nOdes: A Networked Constellation of Handheld Orbs for Community Music-Making

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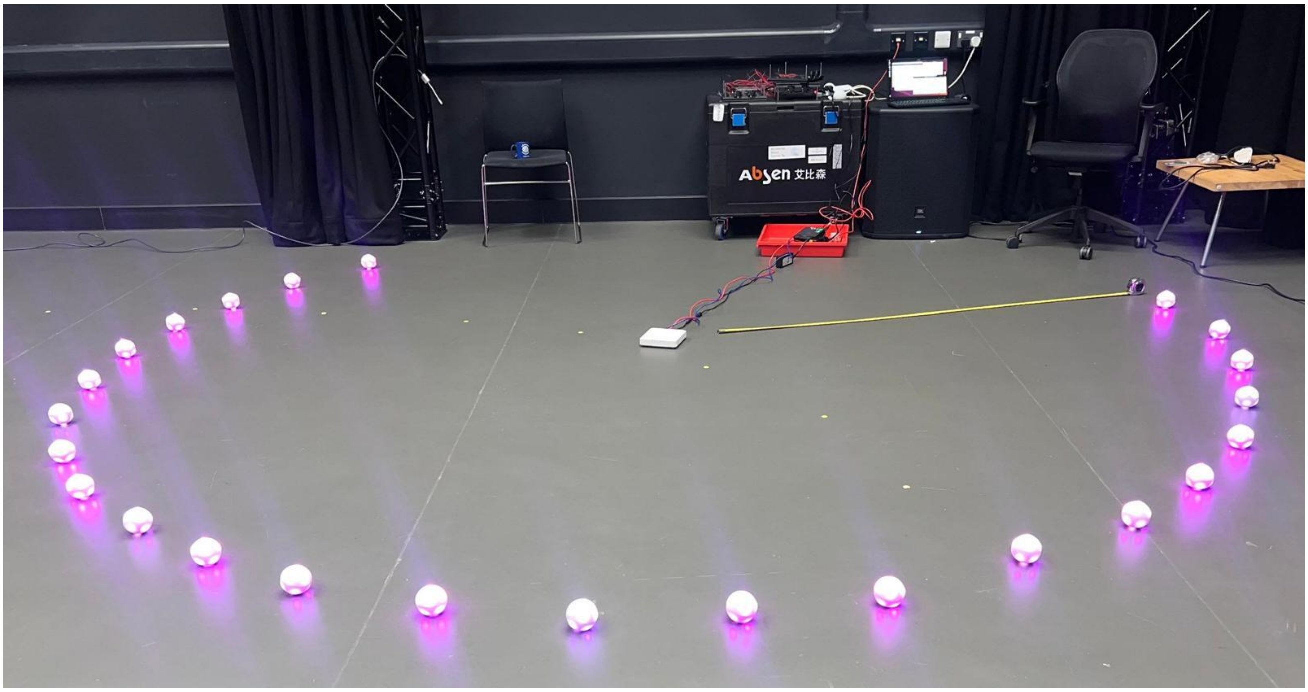

Figure 1: Twenty-four nOdes orbs arranged on a studio floor during a scalability experiment, with the Ruckus R500 access point visible at centre and a tape measure marking distance from the AP.

Abstract

This paper presents nOdes, a platform for networked handheld musical objects designed for collaborative music-making. The system consists of spherical “orbs”, each a self-contained wireless device with motion sensing, twelve icosahedrally arranged RGB LEDs, audio hardware and wireless charging. A central server coordinates up to 24 orbs over Wi-Fi using a frame-based UDP protocol at 50 Hz, supporting low-latency ensemble interaction and structured logging. We illustrate the platform through an example orientation-based mapping in which each orb’s gravity vector selects one of twelve pitch classes, visualised via LED colour. The active pitch classes across all orbs are mapped to the harmonic material of *Cellular Au-Tonnetz* [3], an external generative sound-and-light system. We present timing and scalability measurements and outline future directions in co-design and open dissemination.

Keywords

distributed musical interaction, tangible user interface, real-time wireless systems, gestural control

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1 Introduction

Research on new interfaces for musical expression has produced a rich variety of digital musical instruments (DMIs) beyond keyboard- and mixer-based paradigms [10]. Tabletop and multi-object instruments such as the reacTable [6], Jam-O-Drum [2] and AudioCubes [14] demonstrate how musical structure can be shaped through the manipulation of multiple physical elements in a shared space. Meanwhile, work on handheld devices, spherical controllers [5] and accessible DMIs [4, 7, 18] has emphasised that instrument design is both a technical and a social endeavour, requiring adaptability to different groups and contexts.

In this paper we introduce *nOdes*, a platform for networked handheld musical objects. nOdes consists of spherical "orbs", each a self-contained wireless device with motion sensing, addressable LEDs, audio hardware and wireless charging. A central server coordinates up to 24 orbs over Wi-Fi at 50 Hz, supporting low-latency ensemble interaction and systematic logging. We view nOdes as a contribution to the NIME 2026 theme of *Communities*: the system is inherently multi-user, portable and reconfigurable, designed to be brought into schools, community organisations and workshops and adapted to local practices.

We ask: *how can a portable, low-latency wireless platform be designed so that collective musical mappings can be rapidly iterated and re-deployed across different community settings, without each change requiring a firmware update on every device?* A central design choice that follows from this question is to push interaction logic off the orbs and onto the server: the firmware provides a stable 50 Hz bidirectional sensor/actuator stream, while all mapping behaviour lives in server-side software that can be edited and reloaded on the fly. This separation is the backbone of the platform's extensibility.

This paper contributes: (1) the design of the nOdes orb hardware and wireless charging ecosystem; (2) a real-time networking architecture based on UDP multicast/unicast at 50 Hz with up to 24 orbs; (3) a server-centric mapping model that decouples interaction design from firmware, enabling rapid iteration and easy reuse across groups and venues; (4) an example orientation-based mapping that integrates the platform with an external generative system [3]; and (5) a discussion situating nOdes within community-oriented DMI research.

2 Related Work

nOdes intersects three strands of DMI research: tangible and tabletop multi-user instruments, spherical and ball-shaped handheld controllers, and community-oriented music technologies.

2.1 Tangible and Tabletop Multi-User Instruments

Tabletop and multi-object interfaces frame music-making as the manipulation of physical objects in a shared space. The *reacTable* is the canonical example: its tangible blocks define a modular synthesis patch through position and orientation, supporting simultaneous multi-user interaction around a shared surface [6]. Jam-O-Drum embeds physical drum pads in a circular table with a shared visual display for rhythm-based group collaboration [2], while AudioCubes distributes the interface into several illuminated cubes whose proximity and orientation relationships are mapped to sound-design parameters [14]. More recent tabletop work further widens this design space: AmbiDice uses rolled dice as an ambient music controller for tabletop role-playing contexts [1], and Lui describes a handmade multi-touch music table that generates expressive music from images through simultaneous surface input [8]. Common to all these systems is a *shared surface* that anchors the interface and implicitly constrains the group's spatial configuration. nOdes extends the multi-object tabletop tradition by eliminating the surface entirely: each orb is fully wireless and handheld, so the "table" is wherever the participants happen to be.

2.2 Spherical and Ball-Shaped Handheld Controllers

A second strand of work explores spherical and ball-shaped musical controllers, where the geometry of the object invites whole-body, gestural and social modes of play. Jensenius and Voldsund's *Music Ball Project* systematically surveys acoustic and electronic music balls of different sizes, arguing that sphericity affords rolling, throwing, clustering and inclusive physical engagement across users with very different skill levels [5]. Yamaguchi et al.'s TwinkleBall develops this intuition into a wireless ball-shaped interface for embodied sound media, exploring how motion and handling of the device drive sound production [17]. Nath and Young's VESBALL takes the spherical form in a therapeutic direction, presenting a ball-shaped instrument for music therapy contexts [11]. The *AlphaSphere* takes a different route, exposing the sphere as a discretised tactile surface with a grid of pressure-sensitive pads for expert performance [12]. Relative to these systems, nOdes shares the spherical form and group-play intuition of the Music Ball and TwinkleBall, but differs in two key respects: (i) it is designed as a *constellation* of tens of identical orbs rather than a small number of heterogeneous objects, and (ii) it commits to a fixed twelve-LED icosahedral topology combined with a 50 Hz bidirectional Wi-Fi link, so that each orb functions as a node in a larger networked ensemble rather than a stand-alone instrument.

2.3 Community-Oriented and Accessible DMIs

A third strand frames DMI design as a long-term, situated process within specific communities of practice. Lucas, Schroeder and Ortiz argue that technical design must be accompanied by attention to local skills, relationships and support structures [7]. Zayas-Garín and McPherson's dialogic design study foregrounds performer experience in longitudinal work with disabled musicians [18]. Schroeder and Lucas's distributed participatory design work extends co-design practice across geographically separated collaborators [15], while Samuels and Schroeder document inclusive improvisation practice with accessible DMIs [13]. Frid's review surveys accessible digital musical instruments across experimental, educational and community contexts [4], and McPherson et al. analyse how musical instruments for novices are framed across NIME, HCI and crowdfunding ecosystems [9]. While nOdes does not yet present a longitudinal or ethnographic study, it aims to provide the kind of portable, robust, multi-device hardware and networking infrastructure that this body of work implicitly depends on, complementing these socially oriented approaches with a reusable technical substrate tailored for group and community use.

3 System Overview

The nOdes system consists of three components: a central server, a Wi-Fi access point, and a set of wireless orbs (Figure 2). The server runs on a laptop connected to the access point, periodically broadcasting UDP multicast control frames and listening for

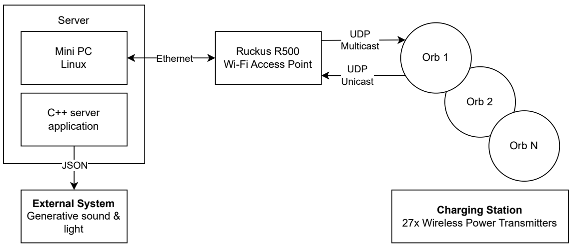

Figure 2: System overview of the nOdes platform. A server connected to up to 24 orbs via a WiFi access point.

unicast replies from each orb. These bidirectional messages form a global control loop at 50 Hz: every 20 ms the server sends a timing reference and global parameters, and each orb responds with a snapshot of its local state.

The server exposes sensor streams (accelerometer, orientation, battery) to external software via JSON, and accepts control messages for switching mappings, tempo or LED patterns. Crucially, this arrangement lets the firmware remain a *thin, stable transport layer* while all musical mapping lives in server-side code that can be edited, hot-reloaded or replaced between sessions. New mappings (e.g. rhythmic triggering on shake events, continuous dynamics from motion magnitude, or timbral control from gesture energy) can be developed and tried out in minutes, without any orb reprogramming. This separation makes nOdes extensible to a much wider range of musical behaviours than those demonstrated here, and is a deliberate response to the scalability and maintenance demands of community deployments, where many identical devices must be updated in lockstep if interaction logic sits on the device.

A typical configuration uses ten to twenty-four orbs and supports interaction through tilting, shaking, passing and clustering. The control loop also supports systematic logging of device telemetry, making nOdes both a performance instrument and a technical research platform.

4 Hardware Design

4.1 Design Goals

The hardware design was guided by four goals: (1) *real-time coordination* within an ensemble, requiring sufficient processing power and stable timing over Wi-Fi; (2) *embodied, gestural interaction*, with a form factor inviting tilting, shaking and passing; (3) *legible on-device feedback*, so device state is directly readable from the orbs; and (4) *portability and robustness* for workshops and installations, with simple deployment and wireless recharging. The design also prioritises reliable sensor access and consistent device identification for research logging.

4.2 Orb Hardware

Each orb is a self-contained, battery-powered device with a diameter of 70 mm (Figure 3). The enclosure is a two-part translucent shell that diffuses light outward while protecting internal components.

At the core is an ESP32-S3-WROOM module (N4 variant, with 4 MB flash and integrated 2.4 GHz Wi-Fi), handling the 50 Hz networking loop, sensor sampling and LED control. An STMicroelectronics LSM6DS-family six-axis IMU provides three-axis accelerometer and gyroscope data.

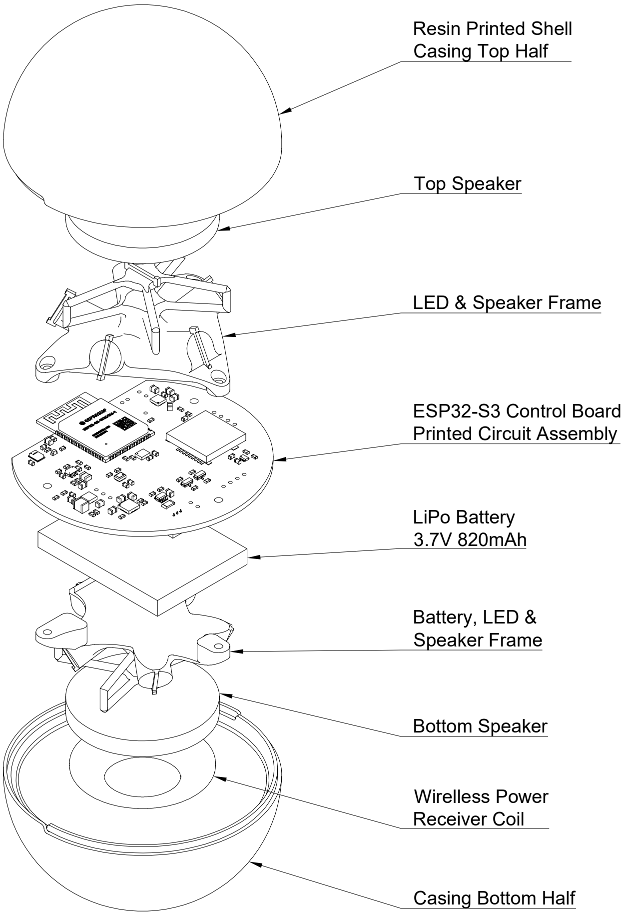

Figure 3: Exploded hardware view of an orb, showing the various component parts.

Visual feedback comes from twelve individually addressable APA102 RGB LED pixels at the vertices of an inscribed icosahedron. This layout creates a regular, evenly distributed set of light sources interpretable as a circular state space (e.g. the twelve pitch classes) or as directional indicators, readable from multiple viewing angles.

Each orb also includes a MAX98357 I2S digital amplifier driving a small loudspeaker, and an ICS-43434 I2S MEMS microphone, enabling future mappings with local sound production. Power is supplied by an 820 mAh lithium-polymer cell providing over 4 hours of continuous use, charged wirelessly via an internal inductive coil.

4.3 Charging Station

To support rapid turnaround between sessions, nOdes includes a dedicated wireless charging station (Figure 4). The station houses an array of inductive coils beneath a contoured surface, each corresponding to a parking position for one orb. Facilitators simply place orbs onto marked positions; LED feedback indicates charging status. A single power input supplies the electronics, which manage per-orb charge negotiation and safety. No connectors need to be plugged, significantly reducing setup overhead when working with tens of devices.

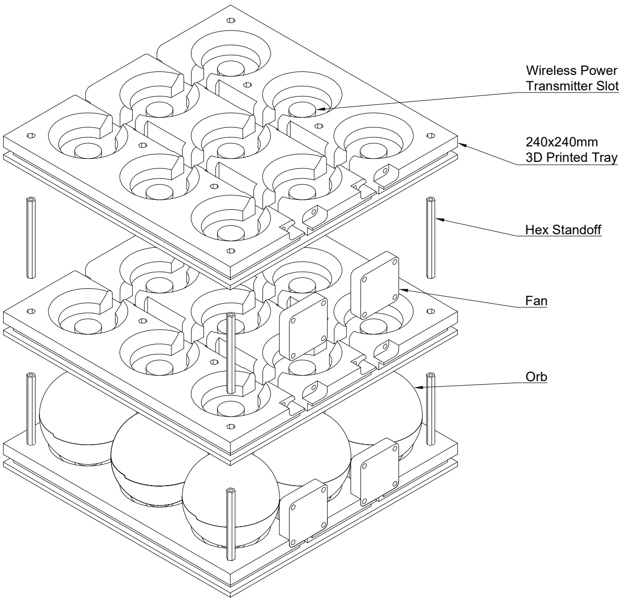

Figure 4: Exploded view of the wireless charging station showing the coil array, 3D-printed trays, fans and orb parking positions.

5 Networking and Timing Architecture

5.1 Network Setup

nOdes operates on a local Wi-Fi network using a Ruckus R500 access point. Each orb connects as a Wi-Fi station, while the server runs on a machine attached to the same network. We use UDP for all time-critical communication: multicast packets from the server provide a global control frame, and unicast packets from each orb return local state. Wi-Fi was chosen over Bluetooth Low Energy for its higher throughput, IP multicast support and the ESP32-S3's onboard Wi-Fi, keeping costs low.

5.2 Frame-based Communication

The control loop runs at 50 Hz (one frame every 20 ms). On the server, a real-time thread with elevated scheduling priority, pinned to a single CPU core, transmits a UDP multicast frame containing a monotonically increasing frame counter and optional global parameters (tempo, scene, mapping presets).

Each orb listens on the multicast group. On frame arrival it records a hardware timestamp, then arms an 8 ms one-shot timer. When the timer fires, the orb sends a UDP unicast response containing its current sensor data and status flags. The result is a tightly structured exchange in which all orbs share a common timing reference and respond within a controlled window (Figure 5).

5.3 Packet Structures

Packet formats are intentionally simple (Figure 6). The 128-byte multicast frame contains a message type, protocol version, 32-bit frame counter, command word, slot allocation bitmap and per-orb LED colour data. The 64-byte unicast response carries an orb identifier, the most recently received frame counter (for drop detection), accelerometer readings, RSSI, timing stamps, battery telemetry and a sequence number. A fixed binary layout is used for efficiency, with reserved space for future fields.

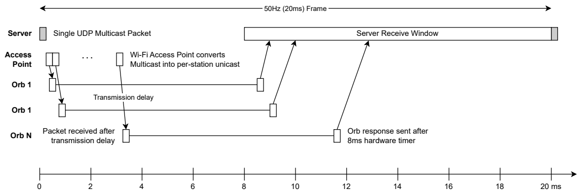

Figure 5: Timing diagram for one period of the 50 Hz control loop. The server transmits a UDP multicast frame at t=0. The access point converts this to per-station unicast and relays it to each orb in sequence. Upon reception, each orb arms an 8 ms hardware timer; when the timer expires, a unicast response is sent back to the server within the receive window.

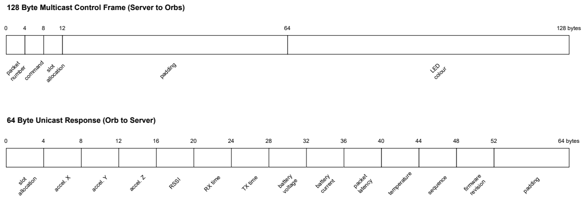

Figure 6: Packet field layouts for the two UDP message types in the nOdes control loop. Top: the 128-byte multicast control frame sent by the server, containing a frame counter, command word, slot allocation bitmap and per-orb LED colour data. Bottom: the 64-byte unicast response from each orb, carrying accelerometer readings, RSSI, timing stamps, battery telemetry and a sequence number.

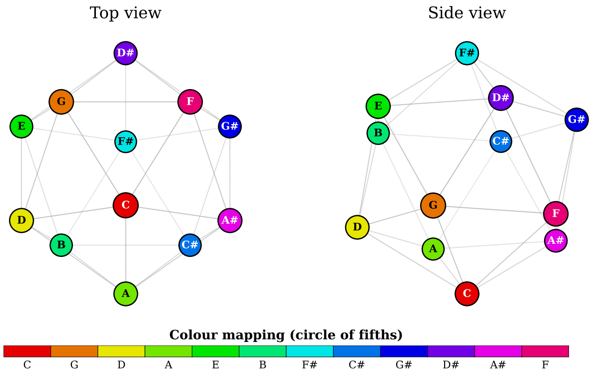

Figure 7: Mapping of the twelve pitch classes to icosahedron vertices, shown in top and side views. Antipodal vertex pairs are assigned tritone intervals (six semitones apart).

5.4 Timing Considerations

On the server, the real-time thread sends frames at precise 20 ms intervals using a sleep-until strategy relative to a monotonic clock, recording deviations for later analysis. On each orb, Wi-Fi power-saving is disabled and a microsecond-resolution hardware timer implements the response offset. Timestamps logged at both ends allow characterisation of end-to-end latency and jitter (Section 7).

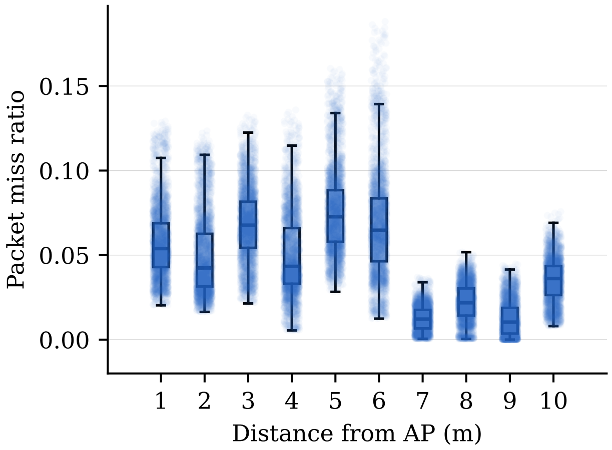

Figure 8: Packet miss ratio as a function of distance from the Wi-Fi access point for a single orb. Each point represents one 50 Hz frame sample; box-and-whisker overlays show the median and interquartile range at each distance.

6 Example Interaction and Mapping

To illustrate the platform in practice, we describe an example orientation-based mapping that exploits the twelve LEDs at the vertices of the inscribed icosahedron: each orb has twelve "faces", each associated with a distinct LED and a musical pitch class.

On the firmware side, the orb estimates a gravity vector from accelerometer data and, for each 50 Hz frame, compares it to twelve precomputed unit vectors corresponding to the LED directions. The closest match (by maximum dot product) is the "active" face, mapped to one of twelve chromatic pitch classes. The active LED is lit in a colour associated with that pitch while the others are dimmed, providing on-device feedback as the orb is reoriented (Figure 7).

The selected pitch class from each orb is transmitted via the nOdes server to *Cellular Au-Tonnetz* [3], an external generative sound-and-light system that uses Tonnetz geometry and cellular automata to produce evolving MIDI patterns and synchronised LED visualisations. Rather than treating the per-orb pitch classes as direct note events, the integration interprets the set of currently active pitches across all orbs as a shared pitch collection or scale that constrains the harmonic material of the generative system. This illustrates how nOdes' server-centric architecture allows a small per-orb mapping (gravity → pitch class) to be composed with an external system into a coordinated multi-orb behaviour.

7 Technical Evaluation and Scalability

Our evaluation focuses on two aspects critical for musical use: server-side timing behaviour and network scalability as orb count increases.

7.1 Timing Behaviour

Server-side multicast send jitter, measured as the deviation from the target 20 ms wake-up time over approximately 40 000 frames, had a mean of 10.6 μs and standard deviation of 11.6 μs, confirming that server-side timing is negligible relative to the frame period and well within musically acceptable bounds.

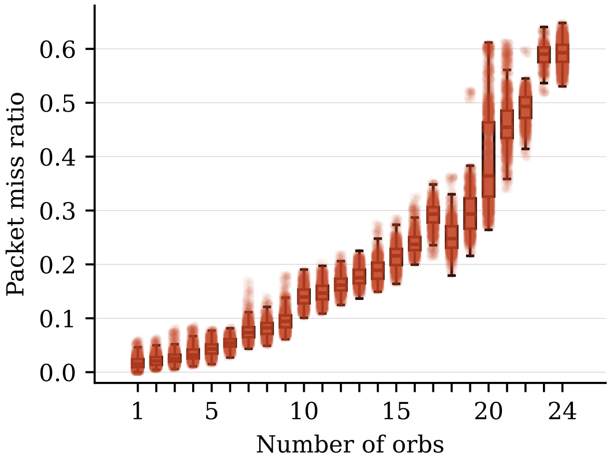

Figure 9: Packet miss ratio as a function of the number of active orbs on the network, measured at a fixed distance of approximately 2 m from the access point. Each point represents one 50 Hz frame sample; box-and-whisker overlays show the median and interquartile range for each orb count.

7.2 Scalability

We conducted two scalability experiments. First, we measured the packet miss ratio for a single orb at distances of 1–10 m from the access point (Figure 8). The miss ratio is elevated at close range (<7 m) and improves at greater distances; the sudden improvement around 7 m is consistent with the received signal level dropping below the RF frontend's compression point, such that saturation/intermodulation distortion ceases to dominate. Multipath interference in the small test room is an additional plausible contributor.

Second, we increased the number of active orbs at a fixed distance of approximately 2 m (Figure 9). We chose 2 m as the operating point for the orb-count sweep because it represents a typical close-range deployment geometry. It is also, per Figure 8, the *worst-case* per-link condition: if the system can scale at 2 m it will only improve with greater separation, so this represents a deliberately conservative test. Packet loss increases steadily with orb count for $n < 20$, consistent with growing collision and contention on the shared medium. Beyond $n \approx 20$, loss worsens more sharply, suggesting that aggregate response traffic begins to exceed the 20 ms frame window. In practice, we tested up to 24 orbs; beyond this, sporadic LED glitches appeared. Within the 10–20 orb range targeted by our design, the system behaved robustly.

We note several limitations of this characterisation. We did not measure the ambient RF environment with a spectrum analyser, nor did we log TX power or instantaneous RSSI at each orb during the sweeps, and the firmware does not currently implement adaptive rate or power control. We also did not directly measure the AP's sequential per-station unicast queue timing, which influences how tightly the orbs' responses cluster in time and therefore the collision probability. A fuller investigation of these variables is left to future work alongside systematic testing under varied network conditions and firmware optimisations for higher orb counts.

8 Discussion and Future Work

By distributing musical control across many identical handheld orbs while centralising timing on a single server, nOdes offers a portable, robust instantiation of the collaborative instrument ideas explored in earlier tangible systems [2, 6, 16]. The spherical design invites playful interaction, while the 50 Hz architecture provides a stable backbone for ensemble behaviour and logging.

From a community perspective, nOdes should be understood less as a finished instrument and more as reusable infrastructure adaptable to different groups [7, 18]. We envisage bringing it into schools, community organisations and festivals, where the same hardware core can support different mappings and workshop formats co-designed with local participants.

The pitch-class mapping reported here is deliberately a minimal demonstration of the platform rather than a statement about its expressive ceiling. Because mappings live on the server, additional musical dimensions (rhythm from tap/shake detection, dynamics from motion magnitude, articulation from orientation velocity, timbral variation from gesture spectra) can be added as independent server-side modules that consume the same 50 Hz sensor stream and emit MIDI, OSC or direct synthesis control. We expect the bulk of future expressive development to take this form, with the firmware changing rarely and the server-side mapping library growing steadily. Future work therefore includes building out this mapping library alongside developing the onboard audio into a local sound engine for hybrid mappings, extending the networking layer with dynamic sub-ensemble clustering, and expanding the scalability measurements under varied network conditions. On the design side, we plan co-creative workshops and longitudinal studies of adoption, and intend to release the hardware designs and firmware as open-source components.

9 Ethical Standards

This paper concerns the design and technical characterisation of the nOdes hardware and networking architecture. It does not report any human-participants research: no observational, interview or user-study data were gathered, and the paper makes no claims drawn from observing people. All measurements reported here (e.g. timing jitter, packet miss ratios) were collected from the devices themselves and contain no personal data. In line with NIME's Principles and Code of Practice, we have considered broader community values including accessibility and inclusion (supporting group participation and legible on-device feedback) and environmental impact (rechargeable devices and reuse-oriented deployment). Any future deployments involving people, such as the co-creative workshops and longitudinal studies outlined in Section 8, will be conducted under appropriate institutional ethical oversight.

10 Conclusion

We have presented nOdes, a platform of networked handheld orbs combining motion sensing, addressable LEDs, audio hardware and wireless charging with a central server architecture operating at 50 Hz over Wi-Fi. An orientation-to-pitch-class mapping integrated with *Cellular Au-Tonnetz* [3] illustrates how the platform composes with external generative systems to produce coordinated multi-orb behaviour. Timing and scalability measurements indicate suitability for small- to medium-sized ensembles. We see nOdes as an infrastructural contribution to community-oriented NIME practice, supporting future co-design, longitudinal evaluation and open dissemination.

Acknowledgments

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