BIKES: A Moving Network Instrument for Music and Sound Art

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***Abstract*—BIKES s a moving network music instrument consisting of four electric bicycles, each equipped with an onboard computer, touch display, and a loudspeaker. The bicycles share control data and metadata over a local-area network, creating sonic interventions in arbitrary locations, either while moving or while stationary, as an installation. BIKES is an instrument in its own right and is intended to be programmed individually for different concepts and compositions, using tools such as SuperCollider, Python, and Ansible. This paper discusses the initial prototype, detailing the hardware, software, and network communication architectures used for musical interaction. BIKES has been used in public performances and installations in a variety of urban contexts, displaying the system's novel ways of interacting with its environment. Future developments will focus on enhancing the system's robustness by improving the hardware design and equipping each bike with a router to form a decentralized mesh network.**

***Index Terms*—Network Music, Mobility, Soundscape**

Fig. 1: BIKES with riders during a show in a public park.

I. Introduction

Located at the intersection of arts and technology, BIKES explores technological concepts to create novel ways of artistic expression and interaction. The moving network music instrument consists of four electric bicycles, each equipped with a computer, a touchscreen interface, and a PA loudspeaker. Connected through a local area wireless network, the four bikes form a distributed musical instrument capable of both temporary installations and performances while in motion. In a collaboration between the Georgia Tech School of Music, the Georgia Tech School of Industrial Design, and the electric bicycle company *Edison Bicycles*, a fully functioning first stage prototype was realized, allowing a proof of concept and first interventions. Figure 1 shows the four bicycles with riders in a public park.

BIKES is driven by practical concerns as well as creative visions. On the practical side, electronic music and sound generation have an inherent sustainability problem, especially when it comes to multichannel setups. It usually takes a car or a transporter to install a system at a specific site. If this site does not provide standard power outlets, additional generators might be necessary to drive a PA system. All this usually involves fossil fuels, causing unwanted emissions and noise. Another practical issue is the accessibility and flexibility of multichannel sound systems. Many remote or hidden locations can be enticing for impromptu concerts or listening sessions. Often, these are not reachable by car and again do not provide power outlets. Bicycles offer a sustainable and accessible way of deploying a multi-channel loudspeaker system to arbitrary locations. The network concept makes it possible to do this without cumbersome cables while still having the individual systems connected, and also allowing for quick system maintenance and configuration.

The moving network music system presented in this paper is a direct descendant of SPRAWL, a local area network system for enhanced interaction between musicians [1]. While this predecessor relied on wired connections to create a fully connected audio routing mesh, BIKES is based on a WiFi network to exchange control and metadata. This network is the backbone of the moving instrument, both in terms of system maintenance and creative possibilities. A wide range of network topologies and communication principles serves as a medium for creative expression, making system design part of the composition process. Performances and installations are centered around the flow of data and the spatial interaction between the bicycles.

A central aspect of BIKES is the possibility to interact with the surrounding environment in performances and installations. The project aims at enriching and challenging urban soundscapes by making use of idiosyncratic acoustic properties, contrasting noise pollution and revitalizing spaces. Following R. Murray Schafer's framework, we understand modern soundscapes as *low-fidelity environments* in which crucial auditory signals are often masked by overwhelming background noise, resulting in diminished clarity of important auditory information [2]. Within Schafer's theory, the moving network instrument is able to introduce *keynotes, signals, and soundmarks* into common spaces, thus changing how individuals experience them. This aligns with Westerkamp's approach of soundscape composition as a form of artistic engagement with environments [3]. BIKES is a system that promotes engagement with urban soundscapes, shaping sonic experiences for the environment's inhabitants and thus creating a dialogical process that fosters awareness of place, time, and environment. BIKES extends this to a socio-environmental dimension, creating an awareness for alternative means of transportation and increasing the visibility of cyclists and pedestrians.

The remainder of this paper explores related works in Section II, outlines the software and hardware architecture in Section III, and describes the use of network topologies for creative expression in Section IV. First experiences created with the BIKES are presented in Section V, followed by a conclusion in Section VII.

II. Related Work

A. Network Music Approaches

Network technologies can serve diametrically different purposes in music. On the one hand, they are a means for transmitting audio between different devices, replacing analog or conventional digital protocols. Professional audio-over-IP (AoIP) protocols like Dante, Ravenna, AVB and AES67 focus on flexible local area routing systems that facilitate massive amounts of channels [4]. Other, more experimental approaches aim at connecting remote locations for distributed real-time performances. Jacktrip [5], Jamulus, and SonoBus [6] are examples for UDP-based protocols that enable low-latency audio streaming over longer distances. While robust over wired connections, AoIP remains sensitive to jitter, package loss, and network congestion in wireless networks [7]. These constraints make synchronous musical collaboration difficult under moving and wireless conditions.

Using networks as creative means is a completely different approach. Exchanging control and metadata over networks is common practice in experimental and electronic music performances. Not only does it overcome the drawbacks of audio networks - it also creates new possibilities for interaction. The network becomes an integral part of compositional, performative, or interactive music making processes [8].

One of the first groups to explore the creative dimensions of computer networks was the League of Automatic Composers (1977), who exchanged algorithmic control data via serial cables [9]. A decade later, The Hub (1986) introduced hub-based routing as a compositional tool [10]. Works such as Talking Drum [11] and browser-based groups such as Female Laptop Orchestra [12] created distributed and autonomous musical interaction systems across wide-area networks. Laptop ensembles such as PLOrk [13] and SLOrk [14] use WiFi networks to send information such as pulses, cue data and gesture tracking via Open Sound Control (OSC) [15] to render audio in a distributed system.

Smartphones are frequently used to create participatory experiences. The use of cellular networks increases the accessibility in contrast to WiFi solutions. *Crown in C[loud]*, for example, explores audience-participation by turning every audience member's smartphone into a node on a locally hosted Wi-Fi network [16]. When audience members join the web application, they are prompted to create a musical profile. Users are then guided towards making music with another node on the network that matches that profile, making use of dynamic network configurations for social match making.

While many of the above listed examples build their individual logic on top of OSC, several protocols are explicitly designed for a synchronization of audio processes in IP networks. In contrast to AoIP applications, which require sample-wise synchronicity, these examples are designed for a synchronization in beats or bars, this tolerating suboptimal conditions and transmission over wireless connections

MIDI-based solutions like *Telemidi* [17] and *RTP-MIDI (AppleMIDI)* [18] wrap MIDI information within UDP messages, providing a shared clock on Wi-Fi or Ethernet. *The Global Metronome* uses a shared absolute time source (GPS/PTP/NTP) and transmits only tempo changes, achieving sub-millisecond agreement over the internet [19]. *LIPS Rhythmic Sync Service* works with broadcast-on-change tempo packets while beat phase is computed from disciplined system time, suited to WAN performances [20].

Ableton Link is a peer-to-peer synchronization protocol that aligns beat, tempo, and phase to a shared clock over multiple nodes on a network [21]. Link operates in a decentralized architecture in which each node sends multicast messages to peer nodes. These messages include a unique peer identifier and a snapshot of the node's current musical timeline. Once updates are received from peers, Link employs a consensus mechanism to determine a global timeline reference. Each node adjusts its local timeline to align with the global timeline, resulting in a synchronized system. As an open standard it is nowadays included in many computer music environments, including SuperCollider, Pure Data and Max/MSP.

B. Movement and Vehicles in Music and Sound Art

Adding movement to sonic experiences introduces new possibilities for composition, performance and sound design. Various projects have thus explored this avenue in a musical context, creating immersive or site-specific works, either with the listener or the sound sources moving. Early examples of the postmodern era leverage minute or moderate movements in a concert situation. This includes works like John Cage's *Musicircus* (1967), or *Persephassa* (1969) by Iannis Xenakis. Movements of musicians and their instruments during a performance shift the spatial scene and add to the timbre of the instruments.

Using vehicles to move either listeners or sound sources shifts the paradigm dramatically. The increased velocity leads to a constantly changing scenery, making the works inherently site-specific. In addition, Doppler shifts and constant changes in acoustics significantly transform the sonic experience. Network technologies and, in a broader sense, communication technologies are often the foundation of these concepts.

In his experimental concept *Drive-In Music* (1967), Max Neuhaus broadcasted sounds over multiple directed FM transmitters in an installation in Buffalo, New York [22]. Any car could receive the signals when driving through a downtown street, resulting in a shifting scene while moving through the zones created by the different transmitters.

Technologies like GPS allow artists to create dynamic site-specific experiences for individual listeners. Many examples in this domain can be considered interactive sound installations, or an evolution of soundwalks in general [23]. Kaffe Matthews explored different Human-powered vehicles (HPVs) to explore site-specific sound installations for moving audiences. This includes her Sonic Kayaks and the Sonic Bikes [24], [25]. Equipped with Rasperry Pis and loudspeakers that are directed at the driver, the bikes play pre-fabricated samples or synthesize sound when moving along a defined route. Matthews expanded on this by using sensors that track the bike's movement and orientation and environmental properties like the air quality.

III. Technology

A. Hardware

1) The Bikes: The prototype presented in this paper is built on a cargo bicycle manufactured by *Edison Bicycles*, an Atlanta-based e-bike company[1]. The model used is a class 2 electric bicycle equipped with a $750\,\mathrm{W}$ motor offering both pedal-assist and throttle control. It is capable of reaching speeds up to $32\,\mathrm{km/h}$ with motor only. The bike itself weighs $24\,\mathrm{kg}$ and provides the necessary structural robustness needed to support the audio hardware. It is powered by a $42\,\mathrm{V}$ lithium-ion battery and can reach up to $96\,\mathrm{km}$ per charge. The bicycle offers a payload capacity of $181\,\mathrm{kg}$ and a towing capacity of $91\,\mathrm{kg}$, allowing for smooth travel when carrying the additional weight imposed by the onboard computer and PA system.

[1]https://edisonbicycles.com/

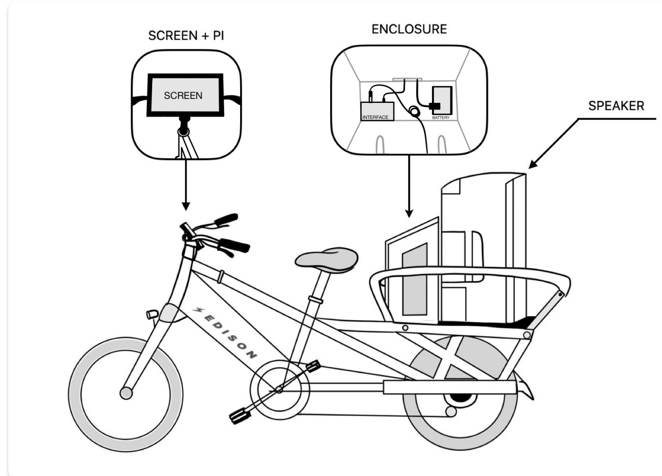

Fig. 2: Detailed setup with mounted hardware.

BIKES' industrial design team developed a custom mounting solution for the project. As shown in Figure 2, a wooden platform is mounted onto the back of each bike to support a loudspeaker and an enclosure for the music technology hardware. A 3D-printed screen housing is attached to the handlebar and holds a Raspberry Pi and a touchscreen display. Two USB cables - one for powering the Pi and one for connecting it to the audio interface - connect the front housing with the rear enclosure. These design decisions result in a compact, secure, and reliable setup that works well in motion.

2) Audio and Network: Each bicycle is equipped with a dedicated set of hardware components that support music generation and network interactions. The main computing unit is a Raspberry Pi 5, paired with a $10.1\,\mathrm{in}$ touchscreen display, both mounted on the front handlebars. The wooden enclosure holds a Behringer U-PHORIA UMC22 2-in/2-out USB audio interface and a $110\,\mathrm{V}$ rechargeable battery. A Mackie THRASH212-GO battery-powered $300\,\mathrm{W}$ loudspeaker is placed on the platform and strapped to the enclosure, preventing it to move while riding.

In the current iteration, one bicycle is equipped with an ASUS RT-AC66U WiFi router. All bicycles connect to this router with the onboard Raspberry Pi WiFi interface.

B. Software

1) Audio Software: The bicycles run a standard Raspberry Pi operating system with full desktop environment. Each system boots a JACK[2] server at a sample rate of $48\,\mathrm{kHz}$, with a buffer size of 128 samples. Although this foundation is intended to run various audio software components, SuperCollider is used as the only platform for audio signal processing at this stage. Each Raspberry Pi runs an independent SuperCollider server and language instance. The Graphical User Interfaces (GUI) are realized with SuperCollider as well, enabling touch control over audio and network processes.

[2]https://jackaudio.org/

Default communication between the bikes - also referred to as nodes - is realized through OSC with SuperCollider's `OSCDef` class. In addition, p2psc [26] is used to simplify communication between the nodes. This OSC path registry and message-routing tool simplifies the configuration of OSC peers. Each bike dynamically registers with with a unique identifier and can subscribe to specific OSC paths that are known by other nodes. This tool allows for rapid routing configuration and can flexibly support different network topologies with minimal overhead.

2) System Management: Rapid configuration and deployment of musical and network concepts is an integral component of BIKES as a musical instrument. The system thus leverages tools from the system administration domain to ensure a reliable workflow. Ansible [27] is a widely used network automation tool that is used by BIKES to remotely manage each node and the configuration of the whole network. Automation in Ansible is achieved by using *playbooks*, which specify a sequence of operations, mostly SSH commands, to be executed on a list of hosts.

BIKES uses a set of playbooks to quickly and remotely launch SuperCollider scripts, route different network topologies, and run maintenance tasks. During this phase of the project, an additional laptop is used to join the WiFi and run playbooks when needed. Ansible also provides detailed feedback, indicating whether each playbook ran successfully or failed on each target node. This architecture allows all nodes to be activated simultaneously by a single command-line prompt, resulting in a quick, streamlined, and robust deployment process with an intuitive feedback system.

C. User Interface

The 10-inch touchscreen mounted on the handlebars is intended to serve as the primary user interface for interacting with the system. Since users need to operate the GUI while riding the bike, certain criteria must be met. Both handheld and hands-free mobile devices significantly increase cyclists' reaction times and reduce their auditory perception of their environment, although hands-free devices were less distracting [28].

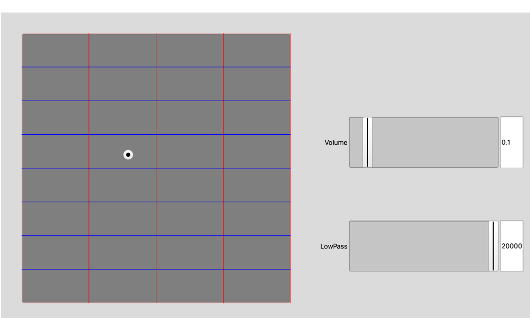

Fig. 3: GUI layout used for the first phase of the project.

In addition to the problem of multitasking, the outside conditions demand simple, high contrast interfaces due to exposure to bright sunlight. Figure 3 shows the basic GUI layout, that has been adapted for different concepts with slight modifications. It features a quantized XY-controller on the left side, and two horizontal sliders on the right. This limited set of controls prevents cognitive overload. For each concept, these basic elements are mapped to different parameters.

IV. Network Topologies and Concepts

BIKES leverages different network topologies and routing principles as the foundation for expression and creativity. Each network configuration is designed for a specific interactive concept. Together with the movement of the nodes and the always shifting relative positions, each topology creates unique spatial relations between the nodes.

A. Independent Nodes

In the most basic concept, each bike operates independently. This mode is referred to as the *Independent Nodes* configuration, shown in Figure 4, and does not implement network communication between nodes.

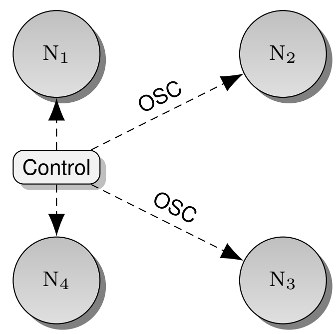

Fig. 4: Independent node topology with control device.

Although the nodes do not interact over the network in this case, the underlying technology is still crucial. The additional control device allows the execution of Ansible playbooks to set certain parameters. In one of the simplest applications, each node plays a looped audio file, creating an immersive spatial sound scene. Using Ansible, the files to be looped can be chosen during the execution of the playbook, while also enabling a delayed start for a better decorrellation.

B. Hierarchical

In the *Hierarchical* network configuration, shown in Figure 5, a single bike functions as the central control node, directing the behavior of all other nodes on the system. The leader node N_1 transmits OSC messages downstream to the remaining follower nodes, which receive, parse, and generate local sound accordingly. The leader node's SuperCollider script functions as a centralized control node and triggers sounds across all follower nodes. Despite this, each follower node retains the ability to produce sound independently but is subordinate to sonic interventions by the leader node.

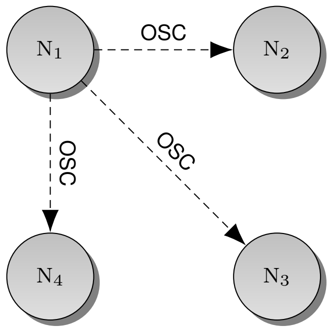

Fig. 5: Hierarchical Network Topology.

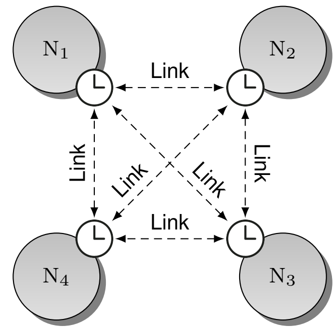

Fig. 7: Synchronized Clock Network Topology.

C. Forwarding

Figure 6 shows the *Forwarding* network configuration. On receiving a matching OSC message, each node generates a sound event, waits for a specific time, and then sends a message of the same type to the next bicycle. The order is either pre-defined or random.

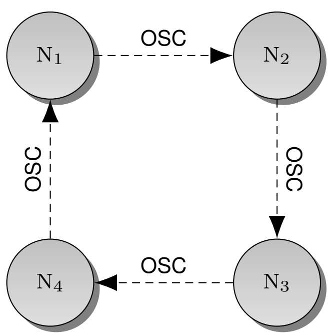

Fig. 6: Message Forwarding Network Topology.

Inherently spatial and network-centered, the forwarding concept can create rich interactive soundscapes with simple means. The recent implementation for BIKES creates simple tone bursts on receiving a trigger message. Their pitch can be controlled through the XY-pad in the GUI. A slider controls the time for the local node to wait before itpasses the trigger message on, scaled between 0 and 2 seconds. This results in decentralized rhythms, patterns and textures.

D. Synchronized Clocks

In the *Synchronized Clock* configuration, shown in Figure 7, Ableton Link is used to coordinate tempo, beat, and phase across all nodes on the BIKES network. A key feature of this mode is its resilience. Nodes can join or leave the network at anytime without interrupting the synchronization of other participants. Ableton Link's built-in peer discovery system and decentralized synchronization process removes the need for manual set up and concern over a node's individual connectivity. This makes it less prone to network dropouts due to WiFi connection issues.

Within BIKES, the synchronized clock configuration is used for a distributed rhythmic piece. A two-bar loop of a techno composition is distributed on the system, each bike playing an individual stem of the mix. The four stems consist of a kick drum track, a bass track, percussion and a synth layer. The ongoing shift in relative positions to the listener adds a natural organic component to the otherwise static loop. The GUI allows riders to adjust the phase of their own loop in relation to the overall clock, with an additional low-pass filter to attenuate the signal.

V. First Experiences

To provide a proof of concept and pinpoint weaknesses and strengths, BIKES was deployed in several public scenarios. This includes basic tests of the user interface and battery life, as well as interactive installations and fully networked rides, showcasing the system in motion. Videos of the interventions can be found on the project's website[3].

A. User Interface and Durability Test

In a first usability test, a single bike was displayed at a research symposium at Georgia Tech. The BIKES team introduced the concept to hundreds of visitors, allowing them to explore the touch interface and resulting sound, as seen in Figure 9.

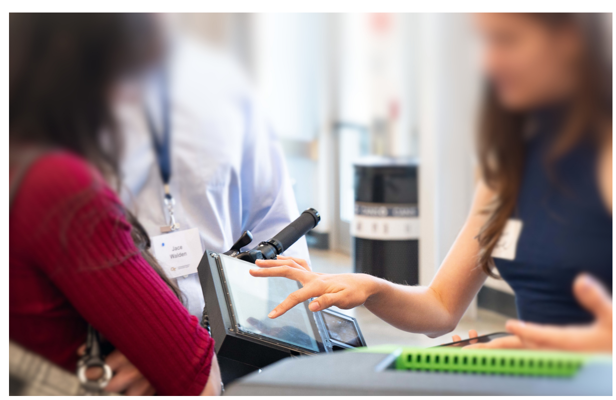

Fig. 8: Introduction to the system at a research symposium.

The bike played a looped harmonic background, while visitors could trigger single harmonic sounds using the XY-pad of the GUI. This two-hour stress test of a single setup provided initial proof that all components worked together robustly in a controlled environment.

[3]https://l42i.music.gatech.edu/projects/bikes

B. Interactive Installation

The BIKES were used to create an interactive sound installation during Launchpad, the annual showcase at Georgia Tech's College of Design. This event attracts thousands of visitors, allowing a serious test of the system for this use case. A quadraphonic configuration was installed in a breezeway with favorable acoustics and audience throughput, leveraging the ability of the bikes to run without power outlets in an arbitrary location. Figure 9 shows visitors while interacting with the bikes in the foreground and background.

Fig. 9: Visitors interacting with the BIKES in an installation.

The independent nodes and synchronized clocks paradigms were used for this installation, allowing visitors to change the sound scape on the touch screen of every bike.

C. Performance in Motion

The first field test of the full system in motion was conducted during the Inman Park Parade, a public event held annually in one of Atlanta's historic neighborhoods. This annual event attracts up to 30.000 visitors, lined up along a route of 2 miles. Figure 10 shows the four fully-equipped bikes while riding through the parade.

Fig. 10: BIKES performance at the Inman Park Parade.

The *Synchronized Clock* model and the *Independent Nodes* model were presented during the parade, offering one rhythmic and a more subtile experience. The GUI supported real-time control of synthesized sound generation and audio processing effects, demonstrating the system's flexibility for expression while in motion. Throughout the parade, the relative positioning of the bikes changed, causing spatial variations of the soundscape.

VI. Discussion

A. Creativity and Interaction

The interactive installation and the performance in motion gave the opportunity to test the creative capacities and interaction qualities in the two primary use cases. Observations of riders and audience as well as open feedback serve as input for identifying the opportunities embedded in the concept.

During the installation at the design show, the BIKES were approached by many visitors. Individuals and groups spent several minutes exploring the GUI and the effects on the resulting soundscape. We could observe groups of visitors splitting up for joint exploration, each using one of the four bikes. The underlying network concepts increased the interaction capacities in this context, allowing the users to play with the installation as a multi-performer instrument.

The parade showed system's ability to contribute to an urban soundscape, and to leverage the concept of motion as integral part of the experience. While riding along between the masses, the four bikes constantly shifted their relative positions, thus shifting the way the four individual signals mix for the listeners. This effect is facilitated through the underlying network concepts. While the BIKES are equipped with quite powerful loudspeakers, this event showed the limits in terms of sound pressure. Other projects in the parade used professional PAs on trucks, dwarfing the bike-mounted sound system.

B. Reliability and Usability

Observation and open feedback from the riders serve as tools to pinpoint reliability and usability issues of the system. Both field tests were successful, as BIKES sustained sound playback for many hours and retained significant battery life, indicating potential for extended use and highlighting the reliability and robustness of the system. During the installation, the system ran for four hours without any complications, even with significant interaction from the visitors. While the performance in motion ran successfully without major complications, it revealed several areas for improvement.

Despite the uneven pavement along the parade route, BIKES' hardware remained intact and responsive, with no cable disconnections, power loss, or overheating issues. However, riding the bikes with the sound system was challenging at times, especially with the stop-and-go during the parade. The placement of the loudspeaker and enclosure on the rear of the bike altered the center of mass, reducing maneuverability, especially for lighter or inexperienced riders.

During the field test, riders reported that the GUI felt intuitive and responsive. Most of the time they were able to contribute to the soundscape while fixing their attention on the road. However, it was challenging to see details of the GUI while riding the bike due to the sun's glare reflecting off the screen.

One of the primary challenges faced with the system in motion are network dropouts. These were caused by individual bikes losing connection to the WiFi router. Some network principles, like the shared clock, are less affected by this problem than a forwarding concept. The network connection was always restored in a matter of seconds, thus not impacting the overall experience. For both scenarios, Ansible never failed as a tool to control the system or launch specific compositions.

VII. Conclusion

The initial implementation of BIKES successfully demonstrated the feasibility of the moving system in real-world applications and highlighted its ability to support musical interactivity across many participants. Phase I of BIKES is intended as a foundation for future development, with future hardware improvements focusing on the robustness of the system and safety concerns. The team is currently working on a more integrated hardware solution by attaching the speakers directly to the bikes in a custom housing. This will lower the center of mass and increase the safety.

Most importantly, the next phase of BIKES is aiming at a decentralized mesh network. The weaknesses of the single-router approach were well known when entering the first tests. Advanced solutions will be more resilient to network dropouts and single-point failures. Using cellular or satellite networks is also considered to create a solution with less spatial restrictions. While the focus will remain on exchanging control data, wireless audio-over-IP solutions will also be explored.

In terms of creativity, phase I of BIKES only scratched the tip of the iceberg. Possible directions include GPS and relative bike positions to control musical parameters, as well as sensor systems, such as accelerometers, to obtain data on parameters of bikes and riders. However, simple concepts are intended as the foundation of the project, focusing on the network as the core technology and movement as the fundamental principle.

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