

Performance Analysis of co-located radios for Networked Musical Instruments

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Abstract—Wireless digital musical instruments (DMIs) enable performers to move freely across the stage and change configuration mid-performance. Unfortunately, wireless protocols have limitations in terms of throughput, latency and reliability, and there is a little benchmarking data on the performance of these protocols for co-located performances with multiple devices. We examine three current generation short-range radios: present generation short-range radios: 5Ghz WiFi 6, ESPNOW and Ultra-Wideband (UWB) and benchmark their latency, throughput, and reliability with a failure-rate metric based on consecutive packet loss, which reflects the musical cost of dropped data. ESPNOW and UWB achieve latencies under 2ms but lose reliability as devices and packet sizes grow, with failure rates reaching 16.8% and 42.9% respectively; 5GHz WiFi 6 keeps its failure rate near 0% and reaches 58.7 Mbps, but its latency rises to 16.58ms with four devices. From these results we recommend ESPNOW and UWB for latency-critical continuous control where isolated packet loss is tolerable, and 5GHz WiFi 6 for triggers and high-throughput data. Wiring the receiving device to the router roughly halves the latency of 5GHz Wifi. Our benchmark data, board designs and reliability metric help DMI designers choose a radio to match the musical data their instruments transmit.

Index Terms—networked music performance, Internet of Musical Things, wireless, WiFi, UWB, OSC, embedded, nmp,

I. INTRODUCTION

The Internet of Musical Things (IoMusT) has been used by various authors to describe the use of the internet for ubiquitous musical activities [1], QR codes pointing to online data about the instrument [2], and as a subset of the Internet of Things (IoT) domain including the hardware, software and radios that enable musicians and audiences to participate in musical activities over the internet [3]. Despite their convenience, wireless protocols such as Bluetooth, ZigBee, Thread, and WiFi used for Networked Musical Performances (NMP) as an alternative to wired tethering have historically been beset with issues of latency and packet loss. These parameters are of particular importance in the live music setting, especially in ensemble performances, where synchronicity between performers and instruments is paramount [4].

As part of his design guidelines for designing Digital Musical Instruments (DMIs), NIME pioneer Perry Cook stated that “Wires are not that bad (compared to wireless)” [5] noting that for many instruments the added complexity of wireless communications is not worth it. While this comment is true,

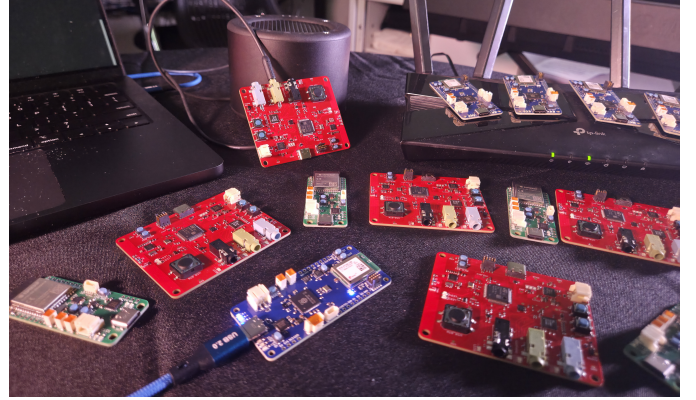


Fig. 1: Short-range radio boards: Red boards (UWB), Green boards (ESPNOW), Blue Boards (WiFi)

giving up wires has desirable potential benefits. Wireless digital musical instruments (DMIs) enable dynamic performances where the signal topology can change drastically in the middle of performance. Being untethered encourages composers and performances to play with the entire space available on the stage allowing more freedom of motion.

Untethered wireless networks enable freedom of movement which opens new avenues for interfaces and performances. Imagine a spatial sound installation where the spatialisation react to where you are in the network. This is already possible with wired musical interfaces, but with wireless interfaces we can take this further. People visiting this installation could also grab the speakers and move them wherever and in whatever orientation, or layout they please. Wireless radios such as ultra-wideband (UWB) radios enable ranging and proximity sensing which means the network could keep track of where everything is related to each other and adapt to the changing circumstances. Audience members can also become part of the performance as the wireless DMIs can be easily passed around and moved without complication. For example, the DIAD system presented by Oliver Bown et al. [6] showcases a distributed interactive audio device that utilised wireless networks to do a dynamic spatial sound. Audience members at performances were able to toss, roll, and move the device around to change the spatial spread.

The difficulty in configuring, and setting up DMIs serves as a barrier for wider use of these instruments [7]. Although most wired interfaces require little to no configuration in terms of networking they are limited by size and ports. Whether it be the number of USB ports on a USB hub or inputs into a mixer, the more devices require larger interfaces. This is not the case for wireless systems where (potentially) hundreds of devices might be connected to a same network without physical connections.

Wireless networks also benefit from tools such as libmapper [8] enable creating complex mappings multiple devices in the same network, handling discovering devices and showing which signals are available. Performances such as Ensemble Feedback Network presented by Rosli et al. [9] which used an AD/DA and a computer as a matrix mixer, could be extended by using wireless networking to connect devices. A wireless radio replacing the matrix mixer enables new topologies, where the performances are able to change how they are connecting to the network, or even deliberately denigrate there connection to the network by interfering with the antenna and radio of their instrument.

In this paper we investigate which current short-range radios (5GHz Wifi 6, ESPNOW, UWB) can support low-latency, reliable, multi-device co-located performance, and what trade-offs they impose. We discuss a reliability metric for wireless DMIs based on consecutive packet loss, which better reflects musical consequences than raw packet loss and benchmark the latency, reliability and throughput of three short-range radios (5GHz Wifi 6, ESPNOW, UWB). We find that ESPNOW and UWB have latencies below 2ms, but the reliability decreases with as the number of devices and packet size grows, with failure rate reaching 16.8% and 42.9% respectively. 5GHz WiFi achieves the highest throughput of 58.7Mbps, and nearly 0% failure rate, but the latency can increase up to 16.58ms with 4 devices on the network. From these results we recommend that ESPNOW and UWB radios are appropriate for low-latency applications where packet loss can be compensated by other measures, 5GHz WiFi is appropriate for high-throughput, high-reliability applications, and the latency and throughput of 5GHz WiFi can be roughly halved by wiring the receiving device to the router. This work shows that each of these radios offer different trade-offs that wireless DMI designers can exploit to create complex and interesting musical performances.

II. RELATED WORKS

Rigorous studies on the performance of various wireless protocols when it comes to networked music performances are lacking especially in terms of large performances with multiple devices connected to the same network [10]. The latency of existing networks are too high [11], [12], existing hardware lack connectivity options [13] and there is a lack of consensus on how to measure reliability in the context of NMPs and IoMusT [14].

Wessel and Wright suggested that DMIs should aim for an input latency below 10ms, which is still a commonly accepted value for the target latency [15]. McPherson et al.

evaluated several common DMI configurations and found that most configurations did not meet this threshold [16]. However, there is evidence that this value may vary depending on the style of music, tempo and instrumentation. Maki-Patola and Hämäläinen found that for playing the theremin, latencies between 20–30ms was acceptable, with higher latencies not being noticed during at slower tempos [17]. The impacts of performer to performer latency on performance has been extensively studied with values around 20–30ms are generally accepted as the ideal latency for performance conditions [18]. Acceptable latencies can range from 30ms - 100ms, due to differences in the dynamics (volume of sound) and articulation (e.g. legato, staccato) [19]. Bartlette et al. found that even when performers adapted different strategies for compensating for latency, the pacing and coordination of duets suffered when latency increased above 100ms [20].

A. Latency and reliability of WiFi and Bluetooth

Dual-band WiFi was investigated by Mitchell et al. who found a mean latency of 5.3ms under good condition, with a 1-5ms jitter [21]. The ESP32 is a family of microcontrollers¹ equipped with a wide range of short range wireless protocols (i.e., WiFi, Bluetooth, Thread, Zigbee). In spite of the ESP32 family's appeal in regards to ensemble NMP, the use of the overlapping channels of 2.4GHz WiFi place a significant constraint on a number of devices transmitting concurrently before non-negligible packet loss and latency is incurred. As seen in [22], it was found that achieving sub 10ms end-to-end latency (which is a generally accepted threshold in the community [15]) for 10 connected devices operating at 100Hz over the same network is still a significant challenge. In addition, not only was low latency found to be a key consideration but also variation in latency, with a range of variation of 1 ms allowed before asynchronicity is noticeable [15]. This further exacerbates the shortcomings of the 2.4GHz WiFi 4 implementation, as jitter becomes a significant issue [22].

Previously, work has been done on wireless protocols alternative to WiFi, such as Bluetooth and ZigBee. Despite their respective merits such as discoverability and self-configuration [23], both have been found to be largely impractical for NMP due to lack of range and scalability, as well as significant latency [4]. ESPNOW is a protocol developed by Espressif which uses the WiFi radio of their microcontrollers (MCU)². It simplifies the networking stack from 7 layers to 3 layers to lower power consumption and latency. Similar to Zigbee and Bluetooth, ESPNOW is also geared towards discoverability and self-configuration. The low latency and low power consumption makes it an interesting choice for networked musical performances.

B. Latency and Reliability of Ultra-wideband communication

Ultra-wideband communication is a popular option for applications requiring accurate proximity detection and localisation [24]. The wide channel bandwidth (> 500MHz),

¹<https://www.espressif.com/en/products/socs/esp32>

²<https://www.espressif.com/en/solutions/low-power-solutions/esp-now>

high throughput (Up to 31Mbps) make it a suitable choice for low-latency data streaming. Tests of small Ultra-wideband networks suggests that they can achieve low-latency and high reliability communication [10]. The UWB radio enabled Turchet et al. [10] to send haptic data to a performers and synchronise that data with the sounds they were hearing. In addition, although they didn't use the ranging functionality of UWB radios they note the possibility of using it to enable dynamic calibration of compensation delay needed to sync the haptic data with the audio the participants were hearing.

C. Reliability of Networked Musical Performances

Reliability consists of three parts. It is a measure of a device's ability to perform a specific *function* under defined environmental and operational *conditions* over a defined period of *time* [25]. In the context of wireless DMIs, reliability refers to the DMI's ability to successfully transmit/receive information (function), in a regular networking environment (conditions), over the course of a performance (time). Although packet loss is the standard way of measuring failure of wireless networks, it fails to consider that the impact of a dropped packet can vary significantly depending on the type of data the DMI is sending and how it is being sent. Turchet et al. note that although the relationship between packet loss, distribution of packet loss and perceived audio quality has not been fully determined, there is a consensus that consecutive packet losses has the most harmful impact on perceived audio quality [14]. This can also apply to certain types of control streams a DMI might send (i.e., continuous sensor data). Occasional dropped packets can be tolerated as long as the consecutive packet losses remain low. However for triggers (i.e., note-on events) dropped packet represents important information that has been missed. This type of data demands nearly 0% packet loss.

III. SYSTEM DESIGN

In this research, we introduce a new board design for experimenting with NMP over UWB networks, WiFi Networks and ESPNOW networks. All the boards used were custom development boards each with similar system architectures and different radios. We design custom boards as for some of the radios (UWB) it was more cost-effective to design a custom board, instead of buying multiple units of a development board.

The boards were developed with the following goals in mind.

- 1) The boards would be as simple as possible in order to minimise errors.
- 2) The boards have some sort of sensor to trial sending live sensor data.
- 3) The boards can operate of a battery to allow them to not need to be tethered to a USB hub or powerbank.

The first goal was achieved by using a similar architecture and board design as used in the EnchantiS3 boards that were designed for the 5th Generation T-Sticks [26]. Figure 2 shows

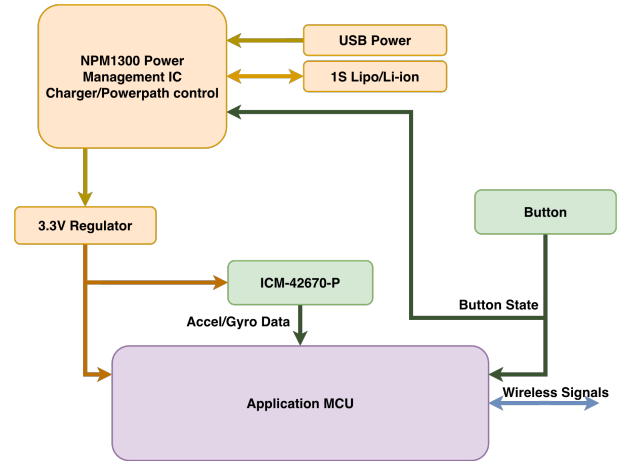


Fig. 2: System architecture of the testing boards

the general system architecture all the boards follow. The ICM-42670-P is an inertial measurement unit (IMU) from TDK Invensense³ which contains an accelerometer and gyroscope. The sensor was used in order to meet the second goal regarding having a sensor to send trial data. It was not used in the testing done for this paper but will be used for future test sending sensor data wirelessly. In order to meet the third goal of being able to operate from a battery, all the boards use the NPM1300 power management integrated circuit (PMIC) from Nordic Semiconductors⁴. This PMIC handles, battery charging, automatic power management between using USB power and battery power and has two step down buck convertors each with at least 200mA output for other peripherals. This was chosen as it simplifies the required power circuitry and the step down convertors were especially useful for the UWB boards.

Figure 3 shows a picture of the WiFi with the different components labeled. The application MCU used by the 5GHz WiFi 6 board used the RP2350 MCU from Raspberry Pi⁵. It is paired with the IRIS-W106 module⁶ which uses the RW612 system on chip (SoC) from NXP semiconductors⁷. This SoC contains a dual-band WiFi 6 radio using 20MHz Channels, with a maximum PHY rate of 115Mbps.

Figure 4 shows a picture of the ESPNOW custom board. The ESPNOW board uses the ESP32-S3 WROOM 2 Module from Espressif⁸. This uses a WiFi 4 Radio, which supports the 2.4GHz Frequency and 20MHz WiFi Channels. The ESP32-S3 doubles as both the application processor and the transceiver as it integrates dual Xtensa 7 cores running at 240MHz, with one of the cores being dedicated to running the networking stack.

³<https://invensense.tdk.com/products/motion-tracking/6-axis/icm-42670-p/>

⁴<https://www.nordicsemi.com/Products/nPM1300>

⁵<https://www.raspberrypi.com/products/rp2350/>

⁶<https://www.u-blox.com/en/product/iris-w10-series>

⁷<https://www.nxp.com/products/wireless-connectivity/wi-fi-plus-bluetooth-plus-802-15-4/RW612>

⁸<https://www.espressif.com/en/products/socs/esp32-s3>

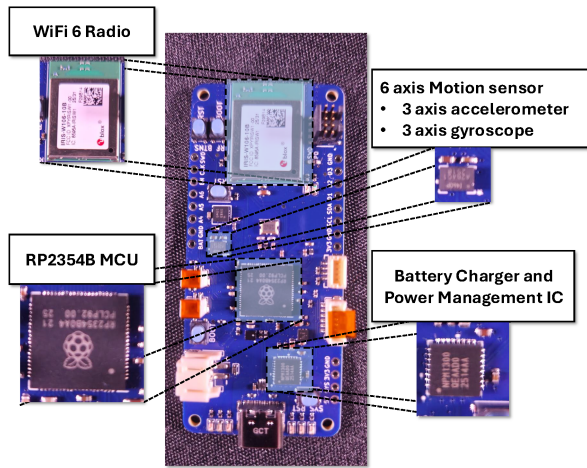


Fig. 3: 5GHz WiFi 6 board, with description of all the major components

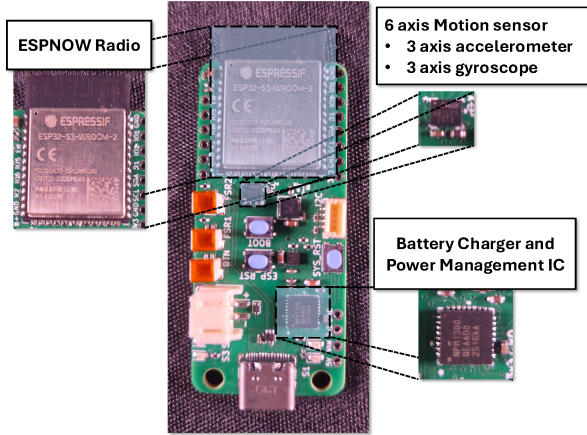


Fig. 4: ESPNOW board, with description of all the major components

Figure 5 shows the UWB board with all of its major components highlighter. The UWB development board uses the STM32U5 MCU from STMicroelectronics⁹. For the UWB radio we use the SR1120 UWB radio from Spark Microsystem¹⁰. We use the SR1120 as unlike other popular UWB modules such as the DWM1000 or the DWM3000 modules from Qorvo¹¹ the SR1120 is designed around sending audio and data at high rates.

IV. TECHNICAL PERFORMANCE OF SHORT-RANGE RADIOS

In this section we discuss experiments to benchmark our new UWB radio boards against the WiFi and ESPNOW boards in terms of reliability, throughput and latency.

⁹<https://www.st.com/en/microcontrollers-microprocessors/stm32u5-series.html>

¹⁰<https://www.sparkmicro.com/product/sr1120-transceiver/>

¹¹<https://www.qorvo.com/products/wireless-connectivity/ultra-wideband>

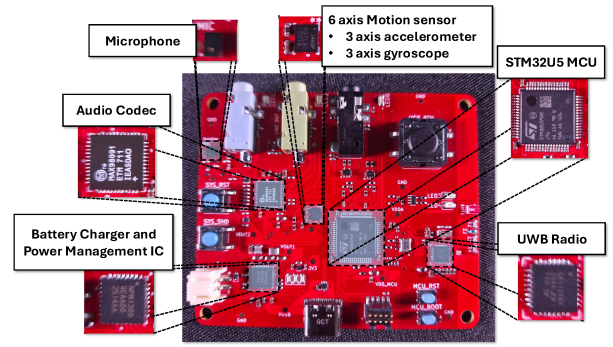


Fig. 5: UWB board, with description of all the major components

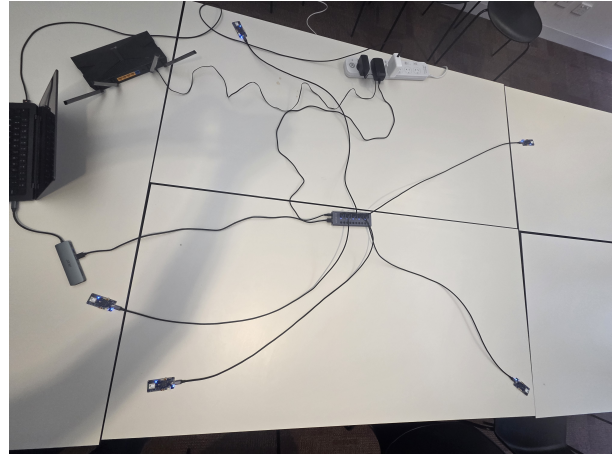


Fig. 6: Example Test Setup featuring the WiFi 6 Boards. The Macbook Pro is used to record the information received from the boards.

A. Testing Configuration

Figure 6 shows an example test setup for the WiFi boards. All of the test were conducted at university with the campus wifi being the main source of interference. The devices were powered by a USB hub and spread out in a star shape on a table, with the main receiving development board being the board closest to the laptop.

For the WiFi test used the TP-Link AX1500 Wi-Fi 6 dual-band Router¹² configured to only use the 5GHz band, with the Macbook Pro laptop being used as the receiver. Both the UWB and ESPNOW test used one of the MCU boards as a receiver.

B. Reliability Test

Instead of using packet loss to define failure of a wireless DMI, we define a failure rate metric based on consecutive packet loss, which better reflects the consequences of packet loss in a performance context. For this research, we define the failure rate using equation 1.

¹²<https://www.tp-link.com/au/home-networking/wifi-router/archer-ax1500/>

$$\lambda = P(x_d > n) \quad (1)$$

where λ is the failure rate, x_d is the number of consecutive dropped packets, and $P(x_d > n)$ is the *probability* that between two received packets, the number of dropped packets (x_d) is greater than n . This definition allows an engineer or designer of a novel DMI to change the value of number of missed packets (n) depending on what kind of data they are sending and how they are sending it.

For the reliability test conducted in this paper we use a value of n equal to 1. This means that the failure rate presented in this paper is the *probability* that between two received packets, at least *one packet* has been *dropped*.

The test is conducted over the span of 5 minutes, with up to 4 devices connected on the same network, and packet sizes ranging from 176 bytes to 1452 bytes. For UWB radio only 176 byte packets were used. The radio boards are all power cycled in between tests. Each transmitting board was configured to send data as fast as possible to maximise the throughput of the network. This ended up being approximately 2000Hz for Wifi, 500Hz for ESPNOW, and 1000kHz for the UWB boards. For the UWB and ESPNOW boards the received packets are sent to the Macbook Pro, over a serial connection. For the WiFi tests the packets are received directly over WiFi. The failure rate is averaged over a rolling window of a 1000 packets. In each window the failure rate is computed using equation 2.

$$\lambda_w = \frac{num_{loss}}{num_{received}} \quad (2)$$

where λ_w is the failure rate, num_{loss} is the number of times at least 1 packet was dropped between two received packets, $num_{received}$ is the total number of received message pairs.

C. Latency Testing

The test is conducted over the span of 5 minutes, with up to 4 devices connected on the same network, with packet sizes ranging from 176 bytes to 1452 bytes. For UWB radio only 176 byte packets were used. For each test condition, the receiving radio sends a ping to all the devices, and waits up to 100ms for a response. The latency of the radio network is found by using equation 3.

$$d_{network} = t_{received} - t_{requested} - d_{ping} \quad (3)$$

where $d_{network}$ is the one-way latency of the network, $t_{received}$ is the time a message is received, $t_{requested}$ is the time a message is requested, and d_{ping} is the latency of the ping message.

V. RESULTS

A. 5GHz WiFi 6

The 5GHz WiFi 6 radio performed well in terms of throughput and reliability, with subpar performance in terms of latency. Table I summarises the data collected for the wifi network.

Average throughput of each device on the WiFi network (Mbps)

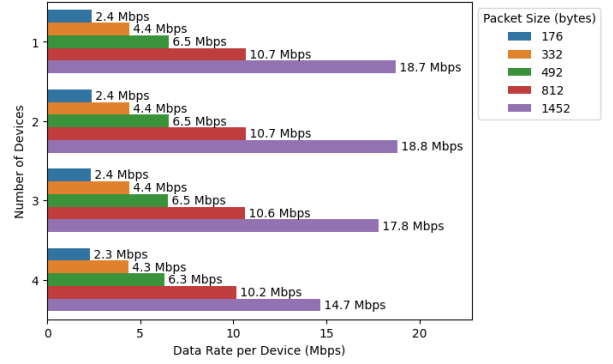


Fig. 7: Throughput of WiFi Network (per device)

Average throughput of each device on the ESPNOW network (Mbps)

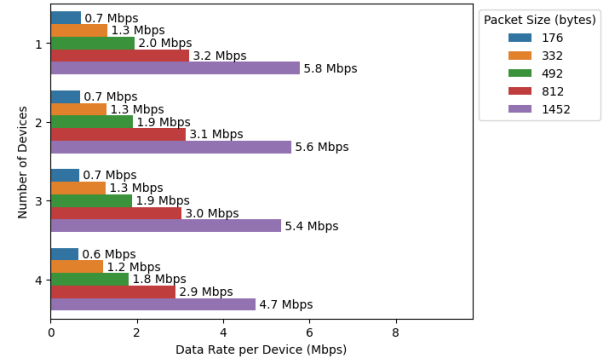


Fig. 8: Throughput of ESPNOW Network (per device)

The network throughput maxes out at 58.7Mbps. Figure 7 shows that for a larger packet size, the throughput per device is decreasing. This may indicate that the WiFi channel is becoming congested which decreases the throughput per device. We can also see that the latency increases significantly from an average of 3.6–4ms to 13.6–16.58ms. In addition, the spread of the latency data as the number of devices increases. Qualitatively it seems that the latency is more closely related to the number of devices on the network than the packet size, as the magnitude of the latency does not significantly change for a given number of devices. The failure rate remains 0% only going above zero with large packet sizes (1452 bytes) and 4 devices connected to the network.

B. ESPNOW

The ESPNOW network performs well in terms of latency with subpar performance in terms of reliability. Table II summarise the results for the ESPNOW network. Network throughput maxes out at 18.98 Mbps. Similarly to the WiFi results the per device throughput decreases with the largest packet size (1452 bytes) and 4 devices connected to the network. Figure 8 shows this decrease. Unlike the WiFi network, the high failure rate implies that at least a portion of the decreased throughput may be attributable to packet loss

TABLE I: Latency, Reliability and throughput of the WiFi Network

Packet Size (bytes)	Number of Devices	Data Rate (Mbps)	Failure Rate (%)	Latency (ms)
176	1	2.36 Mbps	0.00 $\pm$ 0.00%	3.67 $\pm$ 0.18 ms
	2	4.73 Mbps	0.00 $\pm$ 0.00%	4.22 $\pm$ 0.92 ms
	3	7.07 Mbps	0.00 $\pm$ 0.00%	7.72 $\pm$ 1.86 ms
	4	9.23 Mbps	0.00 $\pm$ 0.00%	13.68 $\pm$ 5.19 ms
332	1	4.43 Mbps	0.00 $\pm$ 0.00%	3.75 $\pm$ 0.19 ms
	2	8.87 Mbps	0.00 $\pm$ 0.00%	4.22 $\pm$ 0.83 ms
	3	13.27 Mbps	0.00 $\pm$ 0.00%	7.98 $\pm$ 2.00 ms
	4	17.38 Mbps	0.00 $\pm$ 0.00%	14.35 $\pm$ 5.62 ms
492	1	6.53 Mbps	0.00 $\pm$ 0.00%	3.81 $\pm$ 0.20 ms
	2	13.07 Mbps	0.00 $\pm$ 0.00%	4.28 $\pm$ 0.85 ms
	3	19.49 Mbps	0.00 $\pm$ 0.00%	7.95 $\pm$ 1.78 ms
	4	25.24 Mbps	0.00 $\pm$ 0.00%	14.95 $\pm$ 6.05 ms
812	1	10.68 Mbps	0.00 $\pm$ 0.00%	3.91 $\pm$ 0.21 ms
	2	21.37 Mbps	0.00 $\pm$ 0.00%	4.36 $\pm$ 0.90 ms
	3	31.88 Mbps	0.00 $\pm$ 0.00%	8.10 $\pm$ 1.87 ms
	4	40.74 Mbps	0.00 $\pm$ 0.05%	15.60 $\pm$ 6.28 ms
1452	1	18.72 Mbps	0.00 $\pm$ 0.00%	4.18 $\pm$ 0.24 ms
	2	37.67 Mbps	0.00 $\pm$ 0.00%	4.34 $\pm$ 0.83 ms
	3	53.38 Mbps	0.00 $\pm$ 0.00%	8.14 $\pm$ 2.00 ms
	4	58.71 Mbps	0.30 $\pm$ 0.30%	16.58 $\pm$ 6.69 ms

rather than congestion. The latency of the network ranges from 0.5ms to 1.2ms increasing, as the packet size increases and the number of devices increase. Both the number of devices and the packet size impact the latency

C. Ultra-wideband

Table III summarises the results of the UWB network testing. Due to hardware and software limitations only a packet size of 176 bytes was tested. The UWB network had poor reliability and throughput, but excellent latency, that was mostly unaffected by the number of devices on the network. The latency was between 1.2–1.4ms and the failure rate ranged from 24% - 43%. We note that the reliability of the UWB networks were significantly impacted by a poor onboard antenna. It is possible with a better antenna the UWB radio would have much better reliability.

D. Discussion

The ESPNOW had the lowest latency in all conditions followed by the UWB radio with the WiFi radio in a distant third. In addition, you can see that the latency of the UWB radio did not significantly vary in between testing conditions while the ESPNOW latency doubled from an average of 0.6ms to 1.2ms going from 1 device to 4 devices. The latency of the 5GHz went from 3.67ms to nearly 13.68ms as the amount of devices went from 1 to 4 devices.

The 5GHz WiFi network had the lowest failure rate only going above 0% when sending large packets when 4 or more devices were connected to the network. The ESPNOW

network failure rate ranged from 0.1% to 4% depending on the network condition. The UWB radio had the highest failure rate ranging from 24% to 43%. The latency and reliability results for packet sizes of 176 bytes are shown in Table IV.

The results show that each of the radios have different strengths and weaknesses that can be leveraged by DMI designers. Although the latency of the 5GHz network may leave a lot to be desired in terms of magnitude and jitter it is by far the most reliable of the networks. In addition it has the highest throughput of the tested radios. These properties make it suitable for applications where reliability and high throughput are more important low latency. Although Wessel and Wright suggest DMIs should aim for a latency below 10ms, many acoustic instruments have latencies that are much higher [19]. The spread of the latency can be controlled by using a buffer to even out the latency.

Although the failure rate remains low for 5GHz WiFi, we observed a bandwidth limit with multiple devices on the network. When examining the total network bandwidth, it maxed out at 58.7 Mbps, when 4 devices were connected, and did not significantly increase when more devices were added to the network. It is likely that we are maxing out the bandwidth that can be sent for the channel the devices are connecting to on 5GHz WiFi. The WiFi modules that were used only supported 20MHz WiFi channels, which limits the total bandwidth to a theoretical maximum of 115Mbps [27]. Using a router that supports several 20MHZ 5GHz channels or a WiFi module able to connect to 40/80/160 MHz channels, could improve the latency performance when multiple devices

TABLE II: Latency, Reliability and throughput of ESPNOW Network

Packet Size (bytes)	Number of Devices	Data Rate (Mbps)	Failure Rate (%)	Latency (ms)
176	1	0.70 Mbps	$0.10 \pm 0.10\%$	0.52 ± 0.01 ms
	2	1.36 Mbps	$2.20 \pm 0.95\%$	0.59 ± 0.05 ms
	3	2.01 Mbps	$4.00 \pm 1.35\%$	0.65 ± 0.06 ms
	4	2.59 Mbps	$3.20 \pm 1.00\%$	0.69 ± 0.09 ms
332	1	1.33 Mbps	$0.10 \pm 0.10\%$	0.55 ± 0.01 ms
	2	2.59 Mbps	$1.50 \pm 0.50\%$	0.61 ± 0.05 ms
	3	3.81 Mbps	$3.70 \pm 1.00\%$	0.68 ± 0.06 ms
	4	4.92 Mbps	$2.20 \pm 0.45\%$	0.73 ± 0.10 ms
492	1	1.95 Mbps	$0.90 \pm 0.25\%$	0.57 ± 0.01 ms
	2	3.82 Mbps	$2.10 \pm 0.55\%$	0.64 ± 0.05 ms
	3	5.70 Mbps	$3.20 \pm 0.60\%$	0.71 ± 0.07 ms
	4	7.26 Mbps	$2.30 \pm 0.45\%$	0.77 ± 0.11 ms
812	1	3.22 Mbps	$1.00 \pm 0.25\%$	0.61 ± 0.01 ms
	2	6.28 Mbps	$2.90 \pm 0.60\%$	0.69 ± 0.05 ms
	3	9.12 Mbps	$5.80 \pm 1.25\%$	0.77 ± 0.10 ms
	4	11.62 Mbps	$5.30 \pm 0.95\%$	0.88 ± 0.16 ms
1452	1	5.78 Mbps	$0.40 \pm 0.15\%$	0.70 ± 0.01 ms
	2	11.16 Mbps	$2.90 \pm 0.70\%$	0.78 ± 0.06 ms
	3	16.05 Mbps	$7.60 \pm 1.35\%$	0.93 ± 0.14 ms
	4	18.98 Mbps	$16.80 \pm 1.40\%$	1.17 ± 0.23 ms

TABLE III: UWB network latency, reliability and throughput

Packet Size (bytes)	Number of Devices	Data Rate (Mbps)	Failure Rate (%)	Latency (ms)
176	1	0.87 Mbps	$24.40 \pm 0.90\%$	1.22 ± 0.27 ms
	2	1.36 Mbps	$27.40 \pm 5.95\%$	1.25 ± 0.29 ms
	3	1.57 Mbps	$37.90 \pm 6.80\%$	1.36 ± 0.29 ms
	4	1.74 Mbps	$42.90 \pm 9.00\%$	1.44 ± 0.30 ms

are on the network together. The latency of the 5GHz WiFi 6 radio can also be mitigated by using a software access point or having the receiving device being tethered. As shown in figure 9 this results in the latency remaining below 7ms even when using a packet size of 1452 bytes. In addition, to decreased latency, the maximum data rate increases to 72.2 Mbps from the 58.71 Mbps when the receiving device is also wireless.

The low latency of the UWB and ESPNOW networks make it well suited for closed loop control applications where the relatively poor reliability can be compensated by sending more packets. However, increasing the amount of packets transmitted may increase the latency as more bandwidth is used up. In addition to low latency, the ESPNOW and UWB radios both have vary consistent latency, with vary tight distributions to there latency distributions. The affordances of each radio are summarised in table V.

VI. CONCLUSION

The untethered nature of wireless networks enable interfaces and performances that take advantage freedom of motion

Average Latency of Wifi 6 Network for Packet Size = 1452 Bytes

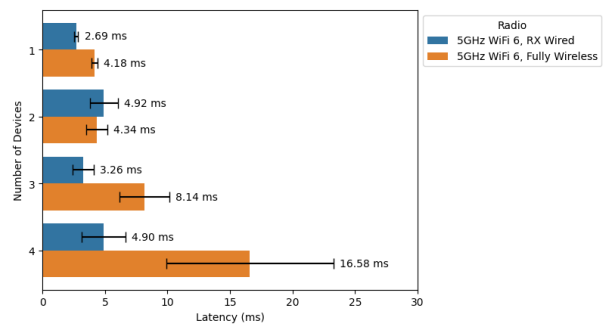


Fig. 9: Latency for 5GHz WiFi where the system is fully wireless and when the receiver is wired to the router. Smaller is better

and dynamic configuration. However wireless DMIs have to deal with issues such as packet loss, latency and jitter to a much greater extent then wired interfaces. In this work we benchmark three potential radios: 5GHz WiFi 6 radio,

TABLE IV: Latency and Failure Rate Results

Radio	Number of Devices	Failure Rate (%)	Latency (ms)
5GHz, WiFi 6	1	$0.00 \pm 0.00\%$	3.67 ± 0.18 ms
	2	$0.00 \pm 0.00\%$	4.22 ± 0.92 ms
	3	$0.00 \pm 0.00\%$	7.72 ± 1.86 ms
	4	$0.00 \pm 0.00\%$	13.68 ± 5.19 ms
ESPNOW	1	$0.10 \pm 0.10\%$	0.52 ± 0.01 ms
	2	$2.20 \pm 0.95\%$	0.59 ± 0.05 ms
	3	$4.00 \pm 1.35\%$	0.65 ± 0.06 ms
	4	$3.20 \pm 1.00\%$	0.69 ± 0.09 ms
UWB	1	$24.40 \pm 0.90\%$	1.22 ± 0.27 ms
	2	$27.40 \pm 5.95\%$	1.25 ± 0.29 ms
	3	$37.90 \pm 6.80\%$	1.36 ± 0.29 ms
	4	$42.90 \pm 9.00\%$	1.44 ± 0.30 ms

TABLE V: Summary of Radio Affordances

	Latency	Reliability	Throughput
5GHz, WiFi 6	↓	↑	↑
ESPNOW	↑	↓	↓
UWB	↑	↓	↓

ESPNOW radio, UWB radio in terms of reliability, latency, and throughput. We find that The latency of the ESPNOW radio and the UWB radio is the lowest with both radios having sub 2ms latency when using packet sizes of 176 bytes. Although the latency of the 5GHz WiFi radio is large, it is the most reliable of the three radios tested, only having a failure rate above 0% when the packet size increases and more then 4 devices or on the network. From these results we would give the following recommendations to designers of DMIs:

- 1) ESPNOW and UWB radios are suitable for low-latency applications, where failure rate can be compensated by other measures.
- 2) 5GHz WiFi 6 radios is suitable for applications where high-throughput and high-reliability is necessary.
- 3) You can improve the latency and throughput of the 5GHz WiFi performance by using a software access point, or connecting the receiving device to the router via ethernet.

This paper shows that these radios each have different strengths and tradeoff for use in wireless DMIs. Our design recommendations show that considering the parameters of the performance use-case is important for choosing a radio standard. This work can encourage designers that there are promising new technologies available that afford complex and interesting wireless networked music performance designs and help them make good design choices. Future work includes extending these tests to larger networks of 10 or more devices,

user studies to understand impact of reliability and latency on the user experience as a performer, and designing a prototype wireless DMI to further explore the possibilities of wireless networks.

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