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A Quantum-Classical Network for Beat-Making Performance

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Abstract

In recent years, quantum computing has emerged as the next frontier in computational and information technologies. Even though it has found potential applications in solving complex problems in fields such as chemistry, machine learning, and cryptography, among other fields, there has been little research conducted on its applications for music and acoustic technologies. This paper will discuss the use of a quantum internet protocol in the context of networked music performance in which quantum computing could play a role in processing musical data via a cloud-based music software application. We also propose an example model for a beat-making performance network using a smart music playlist application deployed on a simulated quantum internet. In the proposed system design and architecture, several beat-makers located remotely from each other are connected live over a simulated quantum internet in a distributed networked music performance. Each beat-maker node transmits and receives audio sample time slices of beat patterns from one another to use in their local performances. This model provides a proof of concept for implementing quantum algorithms, standards, and protocols in music software and network applications when a quantum internet becomes available.

Introduction

Quantum computing is a probabilistic means of computation that uses the properties of quantum mechanics. Instead of a classical bit that can be in either the state of "0" or "1," its quantum counterpart, the qubit, can be in either state or a superposition of both "0" and "1." Another special property quantum computers make use of is "entanglement," a term which defines the state of two or more qubits wherein the state of each qubit cannot be described independent from its

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"entangled" partners.[3] This makes it so that measuring one of the entangled qubits will instantaneously give information about the state of the other qubit(s), regardless of location and distance between them. Quantum internet, as an exploration of a quantum network for the purpose of communication, makes use of these characteristics of quantum computing to both enforce security and speed of transmission of information.

As exciting as the quantum internet may seem, there are still no viable predictions for when such technology might be readily available. That being said, we would like to speculate on the type of implications such an infrastructure could have for music performance, and in particular networked music performance (NMP). For the purposes of this paper we will consider NMP as the performance practice where musicians connect over a local (LAN) or wide area network (WAN). The transmission and reception of information in such scenarios are mostly limited by the network adapter card in each computer, or the type of service provided by the contracted ISP in the case of telematics. However, in current quantum computing systems (and quite possibly for the first generation of quantum internet services that will be available), the amount of information exchanged is severely limited in comparison with the classical counterpart—though at much superior speeds.

Quite possibly as well, by the time quantum internet starts to become a reality, single quantum computers will have evolved to contain higher qubit counts, and fields such as quantum machine learning will be more well established. Given these considerations, the following sections of this article will further explore a possible scenario for NMP where a trio of beat-makers are connected via a quantum internet, exchanging a very limited amount of information (in a decentralized peer-to-peer fashion), while also connected to a central server (in a centralized client-server fashion).[4] This network architecture receives and processes information from the general audience listening to the streams from the aforementioned performers. This is a similar architecture to the mesh network implemented by Ben Freeth, John Bowers, and Bennett Hogg.[5] Our hope is that this proposal will be a good first step towards using and thinking about a quantum internet in music performance. The information exchanged by the beat-makers is composed of the track and beat location used by the other performer(s). In this way, and given the specifics about the technical implementation discussed in the "System Design and Network Architecture" section of this article, we

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[3] Abraham Asfaw et al., *Learn Quantum Computation Using Qiskit*, 2020, Section 2.2 Multiple Qubits and Entangled States, https://github.com/qiskit-community/qiskit-textbook/blob/master/content/qiskit-textbook.bib.

[4] For an overview of terminology, see Grove Music Online, s.v. "Beat-making," by Oliver Wang, accessed June 12, 2020, https://doi.org/10.1093/gmo/9781561592630.article.A2218626; Cristina Rottondi et al., "An Overview on Networked Music Performance Technologies," *IEEE Access* 4 (December 2016): 8823–8843, https://doi.org/10.1109/ACCESS.2016.2628440; and Gil Weinberg, "Interconnected Musical Networks: Toward a Theoretical Framework," *Computer Music Journal* 29, no. 2 (June 2005): 23–39, https://doi.org/10.1162/0148926054094350.

[5] Ben Freeth et al., "Musical Meshworks: From Networked Performance to Cultures of Exchange," in *DIS '14: Proceedings of the 2014 Conference on Designing Interactive Systems* (Vancouver, BC, Canada: Association for Computing Machinery, 2014), 219–228, https://doi.org/10.1145/2598510.2598583.

are suggesting a future practice that is both connected to culturally rooted traditions, such as crate digging, and expanding on networked music performance.[6]

Limitations and Challenges of a Quantum Network

Before diving into a discussion of our proposed model, specific concepts need to be addressed in order to understand the fundamentals of the quantum network. In order to make use of the instantaneous transmission of information offered by entanglement, qubits need to be entangled first, prior to the second step of being "moved" to different locations. However, due to the short life span of the qubit's state, even sending it over short distances becomes challenging. Current research specifies the use of devices such as quantum repeaters to mitigate this issue.[7] The details of such hardware is outside the scope of this paper.

It is also important to note that near-term quantum computers have a fairly limited qubit count. This, in addition to other current limitations of quantum hardware, makes representing uncompressed information, such as audio, in quantum computing extremely difficult. Given the unavailability and complexity of such infrastructure, we relied on simulated quantum internet networks to experiment with our proposed ideas. At the same time, the limitations mentioned in this section also encouraged us to take a green technology approach: transmitting less information between the performers and reducing the bandwidth of the network channels.

System Design and Network Architecture

Our proposed network architecture includes a combination of quantum and classical networks. It defines two types of participant nodes: performer nodes and audience nodes. Each performer node consists of one beat-maker (BM) creating electronic beats in real time using audio samples from playlists generated by the cloud server (for a complete overview of this network architecture, see fig. 1). In fact, the majority of this architecture is composed of two overlapping networks: (1) a classical centralized network between audience members, the cloud, and the performers, and (2) a quantum de-centralized network between the performers only. This hybrid topology is similar to the mesh network specified by Freeth, Bowers, and Hogg, where audience and performer nodes are organized in layered groups.[8] Depending on the layer, they are either connected to other

[6] See Grove Music Online, s.v. "Beat-making," https://doi.org/10.1093/gmo/9781561592630.article.A2218626.

[7] See Axel Dahlberg, et al., "A Link Layer Protocol for Quantum Networks," in *SIGCOMM '19: Proceedings of the ACM Special Interest Group on Data Communication* (Beijing, China: Association for Computing Machinery, 2019), 159–173, https://doi.org/10.1145/3341302.3342070.

[8] Freeth et al., "Musical Meshworks: From Networked Performance to Cultures of Exchange," 219–228, https://doi.org/10.1145/2598510.2598583.

performer nodes with a lower layer assignment in a centralized architecture, or in a decentralized fashion with other performer nodes.

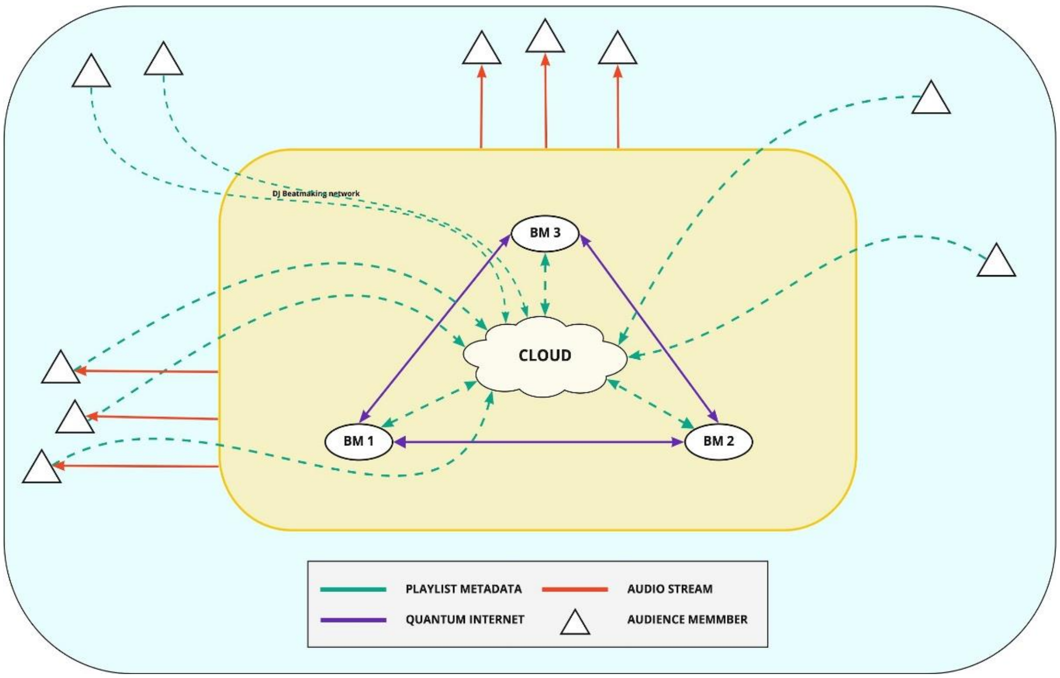

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Figure 1. Complete network architecture

The communication between these performer nodes and the cloud server is established over a classical network in which playlist metadata is transferred from audience nodes to the cloud and then to the performer nodes. Within the cloud server, playlists are generated using a hybrid quantum-classical neural network, making use of a new emerging field within quantum computing itself, known as quantum machine learning (QML).[9] In general, QML replaces one or more of the hidden layers of the neural network with quantum circuits, each consisting of a single qubit prepared in a state of superposition and a rotational unitary gate. This allows for many different layers of neural networks to be executed simultaneously, resulting in a drastic speed up in computation time.[10] In this architecture, more metadata of musical features (i.e., time signature, tempo, beat

[9] For more on hybrid quantum-classical neural networks and quantum machine learning (QML), see Asfaw et al, *Learn Quantum Computation Using Qiskit*, 2020, Section 4.15 Hybrid Quantum-Classical Neural Networks with PyTorch and Qiskit.

[10] For more on quantum neural networks and computation time, see Alexandr A. Ezhov and Dan Ventura, "Quantum Neural Networks," in *Future Directions for Intelligent Systems and Information Sciences: The Future of Speech and Image*

tracking, and key signature) from the audience and performers' music playlists can be sent to the cloud server to generate new playlists without a significant increase in processing time.

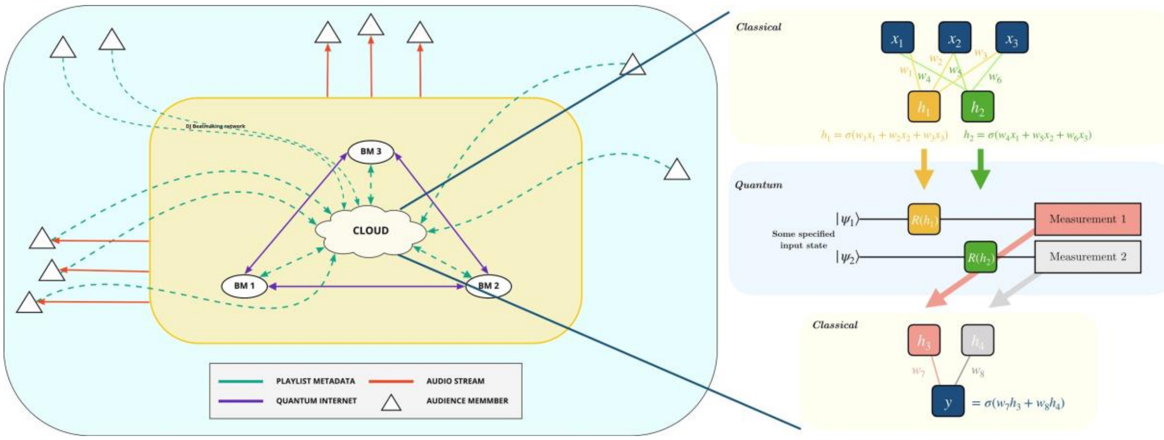

Figure 2. Architecture with QML neural networks (Adapted from Asfaw et al., *Learn Quantum Computation Using Qiskit*, 2020, Section 4.1.5 Hybrid Quantum-Classical Neural Networks with PyTorch and Qiskit)

Once the cloud server has determined the final playlist based on the metadata aggregated from the classical network, it then sends the generated playlist to each of the performer nodes (BM 1, BM 2, and BM 3). After this process has completed, each BM begins to initialize communication over the quantum network.

The Performer Quantum Network

The quantum network itself consists of both quantum and classical channels in order to execute a protocol known as teleportation. Teleportation transfers the quantum state of one qubit to another via several entanglement stages. One must keep in mind that this protocol does not copy the state of one qubit to another but transfers it. It is not possible to copy a qubit state according to the "No Cloning" Theorem.[11] However, teleportation between distant nodes does not work if quantum channels are used alone. Before teleportation can be performed, BM 1, BM 2, and BM 3 must first entangle either pairs of qubits or a quantum register between them. This will be done by

Technologies, Brain Computers, WWW, and Bioinformatics, ed. Nikola Kasabov (Heidelberg: Physica-Verlag HD, 2000), 213–235.

[11] On the "No Cloning" Theorem, see Michael A. Nielsen and Isaac L. Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition* (Cambridge: Cambridge University Press, 2010), 427.

creating a bell pair between a set of two qubits at one of the performer nodes, and then sending each of the entangled qubits to the two nodes that want to connect. For example, BM 1 entangles a pair of qubits and then sends one qubit to BM 2 and the other BM 3 via the quantum channels. This creates a quantum link between BM 2 and BM 3. From here, if BM 2 wants to send a message to BM 3, BM 2 would need to execute the teleportation protocol, transferring the state of the qubit containing the message to the entangled pair. Figure 3 shows the quantum circuit of the teleportation protocol transferring the state of qubit $q4_0$ to qubit $q4_2$. Notice that after the two bell pairs, that are created between the $q4_0$ and $q4_1$, two measurements occur. The results of these intermediate measurements are then used as flag signals to trigger gates on $q4_2$, thereby finalizing the transfer of the qubit state. The final two gates in this circuit put the qubit in the correct basis so that accurate measurements can be taken of $q4_2$.

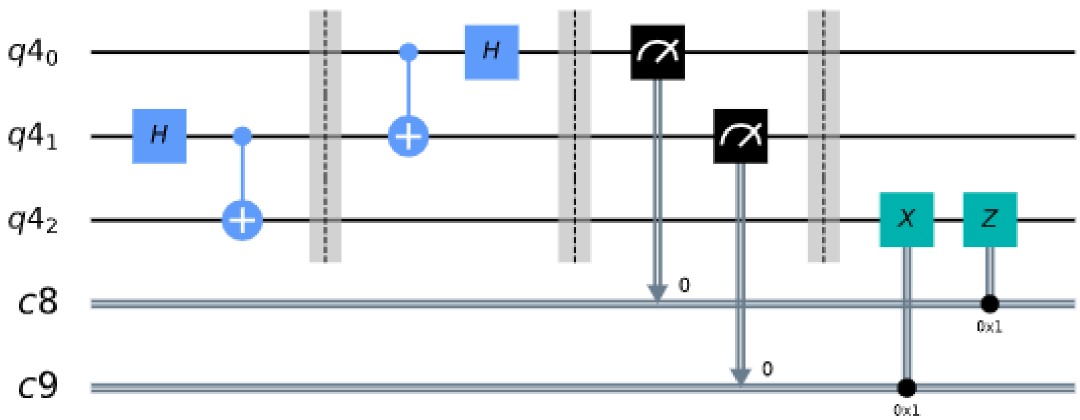

Figure 3: Teleportation quantum circuit (Adapted from Asfaw et al., *Learn Quantum Computation Using Qiskit*, 2020, Section 3.2 Quantum Teleportation)

In terms of our architecture, qubit $q4_2$ would represent the entangled pair of qubits between the communicating BM nodes. The gates within the first three sections (separated by the barriers in fig. 3) would be on the transmitting node, while the gates after the third barrier would be on the receiving node. Going from section 3 to 4 on qubit $q4_2$ implies information travelling through the quantum channel. The measurements stored in the classical registers would be sent through classical channels to flag the X and Z gates on the receiving node.

In many real-time distributed network performances, it is common to send and receive uncompressed audio data. However, due to the current limitation of quantum hardware, representing raw audio data in real-time on a real quantum device is very difficult. Researchers have attempted to develop quantum representations of digital audio signals, but with the current state of this technology, these implementations prove to be less than ideal for NMP applications.[12] Even though the concepts of entanglement and teleportation of quantum states allow for instantaneous transmission of quantum information, the generation of a probability distribution of the desired result requires a large number of measurements. Thus, latencies due to these measurements are introduced and, for the time being, real-time transmission of audio data will not be a good use case for illustrating the unique advantages of quantum devices and networks within a telematic music environment. As a result, the architecture described thus far is intended to be used with information requiring a lower resolution, such as cues from beat-making practices, to illustrate how the unique properties of a quantum network could be used. BM nodes will transmit and receive audio sample slicing information of beat patterns from one another to use locally in their live beat-making. Within the quantum network we propose and compare two possible implementations of existing algorithms to transmit and receive musical data across the quantum network.

Quantum Phase Estimation as Means for Encoding Musical Information

One immediate issue that arises when thinking about this scheme is that in order to receive the correct information from the transmitting node(s) many measurements on the entangled qubit(s) need to be performed. However, once we measure the qubit on each side, the quantum state collapses into either "0" or "1"—thus the entanglement and teleportation processes between the nodes need to be repeated. The solution that we propose is the use of the quantum phase estimation algorithm. Instead of directly teleporting the quantum state of the qubits on the transmitting side, the phase information of the rotational unitary gates being applied to the ancillary qubit(s) will be teleported to the receiving BM node. This algorithm makes use of two qubit registers. The first register consists of control qubits (see q0, q1 and q2 in fig. 4) for U-gates being applied to target qubit(s) in the second register (q3 in fig. 4).[13] The first stage entails putting the first qubit register into a state of equal superposition (50% chance of measuring a "0," 50% chance of measuring a "1"). This is done by applying a Hadamard gate (H) to each qubit in the register. These U-gates being applied on the qubits in the second register cause phase kickback, thus causing phase information of the gates to be encoded in the qubits of the first register in the Fourier basis ($|+\rangle$ or $|-\rangle$). The next step is to then to apply the inverse quantum Fourier transform ($QFT^\dagger$) in order to bring the first register qubits back into the computational basis ($|0\rangle$ or $|1\rangle$) for measurement. In

[12] Fei Yan et al., "Flexible Representation and Manipulation of Audio Signals on Quantum Computers," *Theoretical Computer Science* 752 (2018): 71–85, http://dx.doi.org/10.1016/j.tcs.2017.12.025; and Jian Wang, "QRDA: Quantum Representation of Digital Audio," *International Journal of Theoretical Physics* 55, no. 3 (2016): 1622–1641.

[13] Asfaw et al., *Learn Quantum Computation Using Qiskit*, 2020, Section 3.8 Quantum Phase Estimation; Nielsen and Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition*, 2010.

this case, we insert the teleportation process between the $\text{QFT}^\dagger$ and measurement stages. For example, in figure 4, BM 1 encodes the sample slicing times within the combined phase shift being applied to the qubits in its second register through stages 1 and 2 of the algorithm. The phase being applied by these gates causes a phase kickback, which is then written to the qubits in the first register. Once we have encoded the message to be transmitted, we then teleport the state to the receiving entangled qubits at BM 2 and 3. Once this process is complete, BM 2 and 3 will only have to execute one measurement to obtain the original message from BM 1.

Figure 4: Phase estimation circuit source (Adapted from Asfaw et al., *Learn Quantum Computation Using Qiskit*, 2020, Section 3.8 Quantum Phase Estimation)

Ping-Pong Teleportation

The encoding of audio sample time slices within the phase of the qubits is an efficient method of transmission between communicating BM nodes on the quantum network, since it avoids the execution of many measurements on the quantum register. However, the higher the desired time-step resolution, the more qubits are needed. This is similar to the "6 dB rule" in quantization for digital audio signals, in that each additional bit increases the resolution by 6 dB.[14] In this case, for each additional qubit the phase rotation resolution will increase, such that for n qubits the phase rotation resolution will be $\frac{\pi}{2^{n-1}}$.

As a result, we propose a variant of the teleportation protocol called *ping-pong teleportation*, which allows for an efficient method of encoding more information without having a large increase in the qubit count. This is a crude method to compensate for the limitations of the quantum network for NMP applications, but it acts as a temporary quantum memory of the incoming quantum information on the receiving node. At its core, this algorithm is just a looped and mirrored version of the teleportation protocol performed locally. It makes use of the *deferred measurement*

[14] Marina Bosi and Richard E. Goldberg, "Chapter 2: Quantization," in *Introduction to Digital Audio Coding and Standards* (New York: Springer Science & Business Media, 2012), 13–46.

principle, delaying the measurement of the transferred state until the end of the circuit iteration.[15] In doing this, we can teleport the state of the received qubit from the transmitting node to another qubit locally, without intermediate measurements. This will allow us to have two qubits in the same quantum state (see section 1 and 2 of fig. 5). After this, a measurement is performed on the original qubit, $q9_0$, and is recorded for the probability distribution in the classical register c28, which is then used to trigger the X gate on $q9_0$ to reset it back to ground state ($|0\rangle$). The same process is conducted for $q9_1$. After this, the received state is now held by $q9_2$ and can be teleported back to $q9_0$ using the same process. This can be repeated for many iterations, transferring the received state from $q9_0$ to $q9_2$, and then from $q9_2$ back to $q9_0$. Due to the placements of the measurements, this circuit can generate a probability distribution without having to repeat the entanglement process between BM nodes.

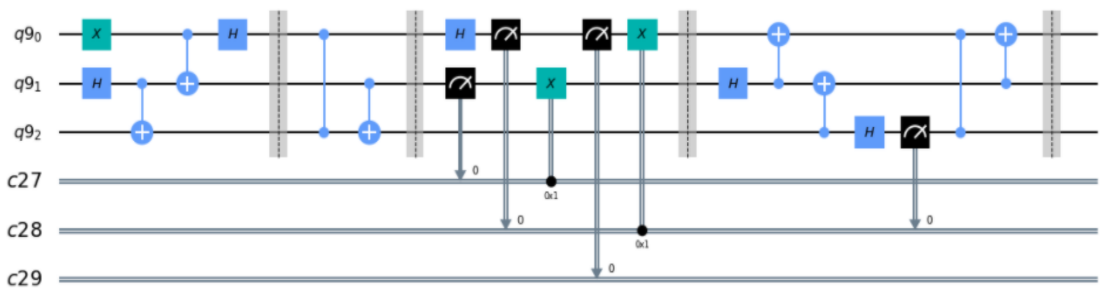

Figure 5: Ping-pong teleportation circuit

As a result, information can be encoded within the quantum state of the qubits themselves which can be sent instantaneously. The shape of the probability distribution from the transmission qubits, when measured, could represent the desired messages and information encoded directly within it. In comparison with phase estimation, this provides a more flexible and robust way of encoding information into a quantum state. However, there is a trade-off between the two methods in that phase estimation can be decoded with higher accuracy while the probability distribution generated on the receiving node, via *ping-pong teleportation*, produces more errors due to the noise introduced by the qubits. Quantum error correction could potentially be used to filter out the noise.[16]

[15] On the deferred measurement principle, see Asfaw et al., *Learn Quantum Computation Using Qiskit*, 2020, Section 3.2 Quantum Teleportation; Nielsen and Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition*, 2010, 186.

[16] For more on quantum error correction, see Asfaw et al., *Learn Quantum Computation Using Qiskit*, 2020, Section 5. Investigating Quantum Hardware Using Quantum Circuits.

Dynamics of a Networked Beat-Making Performance

The proposed system enhances and is inspired by the social dynamics that are found in current music distribution and consumption practices. Streaming services are unavoidable in the way people consume and discover new music nowadays. More often than not, these services are constantly producing metadata and processing it for the purpose of creating suggested playlists.[17] Thus, our proposed system includes the audience—however asynchronous—as an active participant, with their individual playlists being processed by the central cloud server. The quantum beat-maker network mimics what could be the in-person practice of sharing samples and beats, with the added sense of simultaneity for this often individual creative performance practice. This poses an alternative to the production-line paradigm that is often found in such collaborative beat-making practices. As it stands, the proposed architecture still supports simultaneous independent performances that can be streamed back to the outside world. Furthermore, the way in which these two networks articulate within our architecture creates a feedback loop. This is a loop in which the goal is not to encourage competition among the beat-makers, for they are "entangled," but to reinforce the contributions of the creative input of each performer. Another perspective into this architecture reveals an advantage of implementing an NMP approach, that places the beat-makers into separate physical spaces. Even though performers are creating "entangled beats," using shared audio sample time slices, the fact that they don't directly hear each other and only share limited musical information still allows each performer to not be directly influenced or conditioned on their own creative approach.

Conclusion and Summary

This paper has discussed the technological benefits and performance dynamics of a hybrid quantum-classical network architecture for a networked beat-making performance. We outlined the implementation of a quantum network using entanglement and teleportation protocols, along with a discussion of two information encoding schemes using basic quantum algorithms. QML concepts, such as a hybrid quantum-classical neural network, were also considered as a potential method for leveraging computational speed-up for processing music metadata within this architecture. We consider that the proposed model for a beat-making performance network relying on a quantum internet provides a great opportunity to rethink current practices through exploring new and emergent technologies. Given the unavailability of a real quantum-internet

[17] Benjamin Fields, "Contextualize Your Listening: The Playlist as Recommendation Engine" (PhD diss., Goldsmiths, University of London, 2011), http://research.gold.ac.uk/id/eprint/6477.

infrastructure at the time of writing of this paper, future work will necessarily include the implementation of our proposed architecture when a quantum internet becomes available. Until that is the case, this paper may provide ideas for other creative researchers looking into quantum computing, exploring a simulated quantum internet, or trying to understand the minimum amount of information required for establishing a networked music performance.

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