural areas, each served by a Starlink connection.

A. Testbed

We set up a LEO satellite communication architecture involving two nodes located in distinct rural areas. The first was installed in the countryside of Verona, Italy; the second in the mountains to the east of Trento, Italy. The great-circle distance between the two places is about $72\,\mathrm{km}$. The two nodes were connected to the Internet via Starlink with a regular subscription. The measurements were performed on the morning of the 18th of June 2024, with ideal weather conditions (sunny day with no clouds). Fig. 1 shows the placement of the Starlink antenna at the Verona location and the sunny weather conditions (which were very similar at the Trento location).

A schematic diagram of the deployed LEO satellite communication architecture is presented in Fig. 2. According to the satellite map provided by Starlink,[2] the satellites serving the

[1] https://www.starlink.com/legal/documents/DOC-1400-28829-70
[2] https://satellitemap.space/

Fig. 1. A picture of the Starlink antenna in the rural area at the Verona location. The weather was sunny throughout the experiment.

two locations had an altitude comprised in the range from 539 to 571 km. According to the map, traffic from the first node is presumably routed from Milan's ground station to Starlink's point of presence (POP) in Frankfurt, and from there back to Milan, in order to be served to the second node through a satellite link.

Each node consisted of an NMP device (namely, an Elk LIVE box [29]), which was connected to the Starlink router via an Ethernet cable. The router was directly interfaced with the antenna. The NMP device was also connected to a laptop used to handle the initial handshaking procedure and monitor the system status. After the initial handshaking mediated by the laptops, the boxes established a direct peer-to-peer connection autonomously.

We did not involve human performers and live music in the measurements, but rather generated an audio signal at the two nodes. Specifically, this corresponded to the sound of drums and of an electric bass respectively. Each signal was generated thanks to a custom software developed in the Pure Data real-time audio programming language. At each node, the audio signal was routed from a second laptop to an RME Fireface UFX II sound card and then to the Elk LIVE box via an XLR cable. Each box mixed the locally generated sound with the audio signal received from the other Elk LIVE box via the Starlink connection. We used headphones connected to each box to listen to the combined audio stream.

The NMP system used in our study relies on a low-latency

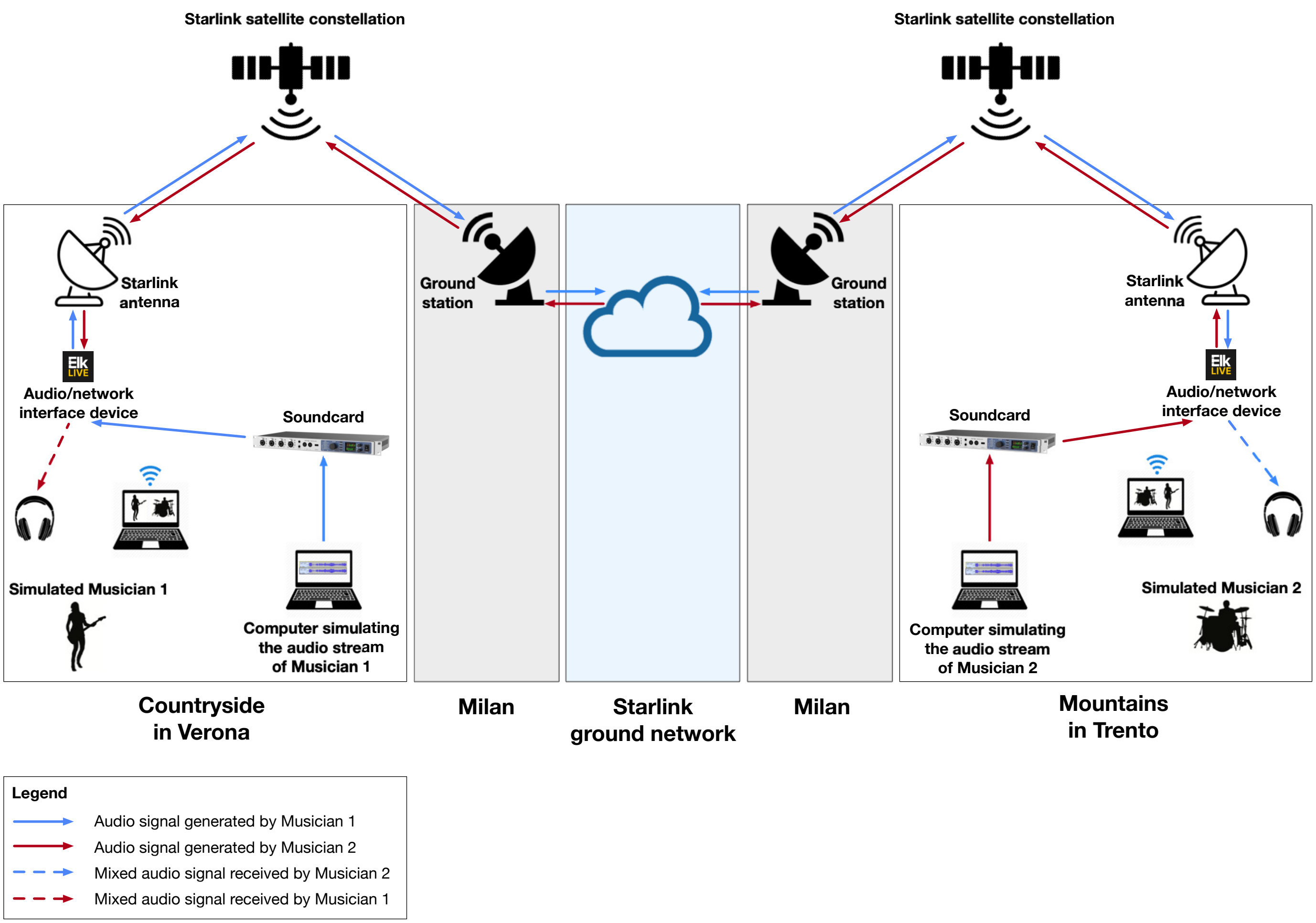


Fig. 2. A schematic diagram of the NMP communication architecture in Experiment 1.

audio operating system [29] and specialized hardware that converts analog audio signals into IP packets for network transmission and performs the reverse operation for received IP-encapsulated audio data. The system's key features include highly stable packet pacing and precise timestamping, as well as minimal analog-to-digital, digital-to-analog, and packetization times. Additionally, the system provides logging capabilities to track IP packet delivery delays, jitter, and packet losses.

The NMP system generates a protocol data unit (PDU) containing 64 audio samples (each of 16 bits) for each of the two audio channels, as well as timestamping data and the User Datagram Protocol (UDP) header length, resulting in a total PDU size of 272 Bytes. To minimize latency, the system uses UDP at the transport layer, without any application layer retransmission scheme. The device operates at 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. Thus, the minimum data rate required for seamless audio transmission is approximately $2\,\mathrm{Mbit/s}$ for both uplink and downlink segments (as measured in our previous study [20]). A constant jitter buffer of $10.66\,\mathrm{ms}$ was used to handle late packets, balancing latency and reliability. With analog-to-digital and digital-to-analog conversion times of less than $1\,\mathrm{ms}$, the primary delay components in the NMP system (excluding the jitter buffer) are due to over-the-air transmissions.

B. Results

First, we measured the Starlink download and upload throughput using the Ookla SpeedTest application[3]. This application selects the closest test server and probes download and upload capacity by opening several parallel TCP connections. We performed two speed tests at the two locations just before starting the measurement sessions. These led to values in the range $[65.83, 296.66]$ $\mathrm{Mbit/s}$ in downlink and $[5.5, 14]$ $\mathrm{Mbit/s}$ in uplink.

Subsequently, we conducted three measurement sessions of 11 minutes, separated by a 5-minute interval. During each session, the NMP devices continuously exchanged audio packets. This allowed us to gather extensive performance data on the network during each NMP session, utilizing the logging system embedded in each Elk LIVE box. Following the methodology reported in our previous study [20], we focused on four key metrics: latency, packet error ratio, missed packets, and the maximum number of consecutive missed packets. These metrics were computed over intervals of approximately $\approx 2.33\,\mathrm{s}$, with each interval containing 1750 packets (each packet comprising 64 audio samples). For each recording, we discarded the first and last $30\,\mathrm{s}$ to eliminate additional delays or synchronization issues caused by the initial handshaking of the devices as well as by the termination of the session. Consequently, our analysis covered approximately 450 000 packets transmitted by each box.

We statistically quantified the four key metrics by calculating their mean, standard deviation, minimum, and maximum values. This analysis was based on the combined log data recorded by each Elk LIVE box during the three recording sessions. The results are shown in Table I. Fig. 3 shows the evolution of the investigated metrics as recorded at the boxes during one of the recording sessions.

TABLE I
STATISTICS OF THE COLLECTED COMMUNICATION METRICS IN EXPERIMENT 1.

	Mean	**SD**	**Min**	**Max**
Latency (ms)	168.21	234.69	41.01	3193.04
Packet error ratio	0.159	0.291	0	1
Missed packets	279	510.89	0	1750
Max number of consecutive missed packets	227.38	505.19	0	2835

We searched for possible correlations between latency and the other three measures. For this purpose we utilized Pearson's correlation tests. Significant correlations of low strength were identified: for latency-packet error ratio, $r = 0.12$; for latency-missed packets, $r = 0.12$; for latency-max number of consecutive missed packets, $r = 0.1$; all were significant at $p < 0.001$.

IV. EXPERIMENT 2: ONE SATELLITE AND ONE WIRED CONNECTION

The aim of this experiment was to assess the performance of a communication architecture including one NMP node in a rural area served by Starlink connection, and one NMP node located in a city neighborhood via a conventional wired terrestrial network.

A. Testbed

Fig. 4 illustrates the components of the deployed testbed. Compared to Fig. 2, in this testbed the node in Verona is connected to a wired terrestrial network rather than via a satellite link.

The data collection procedure, as well as the analysis, were identical to those of Experiment 1. The measurements were performed on the afternoon of the 5th of July 2024, with ideal weather conditions (sunny day with no clouds).

B. Results

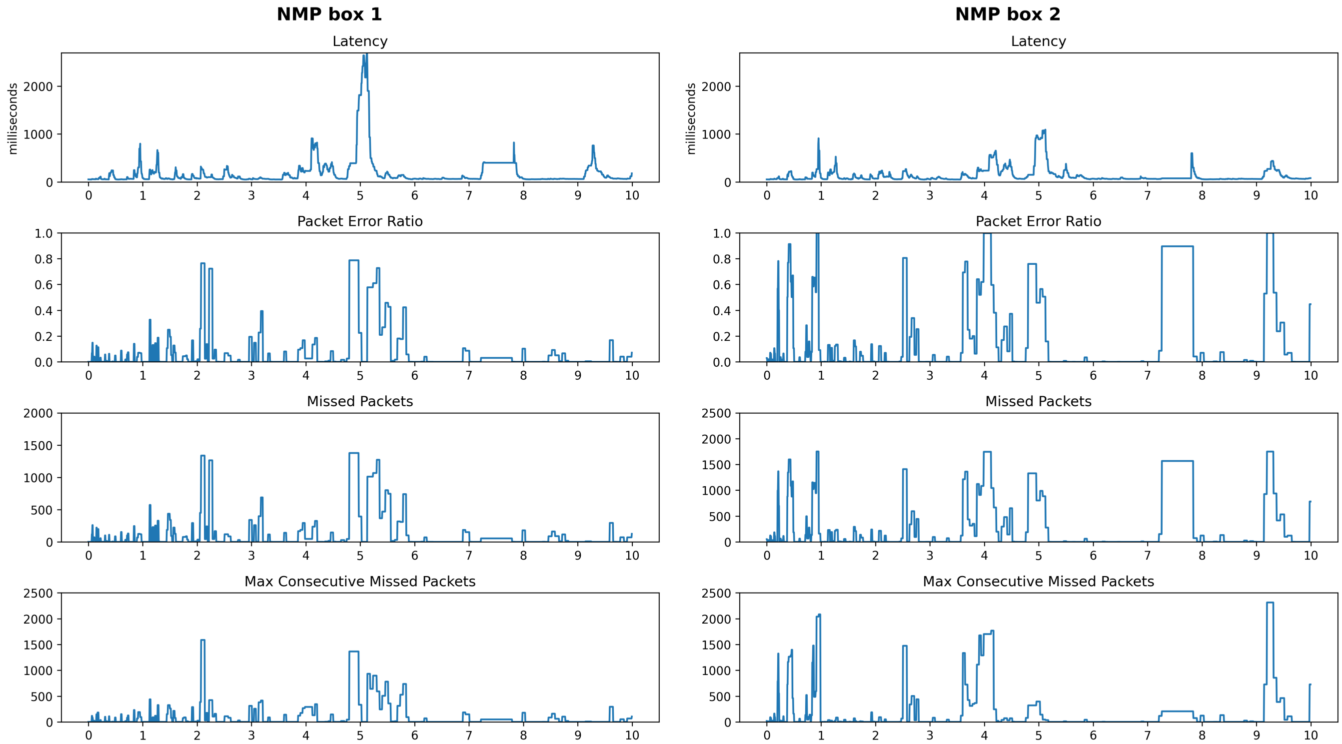
The collected data underwent the same analysis as in Experiment 1. The results are shown in Table II. Fig. 5 shows the evolution of the investigated metrics as recorded at the boxes during one of the recording sessions.

Significant correlations of low strength were identified: for latency-packet error ratio, $r = 0.39$; for latency-missed packets, $r = 0.39$; for latency-max number of consecutive missed packets, $r = 0.38$; all were significant at $p < 0.001$.

V. DISCUSSION AND CONCLUSIONS

In this paper we aimed to quantitatively evaluate, by means of experiments on two different testbeds, the state-of-the-art LEO satellite networks in the context of NMPs.

[3]https://www.speedtest.net/



(a) Box 1.

(b) Box 2.

Fig. 3. Evolution of the four performance metrics over 10 minutes, recorded at box 1 (Fig. 3a) and box 2 (Fig. 3b) during an NMP session in Experiment 1.

Considering the results related to the scenario with two satellite links (see Table I and Fig. 3), the measured metrics and their time evolution are well beyond the NMP requirements for latency and reliability. Accordingly, the listening inspection via the headphones connected to each Elk LIVE box during the sessions resulted in an unsatisfactory experience due to perceivable signal deteriorations, clearly incompatible with collaborative music making.

As for the results related to the mixed satellite/terrestrial network architecture (see Table II and Fig. 5), we observe a clear improvement across all metrics. However, in this case the achieved results are still far from ideal. On average, latency was 15 ms above the perceptual threshold tolerable by musicians, and the reliability metrics indicated that the audio quality was generally low. Notably, these performance deteriorations are related to the sole satellite connection: we performed tests between Trento and Verona using a fully wired connectivity, and clearly showed that the performance evaluation metrics were satisfactory.

Therefore, our findings indicate that the current version of the Starlink service (in the tested geographical areas) does not adhere to the strict latency and reliability requirements of NMPs. Notably, the measurements here reported relate to a session conducted with ideal weather conditions. We would expect even worse values in the presence of bad weather conditions such as storms [27], [28], which are likely to increase the latency and reduce the reliability reported in this study.

Our results are not fully in line with those reported in [6], as the latencies we measured were never in the order of 20 ms, and packet losses were significantly higher. Nevertheless, our tests involved a completely different type of traffic (continuous and periodic) and measurement setup. Moreover, our study relied on the UDP transport protocol, while in [6] the TCP and QUIC protocols were considered.

Significantly, latency and reliability results were found to be uncorrelated in both experiments. This outcome parallels that of other previous studies conducted on NMP systems connected over a different type of wireless networks (namely 5G) [19], [20], and suggests that these two key performance indicators are driven by different root causes.

While our study revealed that currently it is not possible

TABLE II
STATISTICS OF THE COLLECTED COMMUNICATION METRICS IN EXPERIMENT 2.

	Mean	**SD**	**Min**	**Max**
Latency (ms)	45.68	41.34	21.32	574.91
Packet error ratio	0.043	0.14	0	1
Missed packets	76.72	245.72	0	1750
Max number of consecutive missed packets	72.55	280.86	0	2514

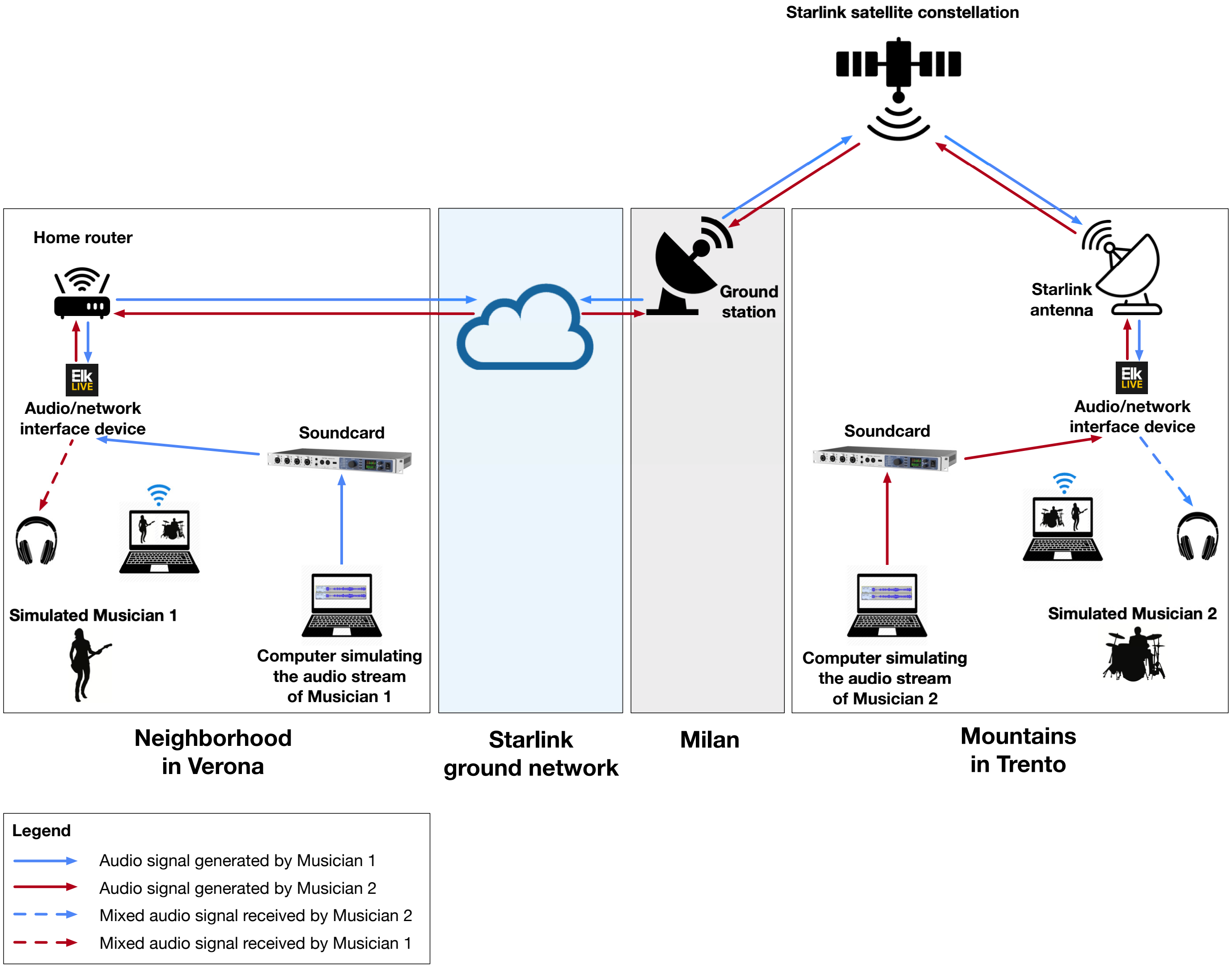


Fig. 4. A schematic diagram of the NMP communication architecture in Experiment 2.

to use Starlink for NMP applications, we believe that our results provide valuable insights into the expected throughput, latency, and packet losses when developing other types of musical solutions compatible with Starlink network access. Ultimately, this work calls for further research on the progress of LEO satellite architectures to support applications with tight latency and reliability constraints such as those in musical and other mission critical activities. For example, bent pipe communication architectures that route packets directly from the transmitting to the receiving Starlink terminal would greatly reduce latency. Advancing these aspects would make it possible to achieve the 6G promise of a seamless low-latency, highly reliable Internet access even in rural areas.

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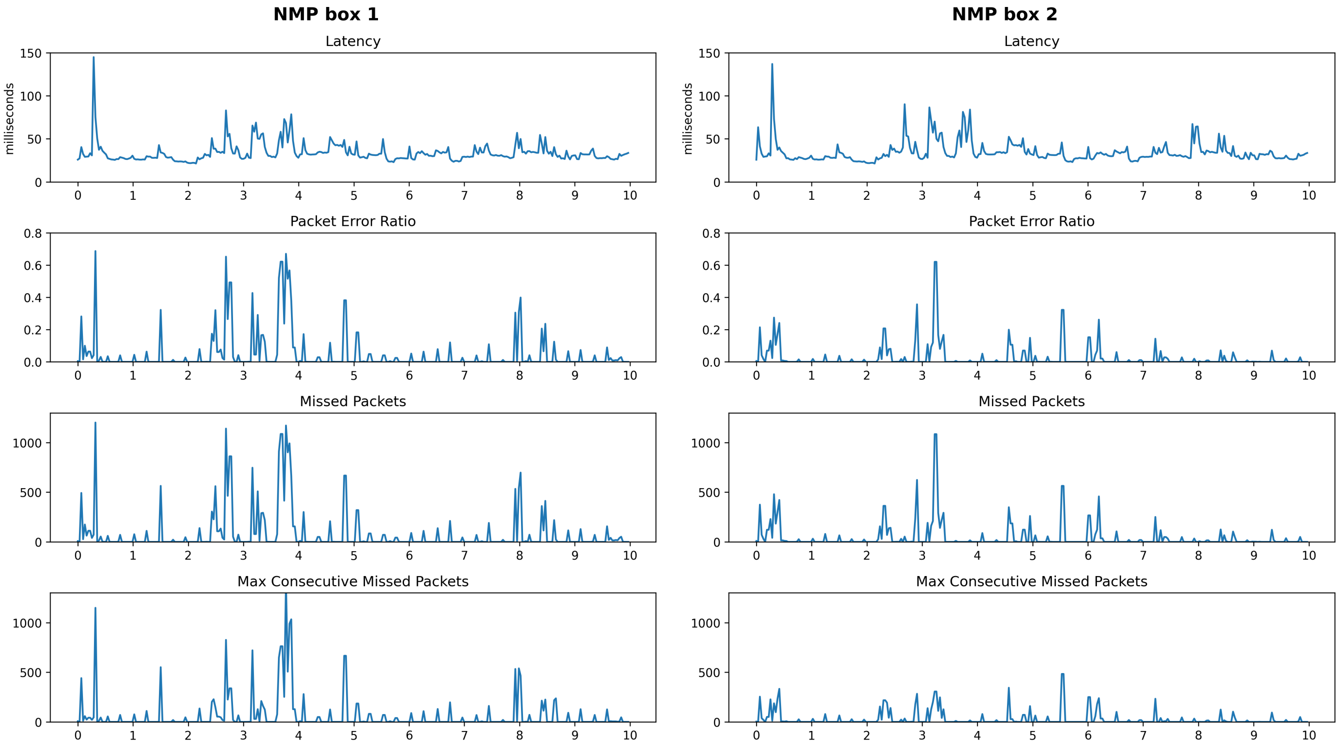

(a) Box 1.

(b) Box 2.

Fig. 5. Evolution of the four performance metrics over 10 minutes, recorded at box 1 (Fig. 5a) and box 2 (Fig. 5b) during an NMP session in Experiment 2.

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