

A Roadmap for Sonification in the Internet of Sounds

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Abstract—This paper presents a roadmap for research into sonification for Internet of Sounds (IoS) contexts. The roadmap is built on top of a taxonomic framework whose dimensions are informed by the auditory display and IoS literature along with the related field of sound and music computing. The taxonomy intends to demarcate the potential boundaries of IoS sonification. The roadmap lays out potential areas for future research across 5 components: technical infrastructure, design and evaluation, creative musical and artistic practices, critical & ethical dimensions, and standards and interoperability. The taxonomy and roadmap provide an initial step towards developing IoS sonification as a distinct research strand, an argument that is made in the paper and supported by the taxonomy and roadmap.

Keywords—Sonification, Auditory Display, Roadmap, Taxonomy, Internet of Sounds.

I. INTRODUCTION

The Internet of Sounds (IoS) is a field of research at the intersection of the Internet of Things (IoT) and Sound and Music Computing [1]. It has been expanding rapidly in recent years and as the field matures it has increasingly adopted techniques and frameworks from related disciplines to solve problems in IoS contexts. One such field is Auditory Display with several researchers highlighting the critical importance of sonification techniques to the IoS [2], [3]. The IoS, however, represents a novel and distinct research context for sonification as it blurs the traditional distinctions between data, sound, listener and technology that have existed in the field since its academic formalisation in the early 1990s [4]. This presents a number of interesting challenges for the field which open up exciting avenues of research. This paper aims to map out some of those potential challenges, revealing key research questions that might provide guidance and inspiration for future work in this developing field.

II. RELATED WORK

Sonification involves the systematic mapping of data to sound to communicate information about the original data source. While it is often paralleled with data visualization, sonification offers distinctly unique advantages over visual methods and often excels where those methods break down. While auditory displays can be used to supplement and reinforce visual displays in diverse contexts from healthcare [5] to air traffic control [6], it is in the domain of highly complex and multivariate time-series data, a domain where traditional graphing and visualization methods break down,

that sonification comes into its own [7]. The perceptual and cognitive apparatus of the human auditory system is highly sensitive, having evolved to identify and track real-time changes in sonic environments that are temporally and spectrally complex. Sonification can allow a listener to identify minute variations and transient anomalies across the frequency and time domains, and to monitor and analyse broad over-arching patterns, both recurrent and aperiodic, with auditory information perceived either peripherally or through focused attention.

Outside of the context of the IoS a number of projects have applied sonification techniques to communications network infrastructures. Applications have focused on the development of software tools for sonifying network data for musical contexts [8] and the application of sonification techniques to network metadata in public art contexts [9]. Others have focused on monitoring security or integrity of networks. Debashi and Vickers' [10] approach identified traffic features from status flags in TCP/IP packet headers, mapping various combinations of features to control elements of a natural soundscape comprised of biophonic (birds, insects, and small animals) and geophonic sounds (thunder, rain, wind). Thus rendered patterns in the timing, loudness, and sequence of sounds across an ambient soundscape provide operators with information on malicious behaviours on the network. This allows for the ambient monitoring of the network through listening, while focusing visual attention on other tasks. Roddy and Bridges present a system for monitoring the integrity of large-scale IoT networks. This approach sonifies network join request info, gateway states, message integrity codes (MICs), signal strength and noise ratios, along with spreading factor (SF) and radio frequency (RF). Combinations of these data are mapped to formant synthesis parameters producing voice-like sequences of sound. This approach reveals the overall integrity of the network as a function of meaningful prosodic transformations in the synthesised voice-like sounds to which listeners are keenly attuned [11]. Other examples apply rich mapping strategies and sound synthesis techniques to sonify IoT sensor data at the network layer [12] and both the network and device layers simultaneously [2]. Smart City sonification has been a running theme in IoT sonification with one application employing machine learning (VAE architectures), with embodied cognitive design and web-audio-based generative music systems to sonify real-time urban data streams for listening stakeholders [13]. Conceptual frameworks for pairing musical sonification techniques with potential

machine-learning-based feature extraction have been proposed by Sarmiento et al. [14], while data-driven approaches using machine learning (e.g., LSTM) for environmental data have been demonstrated by Kalonaris [15], and real-time interactive sonification techniques have been developed by Zhao and Tzanetakis [16]. More recently researchers have begun to turn their attentions to sonification within dedicated IoS network contexts.

III. IOS SONIFICATION

While IoT refers to networks of connected devices that sense, process and exchange data about physical and digital phenomena, IoS can be understood as a specialised domain of IoT in which audio signals and sound-related data form the primary medium of communication and interaction. This could include networked music performance, distributed soundscape monitoring, remote audio production and other applications that require the real-time transmission of high-quality audio streams. IoS sonification extends more traditional sonification techniques into this context by representing the state, behaviour and data of IoS systems through sound. For example, sonification may be used to communicate network conditions such as latency, jitter and packet loss, to represent audio features extracted from distributed sensors, or to support monitoring and decision making across complex audio-centred network infrastructures.

A. 6G & the Need for IoS Sonification

Three key technical problems that have faced the development of real-time IoS applications on 5G network infrastructures are latency, jitter and frame dropouts [1], [17], [18] with latencies above 30 ms, jitter values above 20 ms and dropped frames around 12 ms (512 samples at 44.1 kHz) becoming detectable to the ear and thus problematic for networked audio applications where high-resolution audio streamed in real-time is critical to quality of service (QoS). As we approach the arrival of 6G, it is expected that the IMT-2030 framework under development by the International Telecommunication Union Radiocommunication Sector (ITU-R) alongside the technical specifications expected from the 3rd Generation Partnership Project (3GPP) will help to mitigate these issues thus supporting the development of IoS communications infrastructures which are faster, and safer with more predictable QoS guarantees. At the same time however, the data transmitted across these networks will become increasingly complex as 6G networks are expected to involve exceptionally complicated streams of highly dynamic and heterogeneous data, flowing across labyrinthine and dynamically changing network topologies, at the zettabyte scale [19]. The sheer mass and complexity of the data involved in 6G means it will be exceptionally difficult to represent and understand through the familiar dashboards and graphing methods used for 5G networks. Traditional 2D and 3D visual methods are largely thought to be inadequate for the 6G networks, but here again sonification techniques may provide an alternative approach.

B. Specific Challenge of IoS Sonification

As IoS sonification develops as a field, it will continue to differentiate itself as distinct from traditional methods in

network and IoT sonification. Initial research efforts have laid out the parameters of a Sonification-Enabled IoS network schema [3] wherein the data travelling across the network is primarily audio data or data that is somehow otherwise concerned with sound. In comparison to traditional IoT networks which transmit small packets of data on intermittent duty cycles, IoS networks require continual high-speed throughput of rich audio data to support their applications. While this presents challenges from resource and infrastructural points of view it also poses some interesting design challenges for IoS sonification. Specifically, how can sonification be used to represent audio and sound-related data? While the direct sonification of sound signals themselves may prove redundant in some cases, sonification can nonetheless prove effective for perceptualising task-relevant data extracted from audio signals as well as metrics associated with the encoding and transmission of sound data across a network. The advantage of on-device sonification running at the edge of an IoS network is that those stakeholders monitoring or carrying out tasks with the devices can access the data on the device via sonification. Thus, they can address problems in or related to the measured phenomenon as indicated in the sonification in which the sensor data is encoded. This differs from sonification at the application layer of a network, which is often geographically and temporally isolated from the site and timeframe in which the data was collected. Tasks at this level tend to focus instead on monitoring and analysis across subsets of interest determined from the aggregate of devices that compose the network edge. While individual sensor values are accessible at the application layer, it is important that devices also make their data available at the edge for contexts where stakeholders need to monitor and react to sensor values, logged or live, in real-time. The challenges and opportunities described here reveal research gaps which provide motivation for the taxonomy and roadmap developed in the subsequent sections. While sonification intelligibility has always been reliant on mapping design, IoS sonification is also susceptible to a wide range of network conditions which can shape and change perception and interpretation. On-device sonification requires sustained research attention as it is currently an underdeveloped topic though one with transformative implications for the IoS. IoS sonification must develop robust and reliable strategies to account for the wide range of heterogeneous data types that populate the IoS ecosystem. Drawing from this, interoperability will become critical to the successful deployment of sonification methods across IoS networks. Finally, IoS sonification requires new evaluation tools. Perceptual evaluation still remains paramount to understanding the final efficacy of a given design, but computational methods will be needed to address network performance, signal-level analysis, feature-space separability, quality of experience, and task-based validation questions. A taxonomy describing the IoS sonification design space and an associated roadmap for research in that space is required to help address these gaps.

IV. TAXONOMY OF IOS SONIFICATION

Walker and Nees [7] draw on earlier definitions of sonification by Kramer [20] and Hermann [21] to argue that sonification "seeks to translate relationships in data or information into sound(s) that exploit the auditory perceptual abilities of human beings such that the data relationships are comprehensible". While this definition also holds for

Type	Dimension	Justification	Example categories
1. Sonification Characteristics	Data Rendered	Defines the data sonified.	sensor data, network metadata, control data (OSC, MIDI, Serial), device data.
	1 Architectural Layer	Locates sonification within the layered IoS system architecture.	device layer, edge layer, application and services layer, multiple layers.
	1 Listening purpose	Specifies the intended function of listening.	monitoring, anomaly detection, situational awareness, decision support.
	1 Sonification strategy	Identifies the auditory-display technique used to render data.	parameter mapping, model-based sonification, auditory icons, soundscape sonification.
	1 Listeners and stakeholders	Identifies the intended listener and their listening requirements.	network engineers and administrators, performers, users, public stakeholders and audiences.
2. Design constraints	Perceptual constraints	Determines whether sonified information is detectable, discriminable, interpretable, and usable.	discriminability, temporal and timbral resolution, stream segregation, learnability.
	2 Temporal mode	Specifies the temporal relation between data generation and auditory display.	real-time, near-real-time, compressed retrospective, long-duration.
	2 Interaction mode	Describes the degree of listener agency in the sonification process.	passive monitoring, active querying, collaborative control, audience interaction.
	2 Network and QoS dependency	Captures the extent to which system performance depends on network conditions.	latency-sensitive, jitter-sensitive, loss-sensitive, connectivity-dependent, etc.
3. Field Development Dimensions	Evaluation mode	Identifies how system performance and listener interpretation are assessed.	QoS evaluation for network and audio applications, objective signal-level and feature space evaluation, perceptual and user evaluations.
	3 Intelligence and adaptivity	Captures the role of machine learning, prediction, and context-aware adaptation.	adaptive mapping, AI-assisted sonification, predictive sonification, context-aware mapping.
	3 Ethical and social context	Addresses the broader implications of sonification in public, networked, or data-sensitive contexts.	privacy, security, consent, accountability.
	3 Interoperability & standardisation	Determines whether systems can be reproduced, compared, integrated, and deployed across heterogeneous IoS infrastructures.	mapping-description formats, metadata standards, protocol compatibility, datasets, evaluation benchmarks.

Table 1: IoS Sonification Taxonomy

sonification in IoS environments [3], the taxonomic dimensions underpinning the definition must be expanded to account for IoS environments. Table 1 presents a taxonomy informed by a reading of foundational literature across auditory display [7], [20], [21], [22], IoS and IoS sonification [1], [3], network and IoT sonification [8], [9], [10], [12], [13], musical approaches [14], [15], [23] and key advances in design and evaluation [24], [25], [26], [27], [28], [29], [30], [31], [32], [33]. It is both descriptive and productive, being derived from existing systems with an eye towards guiding the design and implementation of future IoS sonification research.

The taxonomy treats musical and artistic practice as a concern across multiple taxonomic categories rather than consigning it to a single dimension and as such, a number of categories account for musical components alongside more general sonic ones. This is due to the fact that IoS networks support both musical and non-musical sonic processes. The taxonomic dimensions presented in Table 1 are organised into three core groups. The sonification classification dimensions specify what data is sonified, from where in the IoS network schema the sonified data is derived, what tasks or functions are supported by the sonification, the sonification mapping strategy at play and the listeners for whom the sonification solution is designed. The design constraint category considers the conditions and parameters that shape the design of a given solution accounting for perception, data temporality, interaction mode and networked QoS. These categories are critical to IoS sonification where the delivery of high-quality

real-time data streams across distributed network infrastructures is challenged, as previously noted, by technical issues like latency, jitter, packet loss, and the processing limitations of edge-devices. The final set of categories is concerned with dimensions necessary to the continued development of IoS sonification as a distinct research and technical programme. Modes of evaluation, adaptive and context-aware mappings, ethical, social and cultural dimensions, and questions of standards and interoperability provide an apparatus for benchmarking system performance, ensuring broad compatibility and ensuring ethical and sustainable approaches to research and development. This taxonomic framework represents a synthesis of empirical research, implemented systems and theoretical frameworks from across the auditory display, internet of sounds, and sound and music computing literature. Thus, the taxonomic dimensions are analytically constructed and not intended to be orthogonal or exhaustive. Rather, this analytical approach to taxonomy ensures that knowledge and results across these fields are incorporated into a common framework. Thus it provides a common set of dimensions for the description and comparative analysis of IoS sonification systems. For example, the network sonification system presented by Roddy and Bridges [11] can be characterised using the taxonomy. The Data Rendered consists of join requests, gateway states, MICs, SNR, spreading factor and RF and the Sonification Strategy involves parameter mapping with formant synthesis. The stated Listening Purpose is the monitoring of network activity to assess overall health by Listeners and Stakeholders

including network administrators in a real-time Temporal Mode. Network & QoS dependency provides another important category here as much of the sonified data represent the state and performance of the network in question.

V. THE IOS SONIFICATION ROADMAP

This section builds on the taxonomy presented in Table 1 which circumscribes a design space that is translated into actionable research priorities in the roadmap presented in Figure 1. The roadmap is intended to provide guidance for future IoS research and development across five interrelated domains.

A. Technical Infrastructure

The technical component of the roadmap is concerned with the technologies needed to enable a robust sonification-enabled IoS ecosystem. It explores the infrastructures, architectures, data specifications, and computing methods required for this task, building on the Data Rendered, Architectural Layer, Network & QoS Dependency, along with elements of Temporal Mode and Interaction Mode. IoS sonification has been successfully applied across device and network levels to sonify a range of relevant data. These implementations have involved a diverse variety of architectures, data types, sound synthesis methods, use cases and deployed listening conditions. To this end Roddy [3] provides a generalised schema for sonification-enabled IoS networks. Future work should extend this schema and develop additional reference architectures to account for an expanded set of IoS sonification use cases beyond this initial network and device-level components.

A key technical challenge is the development of a common scheme of representation between broadly heterogeneous and seemingly incompatible data types. For example, sensor data, network traffic data, audio information, device state data, and user interaction data are not necessarily commensurate. While a wealth of previous auditory display research has attempted to develop systematic standards for data-to-sound mapping strategies this has proved to be a substantial challenge (as explored below). However, sonification research has instead produced a common set of design principles [27], [28], [29], [30] and best practices for implementation and evaluation over imposing a strict universal mapping scheme. Drawing from this IoS sonification research should seek to develop and make explicit a common set of design guidelines and best practices for both implementation and evaluation that account for the unique relations between specific data types, sonification tasks and listening conditions.

IoS sonification differs from standard approaches in that it will, in many contexts, depend on real-time data flows across networked infrastructures, the performance of which will have a direct impact on the final quality of the sonification experience. As such, questions of QoS become critical when designing IoS sonification. In such a configuration, the intelligibility of a sonification becomes a factor of upstream network dynamics like latency, jitter, packet loss, bandwidth variation, buffering, clock drift, and edge-processing delays. As such future work should explore strategies for adapting sonification solutions to changeable underlying network conditions so that changes in those conditions which produce audible impacts on a sonification are not mistaken for changes in the given data source being sonified. Further, strategies

should be developed to ensure sonified data and signal impacts remain differentiable to a listener in contexts where signal impacts are unavoidable.

Another priority is the development of lightweight sonification strategies for edge-level devices. While the sonification-enabled IoS network schema supports sonification at the application layer with streaming to edge devices, it also supports on-device sonification for contexts where there are latency, privacy, energy, connectivity, or reliability constraints as well as contexts in which the edge device is implicated in some task for which sonification can provide support and enhancements. As such future work should explore the production of the aforementioned synthesis techniques as well as efficient mapping functions, adaptive buffering strategies, and resource-aware audio signal processing and feature extraction pipelines for the low-resource environments of embedded devices. Finally, given that IoS sonification is susceptible to changeable network conditions, as discussed previously, adaptive and intelligent approaches to mapping data to sound are needed to ensure robust and reliable performance. Moreover, as IoS infrastructures continue to complexify, rich streams of dynamic high-throughput multivariate data may become increasingly difficult to account for with the kinds of fixed mapping strategies that have tended to define offline modes of sonification. Context-aware mapping strategies informed by machine-learning-driven predictive modelling and anomaly detection algorithms will become increasingly useful for rendering critical data relations salient and detectable even under sub-optimal network conditions. Care will need to be taken in the design of these adaptive mapping strategies to ensure that they remain representative of the data and clearly legible to a listener even as they reconfigure themselves to account for complex data and network conditions. As such, research must examine the trade-offs between mapping strategy adaptivity on the one hand and questions of perceptual discriminability and learnability on the other. To that end recent developments in what is being termed AI-assisted sonification apply machine learning techniques to identify relevant data in a complex multivariate EEG stream and then apply sonification techniques to represent that data sonically [33], [34]. Thus, decisions about how the data should be interpreted ultimately reside with the listener.

B. Design and Evaluation

Given the nature of the field, standard engineering design approaches spanning media, communications, and systems engineering are critically important to the development of IoS applications as demonstrated repeatedly across the literature [1], [35]. The application of theories and frameworks from design research [36] to sonification has produced a number of critically important innovations for the field [28]. These methods are of particular importance in an IoS context where these research methods have the potential to support the development of effective implementations. The taxonomic dimensions involved here are Data Rendered, Listening Purpose, Sonification Strategy, Listeners and Stakeholders, Temporal Mode, Interaction Mode, Perceptual Constraints, Intelligence and Adaptivity, and Evaluation Mode. Future research should explore the validation of design methods that translate these taxonomic dimensions into effective IoS

Evaluation category	Example Evaluation Questions	Example methods	Example measures and metrics
QoS & system performance	Does the infrastructure deliver data or audio reliably and on time?	Network testing, logging, profiling and audio pipeline testing.	Latency, jitter, packet loss, synchronisation, dropouts, buffering, CPU load and energy usage.
Objective signal-level evaluation	What measurable acoustic structures are present in the signal?	Computational audio analysis methods (e.g. feature extraction and analysis), time-series analysis, frequency spectrum and quefrency cepstrum analysis.	Spectral centroid, spectral flux, RMS energy, MFCCs.
Objective feature-space evaluation	Are sonified data classes, events, or network states acoustically separable?	Dimensionality reduction, cluster analysis, classification and visualisation.	Class separation, separation ratio, silhouette scores, classification accuracy, confusion matrices.
Perceptual evaluation and QoE	Can listeners detect, discriminate, and interpret sonified structures?	Listening tests, perceptual and psychoacoustic evaluations, audibility testing.	Thresholds, discrimination accuracy, response times, subjective quality ratings.
Expert listening and aesthetic evaluation	Do trained listeners judge the system as coherent, meaningful, expressive, or diagnostically useful?	Expert review, diagnostic review, practitioner review, stakeholder review, comparative listening, thematic analysis.	Expert and diagnostic ratings, stakeholder and practitioner feedback, identification of recurring themes in feedback, design recommendations.
Task-based and user evaluation	Does the sonification support the intended real-world task?	User and usability testing, task-based evaluations, user preference studies, field and longitudinal studies.	Task performance, response time, preference ratings, usability scores, cognitive load.

Table 2: Evaluation Methods

sonification systems. Perceptual constraints are particularly relevant here as dense and perceptually complex IoS sonifications will need careful design to ensure that concurrently presented data streams remain intelligible. The principles of perceptual organisation and stream segregation outlined in Bregman's ASA [37] remain relevant in this regard. Sonification takes place within diverse and complex network environments to which evaluation methods must be sensitive. As such, the entire toolbox of evaluation methods developed across more than 30 years of sonification research is relevant and accessible when validating IoS-based designs. However, the IoS environment calls for the introduction of evaluation methods that are less used in sonification. Table 2 represents a tiered evaluation framework for IoS sonification starting from network-level QoS and system performance and working up towards task-based and user-based evaluations. It is not intended for use with every implementation but rather presents a framework from which the appropriate modes of evaluation might be selected to answer design questions similar to the examples provided. The table includes a number of evaluation methods that are less explored in sonification research but become critical when we are evaluating sonification delivery and performance across IoS networks. These involve methods for quantifying QoS and system performance that are important for measuring the operation of sonification in real-time networked environments. As IoS research continues to develop, approaches such as these should guide the application and development of reusable

evaluation protocols and benchmarks that allow for comparison of IoS sonification systems across a wide range of tasks, applications and deployment contexts.

C. Creative, Musical & Artistic Practice

The relevant taxonomic dimensions for Creative, Musical & Artistic Practice include Data Rendered, Architectural Layer, Listening Purpose, Sonification Strategy, Listeners and Stakeholders, Perceptual Constraints, Temporal Mode, and Interaction Mode. Sonification and music have always had a complex relationship with much debate surrounding where the boundaries between the fields might be drawn. This is explored in depth by Supper [38] who identifies two distinct cultures of evaluation at play in sonification research, one grounded in the evaluative methods of psychology, computer science and engineering and a second that relies on expert listening and aesthetic practices. Scaletti [39] argues that sonification alone does not constitute musical composition although musical elements may be integrated into sonification and vice-versa. Nonetheless there has been a long history of composers embracing sonification in their practices dating back to Charles Dodge's sonification of the earth's magnetic field for Nonesuch Records in 1970 [40]. Similarly, sonification researchers have been exploring the application of aesthetic strategies to design more effective and convincing sonification systems [41], [42] with recent research focusing on IoS sonification [3]. Thus the

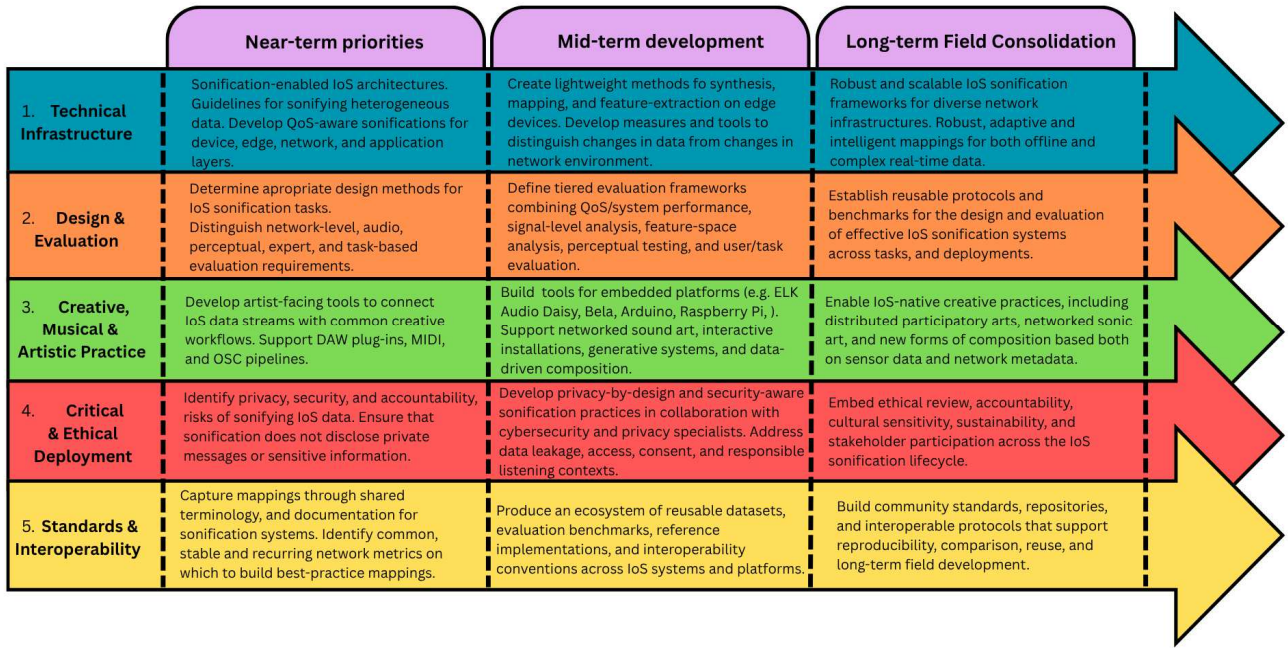


Figure 1: The IoS Sonification Roadmap

relationship between sonification and music has historically been both entangled and contested. IoS sonification, however, proves a particularly interesting case in which the dynamics of this relationship are transformed.

The IoS is often directly concerned with music and music-related data, at the levels of listening, performance and production, with, for example, networked musical performance (NMP) [43], distributed real-time audio streaming and interactive audio installations and experiences providing novel contexts in which the relationship between sonification and music is enriched. Sonification can be directly incorporated into this ecosystem where it can be applied across these sonic practices. Simply put sonification-enabled IoS network infrastructures can provide key infrastructural components for the realisation of a given creative or artistic work. This can happen in one of two ways. Sensors attached to sound things can collect and sonify data of interest to a given creative work. These could be environmental sounds collected by a wireless acoustic sensing network for example. Sound things can also collect data to be sonified elsewhere, by other sound things or at the application layer on network servers. In the second case, metrics associated with the data flowing across the network can also be sonified thus becoming the object of a given artistic work. Both of these contexts, the sonification of sensor data and the sonification of network traffic data have implications for creative practice, opening new possibilities for data-driven music composition, generative music, networked sound art, and distributed participatory arts practices. The development of tools to support artists in exploring IoS sonification is a key roadmap priority. Ideally such tools would sit comfortably within artists' creative workflows bridging IoS ecosystems with the tools and instruments with which artists have already developed advanced fluencies. At the software level DAW-based plugins and extensions that bring IoS data streams into applications like Ableton Live, Logic Pro and Pro Tools represent an immediate priority. Such pipelines should

support common creative protocols like MIDI and OSC to ensure compatibility.

At the embedded-hardware level hardware designs, libraries and codebases are needed to extend the capabilities of music systems built on platforms like the Daisy Seed and Bela board, embedded audio environments like Elk Audio OS, and more traditional microcontrollers and microcomputers in the Arduino and Raspberry Pi ranges. These embedded systems need to support sensing, data processing, mapping, sound synthesis, and network communication in resource-constrained environments. The aim here is to empower artists to work across IoS edge and application layers using workflows and techniques with which they are already comfortable, thus allowing them to exploit the full advantage of their existing expertise. This in turn supports artistic experimentation and opens the potential for the development of new forms of networked sonic art.

D. Critical & Ethical Deployment

While broader questions of ethics have been discussed as they relate to the IoS [44], there are a number of critical and ethical issues to be taken into account in a sonification design context. Critical & Ethical Deployment draws heavily from the related taxonomic dimension Ethical & Social Context but is linked to all of the taxonomic dimensions. Care needs to be taken in the design of sonification strategies to ensure that message privacy is maintained. Sonification should not reveal any information that was intended to represent private communications between a sender and receiver. Similarly, sonification techniques should not reveal information that would degrade the security of a given network, leaving it open to attack or capture by hostile actors. In contexts where payload data remains confidential, there is still scope for sonified network data (SNR, RSSI, packet loss, etc.) to reveal sensitive information to an assailant. Questions of accountability and transparency are important from an ethical point of view and can help determine a framework in which the standards and protocols discussed in the next roadmap

section might operate. Sonification designs must be documented and explained so that designers and users understand what data is involved, what data is omitted, how mappings operate and the original purpose for which a sonification is designed.

While IoS sonification inherits security and privacy risks associated with networked communications more generally, new risks are introduced when data that might otherwise remain obscure is perceptualised through sonification. In cases where message payloads are private and secure, sonified metadata (e.g. SNR, RSSI, RF, etc.) could potentially reveal sensitive information to hostile actors [45]. Researchers and developers working in IoS sonification must adopt a privacy-by-design approach [46], collaborating with cybersecurity and privacy specialists to ensure safe, secure and private IoS sonification applications. An underexplored yet increasingly valuable aspect of sonification is its ability to reveal the social and cultural dynamics of the complex technosocial systems that increasingly shape and define modern life. The burgeoning IoS ecosystem represents one of many such systems being an ecology of complex network communications infrastructures designed to support a wide range of human activities concerned with listening and sound-making. By rendering the often-opaque interactions between these systems and their stakeholders acoustically legible, an opportunity is created for those stakeholders to better understand their relationships to, and positions within these systems. From there they can begin to consider alternative potential system designs that might produce relationships better suited to their own personal goals as well as societal and cultural needs.

E. Standards & Interoperability

The Standards & Interoperability component draws primarily on the related taxonomic dimension but necessarily involves elements of all taxonomic dimensions. The development of standard and agreed-upon protocols for sonification is a complex issue that provides a common focus of research efforts across the literature [20], [47], [48], [49]. It is a challenge to prescribe a single unique data-to-sound mapping strategy for a given data type due to the myriad perceptual [7], [27], [49], [50] and cognitive factors [51] which can reframe a listener's interpretation of a given sonification on the basis of highly variable factors including the task for which the data is sonified [52], the metaphors involved in the mapping [41], [52], [53], [54], listening context [29], and even cultural factors [55]. However, in network monitoring contexts certain metrics remain quite semantically stable. For example, at the transport layer of the standard OSI (Open Systems Interconnection) model [56] a range of IoS applications might rely on UDP to overcome the delay overheads associated with TCP [1]. Low and variable signal-to-noise ratios (SNR) at the physical layer can contribute to packet loss and increased jitter at the transport level. These are factors that greatly impact QoS, making the SNR of a given message a good candidate for monitoring in network sonification contexts where QoS and network 'health' are paramount. SNR can be treated as a form of 'metadata' that describes how well a given message payload has been received and as such the semantic meaning of the metric is somewhat stable. The contents of the message payload can change, but the 'meaning' of the SNR remains consistent. This is also true of other network and media-

delivery metrics such as RSSI, packet loss, burst loss, latency, jitter, buffer underruns, dropped frames, clock drift, codec delay, packet-loss-concealment events, MIC, SF, and RF. While it is difficult to standardise sonification mapping strategies more generally, it may be possible to produce best-practice mappings for network metrics whose semantic dimensions are technically defined and remain somewhat consistent across contexts. This stability of meaning will not hold across all metrics, however. For more context-sensitive data, future work will need to develop shared resources and documentation that support appropriate mapping strategies for well-specified tasks and data sources. To eventually enable the development of useful community standards, repositories, and interoperable protocols, a foundation of well-documented and reusable mapping strategies, datasets, reference implementations, and interoperability conventions must first be established.

VI. DISCUSSION AND CONCLUSION

As evidenced in the taxonomy and roadmap outlined here, IoS sonification constitutes a unique and distinct research concern that, while deeply linked to contemporary auditory display and IoT sonification research, differs with a significance that suggests that it represents more than a simple extension of either field. This is mainly due to the entangled and complex nature of the relationships between sound, data and network infrastructure and how these relationships in turn influence listening and analysis. For example, conventional questions of sonification intelligibility are complicated by factors like network performance and the lines drawn between sonification and music become somewhat obscured when the data to be sonified is itself musical. The taxonomy put forward here aims to provide some guidance and structure for approaching IoS sonification design by making explicit some of the factors constraining design decisions. The roadmap is intended to complement this by translating the taxonomy into an initial map of key areas where focus is needed to support the development of this unique strand of research. All of the roadmap components presented here have some form of relationship to one another. For example, technical performance is not easily separated from perceptual intelligibility as issues like jitter and packet loss will manifest in the heard sonification thus impacting its interpretation. Thus, the technical and design and evaluation components are linked. Creative and artistic applications also depend on the development of usable tools built with standardisation and interoperability at their core. Ethical concerns permeate each layer of the roadmap and are only grouped here under one heading to ensure that they are represented prominently. These ethical concerns become a critical interest in scenarios where sonification might reveal sensitive information. Given the complex nature of the research strand, standardisation efforts must focus less on producing universal mappings and more on the production of best practices that remain flexible and context-sensitive.

In conclusion, the framework outlined here should be read as provisional and open to adaptation, extension and eventually transformation. IoS sonification is still a novel contemporary practice that will evolve and grow as the IoS itself matures. As this process unfolds, taxonomic dimensions and roadmap priorities will invariably shift and develop. Further work is needed to understand the framework as it

relates to the growing diversity of contexts in which IoT systems are embedded. As such, the taxonomy and roadmap provide a starting point for further development and discussion as opposed to a prescriptive instrument.

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