# Making the Most of Wi-Fi: Optimisations for Robust Wireless Live Music Performance

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## ABSTRACT

Wireless technology is growing increasingly prevalent in the development of new interfaces for live music performance. However, with a number of different wireless technologies operating in the 2.4 GHz band, there is a high risk of interference and congestion, which has the potential to severely disrupt live performances. With its high transmission power, channel bandwidth and throughput, Wi-Fi (IEEE 802.11) presents an opportunity for highly robust wireless communications. This paper presents our preliminary work optimising the components of a Wi-Fi system for live performance scenarios. We summarise the manufacture and testing of a prototype directional antenna that is designed to maximise sensitivity to a performer's signal while suppressing interference from elsewhere. We also propose a set of recommended Wi-Fi configurations to reduce latency and increase throughput. Practical investigations utilising these arrangements demonstrate a single x-OSC device achieving a latency of <3 ms and a distributed network of 15 devices achieving a net throughput of ~4800 packets per second (~320 per device); where each packet is a 104-byte OSC message containing 16 analogue input channels acquired by the device.

## Keywords

Wi-Fi, Wireless, Digital Musical Instruments, Open Sound Control, Antenna design, Throughput, Latency, Live performance

## 1. INTRODUCTION

Wireless technology offers many benefits to new musical instruments including increased mobility, dynamic network formation, low cost, ease of deployment as well as increased design and aesthetic flexibility [13]. However, when compared to their wired counterparts, wireless systems show significantly reduced performance due to the effects of path loss, half duplex operation, increased physical layer overheads and channel errors [25].

In the past, the above disadvantages have restricted the application of wireless technology within the NIME community, which was reflected in the familiar Cook quote: "Wires are not that bad (compared to wireless)" [3]. Although Cook has since stated that this is no longer the case [4], the vulnerabilities of wireless communication channels remain a practical concern for developers of wireless musical interfaces [24]. And rightly so: an unreliable communication link can cause major performance disruptions, which can be frustrating for audiences and embarrassing for performers. The factors contributing to transmission problems in wireless systems can generally be considered to be the result of one or more of the following [11]:

1. path loss (distance, occlusion)
2. interference from other RF sources
3. packet collisions (simultaneous client transmissions)
4. network contention

In this paper we examine a number of optimisations to improve the reliability of wireless communications specifically for live music performance and related applications. To address problems associated with path loss and interference, we designed, manufactured and tested a directional patch antenna to maximise reception of signals radiating from a performer whilst simultaneously suppressing interference emanating from elsewhere. We present the results of a series of throughput and latency tests using a Wi-Fi (802.11g) interface device called x-OSC, the design of which has been optimised for music/creative technology applications [14]. The documented experimental methods may themselves be used as a reliable and repeatable means of quantifying the throughput and latency of wireless systems. We also present a number of network configuration recommendations that practitioners may apply to improve the reliability and performance of wireless systems for live music applications.

## 2. BACKGROUND

With the exception of several proprietary solutions [9, 16, 1, 8] the majority of wireless systems adopted for music and creative applications typically utilise Bluetooth (originally IEEE 802.15.1), ZigBee (IEEE 802.15.4) or Wi-Fi (IEEE 802.11b/g). Bluetooth was originally designed to facilitate short-range, low-cost, low-power wireless personal area networks (WPANs) and while widely adopted it is equally widely regarded as a problematic option for the development of reliable wireless musical interfaces [23, 24]. Concerns range from unpredictable connection dropouts and long reconnection times [10], problems with high latency [15] and jitter [6]. ZigBee and related 802.15.4 based devices have been documented to provide substantial improvements in connection stability [10] and reduced latency [15] when compared with Bluetooth, and are consequently growing in popularity. The least prolific wireless technology used in the development of custom made music performance systems appears to be Wi-Fi, although a number of notable examples are now beginning to emerge [5, 21, 14, 22].

| | Bluetooth | ZigBee | Wi-Fi |
|---|---|---|---|
| IEEE Spec | 802.15.1 | 802.15.4 | 802.11g |
| Data rate | 1-3 Mbps | 250 Kbps | 54 Mbps |
| Range | 10 m | 10 to 100 m | 100 m |
| TX power | 0-10 dBm | (-25)-0 dBm | 15-20 dBm |
| Channels | 8 | 16 | 11 (EU) |
| Channel BW | 1 MHz | 2 MHz | 22 MHz |

**Table 1: Bluetooth, ZigBee and Wi-Fi Comparison**

Table 1 provides a useful comparison of the three different wireless technologies compiled from [12, 24], indicating that Wi-Fi is a strong candidate in applications where throughput, operating range, transmission power and channel bandwidth are of importance. As all three technologies operate within the same licence-free 2.4 GHz industrial, scientific and medical (ISM) radio band, they are likely to suffer diminished performance when co-located, due to interference and consequent packet loss. Indeed, these interference effects have formed the subject of several studies in which the mutual effects of these competing systems have been explored. Each wireless system clearly has the capability to impact on the performance of the others; however, Wi-Fi is consistently more resilient in the presence of ZigBee and Bluetooth, even when communications channels exactly overlap [19, 20]; these findings are due in part to the higher transmission power and channel bandwidth of Wi-Fi. The ubiquity of Wi-Fi ensures immediate compatibility with most modern personal computers and operating systems. Furthermore, communication via TCP/IP enables systems to utilise low cost consumer hardware such as wireless routers and ethernet switches with the potential to create flexible infrastructure networks.

Perhaps one explanation for the limited applications of Wi-Fi for custom made music performance systems is its high power consumption relative to ZigBee and Blutooth [1, 23]. While low-power modes are available [22], Wi-Fi may not be ideal for battery powered systems that require long-term continuous operation. However, in practice, music performances typically do not last more than several hours. Furthermore, Wi-Fi appears very efficient when power consumption is normalised against throughput, an important feature for high-sample rate, low-latency systems [13].

We are interested in maximising the reliability of Wi-Fi systems in performance environments where audience members may be equipped with a plethora of mobile devices radiating a range of interfering signals. The performance itself may also require multiple wireless nodes to coexist; each with the potential to interfere/interact with one another.

# 3. PROTOTYPE DIRECTIONAL ANTENNA

Antennas form an integral component of wireless systems, responsible for the transmission and reception of radio signals between devices. Wireless access points (APs), and other general purpose Wi-Fi devices are designed with antennas exhibiting omnidirectional radiation characteristics to ensure that reception and radiation quality is orientation independent. Omnidirectional antennas are well suited to domestic wireless networks as the orientation of clients with respect to an AP tends to be arbitrary. However, in music performance scenarios, a performer is typically positioned at a known orientation with respect to the AP. By exploiting this domain specific knowledge, we may design a directional antenna such that the desired signal radiated by the performer is maximised, while undesirable interference from the audience is suppressed, as shown in Figure 1.

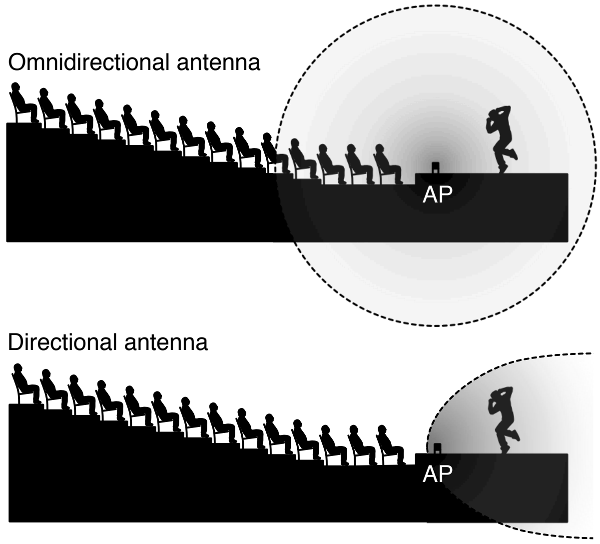


**Figure 1: Performance scenario showing omnidirectional radiation pattern (top) verses a directional radiation pattern**

## 3.1 Antenna Design

Informed by a short study of proscenium width and height measurements from a number of performance venues, it was established that a directional antenna should be designed with a 3 dB beam-width of ~60°. To suppress interference radiating from the audience, the antenna should have a large front-to-back ratio: the ratio of the antenna's sensitivity to signals arriving from the front and rear. A patch antenna was therefore considered whose required dimensions may be calculated approximately as follows:

$$a \approx \frac{c}{2 f_{min} \sqrt{\epsilon_{eff}}} - 2\Delta a \quad (1)$$

where $a$ is the dimension of the square patch, $c$ is the speed of light, $f_{min}$ represents the patch resonant frequency (2.44 GHz ISM band), $\epsilon_{eff}$ is the effective relative permeability of the antenna substrate (from data sheet) and $\Delta a$ represents the effects of fringing, which is typically measured to be half the substrate thickness [2]. Furthermore, the actual size has to be fine adjusted to take into account the position of the antenna's connector.

## 3.2 Manufacture and Testing

The 2.67 cm prototype patch antenna was manufactured using double sided copper-clad FR4 substrate. The resulting antenna array is shown in Figure 2 and consists of three identical patch antennas mounted on a larger ground plane. Each patch is spaced a full wavelength apart (i.e. 12.3 cm) to take advantage of space diversity [17]. Two of the antennas are vertically polarised with the third being horizontally polarised in order to take advantage of polarisation diversity [2].

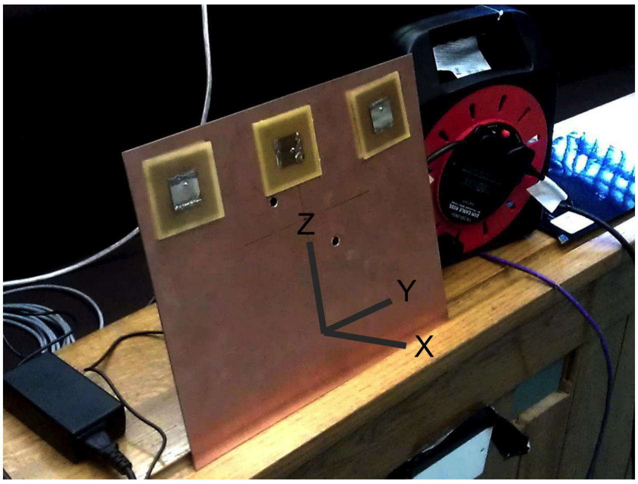


**Figure 2: Completed AP prototype patch antenna array**

The performance of the assembled antenna was evaluated inside an RF anechoic chamber (Figure 8) using a Vector Network Analyser (VNA). The complex polarimetric fields (for both horizontal and vertical polarisations) were measured as the patch was rotated through 360° over 19 cross-sectional planes. Figure 3 shows one of the patch antenna element power patterns (irrespective of polarisation) at 2.4 GHz. For comparison, a typical AP antenna pattern measured using the same process is shown in Figure 4.

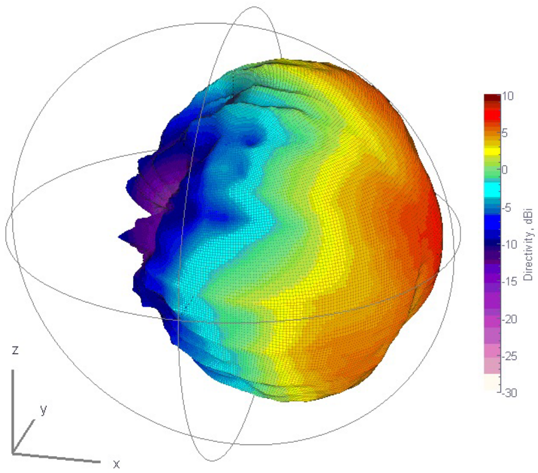


**Figure 3: Far-field radiated power pattern for prototype antenna**

The prototype antenna plot clearly shows a significantly higher signal in the positive $x$ direction (towards the stage), resembling the intended pattern shown in Figure 1. Directional antennas are often characterised in terms of their front-to-back ratio [2], which was an average of 20.1 dB for the patch antenna elements. However, this is not an especially helpful metric in practice, and a more useful comparison is the ratio of the received power level from the area illuminating the stage (desired), relative to the area illuminating the audience (undesired). This gives an average reading of 14 dB, meaning that the antenna is ~25 times more sensitive to signals from the stage than signals from the audience. For a fuller discussion of this design process see [18].

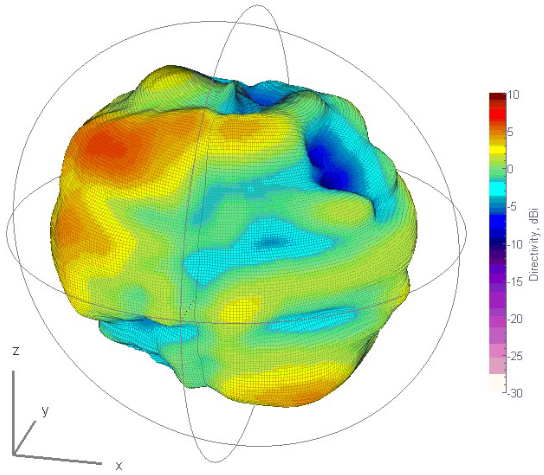


**Figure 4: Far-field radiated power pattern for typical AP antenna**

## 4. NETWORK CONFIGURATION

The antenna developed in section 3 is intended to ensure a good wireless signal. A carefully considered network configuration can also be established to significantly improve throughput and latency. An optimal arrangement was found though extensive investigation of various network configurations using the x-OSC Wi-Fi interface/sensor device. x-OSC is a development board featuring 32 channels of analogue, digital and serial I/O as well as on-board sensors (gyroscope, accelerometer, magnetometer) [14]. Communicating via Open Sound Control (OSC) [26], x-OSC incorporates the Microchip MRF24WG 802.11g, 5 Mbps Wi-Fi module utilising their TCP/IP Stack v5.42.06. The authors of this paper are contributors to the development of x-OSC, which has enabled us to easily customise firmware and Wi-Fi settings for the purposes of testing. The following items summarise key aspects of an optimal network configuration found to achieve best performance.

### *Use Infrastructure Networks*

x-OSC supports two network modes: ad hoc and infrastructure. Ad hoc is where a network is created by x-OSC to which one or more client devices may connect. An infrastructure network may incorporate APs, routers and Ethernet switches to facilitate communication between one or more x-OSCs and other client devices. The highest throughput and lowest latency were obtained when x-OSC was used in infrastructure mode in conjunction with a router/AP. In [22], Torresen *et al* suggested that use of an external router/AP introduced additional latency; we observed no significant difference in our tests.

### *Use Open Security*

The increased overhead involved with packet encryption (WPA/WPA2) negatively impacts on throughput and latency, due to the increased load on the x-OSC microcontroller. The best performance was recorded when an open network (security disabled) was used. For example, the maximum throughput of 400 packets per second presented in section 5.2 would decrease to 350 with security enabled. Furthermore, the network connection delay would increase from approximately 5 s to 30 s. A practical level of network security may still be achieved by hiding the network (disabling SSID broadcast), and/or enabling MAC address filtering.

### *Unicast, Don't Broadcast*

Broadcasted messages (destination IP: `255.255.255.255`) are received by all devices on the network; although this may be convenient, it causes increased network activity and imposes an unnecessary processing load on each device. Targeted unicast messages (to a specific IP address) were found to provide measurable improvements.

### *Use Correct AP Mode*

x-OSC is an 802.11g device, with a maximum bitrate of 54 Mbps. While many modern routers support 802.11n for up to 600 Mbps, improved throughput was observed when the router/AP was limited to support 'g' only.

### *Use Large Packets for High-Throughput*

The large channel access overhead involved in the transmission of 802.11 packets produces a tradeoff between throughput and latency [25]. For example, the x-OSC firmware was modified to demonstrate a maximum throughput of ~400 packets per second with a 1 byte payload (0.4 kB/s), and ~295 packets with a 1472 byte payload (~434 kB/s). This corresponds to a 1000 times increase in throughput at the cost of a ~25% reduction in send rate. As low-latency is a priority for music performance systems, sensor readings must be transmitted as promptly as possible. However, the resulting smaller packets will typically utilise only a fraction of the maximum possible throughput.

### *Use Multiple Channels*

Applications requiring multiple wireless nodes can achieve greater throughput by distributing nodes evenly between Wi-Fi channels 1, 11 and 6 using three APs. These channels are non-overlapping and enable simultaneous communication without co-channel interference. However, as will be shown in section 5.2, channel 6 can cause adjacent channel inference on channels 1 and 11 [7]. If two channels offer sufficient bandwidth then use of channels 1 and 11 will provide the best performance.

## 5. PRACTICAL LATENCY AND THROUGHPUT

Investigations were conducted to demonstrate the practical latency and throughput that could be achieved for up to 15 x-OSCs using the configurations proposed in section 4. The experiments were conducted in controlled conditions and did not incorporate the prototype antenna presented in section 3.

Experiments were carried out in a university lab in the presence of other Wi-Fi networks, which were revealed using a Wi-Fi scanning application. A spectrum analyser was used to confirm that any significant use of the 2.4 GHz spectrum was limited to the visible Wi-Fi networks. When only one Wi-Fi channel was required, the scanning application was used to select an appropriate channel. Each investigation used a Late 2013 13" MacBook Pro running WireShark v1.10.5, fitted with a Broadcom BCM4360 transceiver and a Thunderbolt to Ethernet adaptor. All OSC messages were sent as unicast UDP packets. The infrastructure network was provided by a LevelOne WBR-6805 pocket router/AP configured as *open* (no encryption) in 802.11g mode (54 Mbps) with an Ethernet connection to the host computer.

### 5.1 Round-trip Latency

The round-trip latency was evaluated by wiring an x-OSC digital input and output together and then measuring the time between an output toggle message being sent by the host computer and the input change message being received from x-OSC. The *digital input* and *digital output* OSC messages are 100 and 32 bytes long respectively, each incorporating an address pattern and either 16 or 1 *int32* argument/s. Software was written to send a message to toggle the digital output every 50 ms and WireShark was used to log the time of each packet sent and received by the Wi-Fi adapter. This method of evaluating latency is different from that previously proposed [14] and has the advantage of eliminating the application software from the measurements, which may contribute additional latency specific to the software, OS or processing load of the computer. The infrastructure network was created by connecting the computer and x-OSC to a single router/AP.

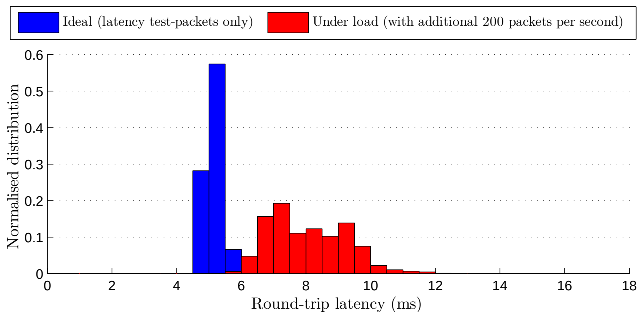


**Figure 5: Normalised distribution of measured round-trip latency**

Figure 5 shows the round-trip latency distribution of over 13000 samples achieved for either 'ideal' conditions, where communication is limited to only the *digital input/output* messages; and 'under load' conditions, where x-OSC was configured to simultaneously send *analogue input* data at 200 messages per second. Table 2 summarises the results. It may be assumed that the latency for communication in either direction is approximately half that of the observed round-trip latency, for example, <3 ms for 'ideal' conditions.

| Test condition | Mean | 95% less than |
|---|---|---|
| Ideal | 5.30 ms | 6.59 ms |
| Under load | 8.09 ms | 9.96 ms |

**Table 2: Summary of measured round-trip latency**

### 5.2 Throughput

Throughput was evaluated as the total packet rate achieved by up to 15 x-OSCs, each attempting to send 450 *analogue input* messages per second. This rate is intentionally greater than can be achieved by a single x-OSC to demonstrate saturated throughput. Each message is a UDP packet containing a 104 byte OSC message including 16 *float32* arguments. WireShark was used to log the time of arrival of each packet and packets per second was calculated as the number of packets arriving from each x-OSC within each one second window. Each experiment starts with a single running x-OSC. At one minute intervals, an additional x-OSC is activated for a period of 15 minutes, to yield a recording of throughput for 1 to 15 x-OSCs. Tests were conducted with the 15 x-OSCs sharing a single channel and evenly distributed between three non-overlapping channels to investigate the benefit.

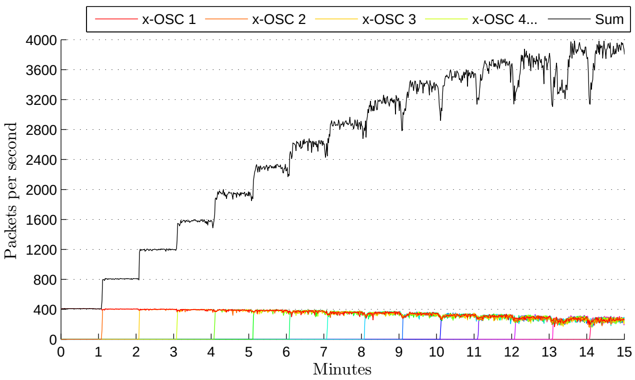


**Figure 6: Throughput of 1 to 15 x-OSCs sending to a single AP on one channel**

Figure 6 shows the throughput for 1 to 15 x-OSCs connected to a single AP and indicates that up to four x-OSCs can operate on a single channel without significantly impacting the 400 packets per second ceiling of a single x-OSC. Beyond this, additional x-OSCs reduce the throughput of each device so that when all 15 are active, the net throughput is ~3800 packets per second. An important observation is that this over-saturated network reduces the throughput of each device equally (from 400 to ~250 packets per second).

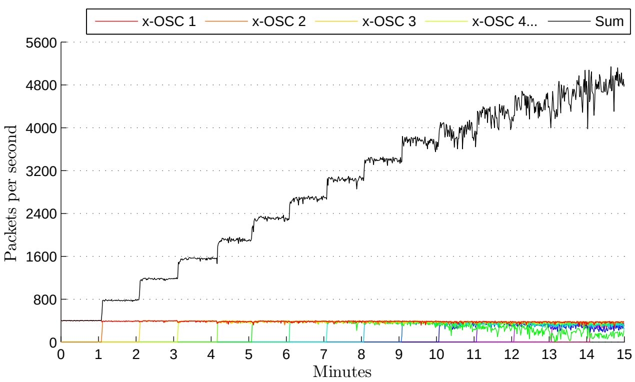


**Figure 7: Throughput of 1 to 15 x-OSCs sending to three APs on three non-overlapping channels**

Figure 7 shows the throughput for 1 to 15 x-OSCs connected to three APs, each operating on a separate non-overlapping channel. Distribution between multiple channels can be seen to produce an increased net throughput of ~4800 packets per second. The first group of five x-OSCs were configured on channel 1, the next on channel 11 and the final five on channel 6. This specific order demonstrates that the channel 1 and 11 groups are able to operate simultaneously without interference. After 10 minutes, the inclusion of the final group (channel 6) increases the net throughput proportionally but with significantly increased variance. Crucially, it can be seen that the the throughput of an x-OSC in the channel 11 group (shown in green) falls below that of the rest once the channel 6 group appears. This demonstrates the potential for channel 6 to interfere with channels 1 or 11 [7].

### 5.3 Anechoic Tests

The investigations presented in sections 5.1 and 5.2 were repeated in an RF anechoic chamber to eliminate the possibility of external interference. Figure 8 shows the computer and x-OSC positioned in the anechoic chamber for a latency investigation. The results were found to be equivalent to those collected in the lab.

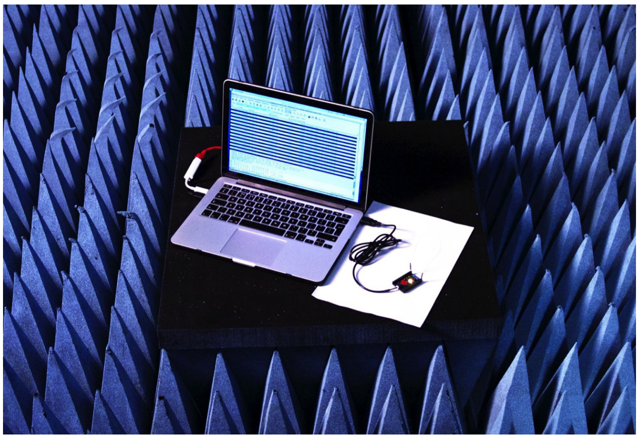

**Figure 8: x-OSC with computer inside the anechoic chamber during latency investigation**

## 6. CONCLUSION

Despite its ubiquity and impressive specifications, Wi-Fi appears underused as a platform for new musical interfaces. In this paper, we demonstrate the great potential that Wi-Fi has to offer as a robust, low latency and high throughput wireless communication technology. We have proposed a number of configurations intended to limit the disruptive effects of interference and to optimise a WLAN for live music performance. In section 3, a 2.4 GHz directional patch antenna was developed and tested that had been designed to maximise sensitivity to signals from performers, while suppressing interference from elsewhere. In section 4, a number of recommendations were proposed that we have found to provide the lowest latency and the highest throughput. These recommendations can be summarised as follows:

- avoid device hosted ad hoc networks
- do not use encryption
- unicast, don't broadcast
- match your AP to your device network type
- use large packets where possible
- use multiple non-overlapping network channels

Practical results obtained when following these recommendations were presented in section 5. Using the x-OSC interface device, a latency of <3 ms and a throughput of up to 4800 messages per second were recorded. This throughput reading was made with 15 x-OSCs simultaneously transmitting ~320 OSC messages per second, corresponding to the successful transmission of 240 analogue input readings every 3 ms. These results were obtained using an 802.11g WLAN offering a maximum throughput of 54 Mbps.

As affordable low-cost devices begin to emerge that are compatible with the 802.11n (600 Mbps) and the recently approved 802.11ac (1300 Mbps) specifications, these figures will continue to improve.

In future work we intend to rigorously evaluate the complete system (network infrastructure and antenna) in the context of 'real-world' performance scenarios. In particular, given the high throughput measured in our studies, we are interested in examining the use of x-OSC as an enabling technology for collaborative live performance using a wireless sensor network.

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