The article in review is Music-Defined Networking (MDN), a research paper written by Mary Hogan (Princeton University) who is Ph.D. candidate at the time of writing and Dr. Flavio Esposito (Saint Louis University). I break down this report into three sections: In Section A, I provide a brief summary of Hogan and Esposito's work. Then, in Section B, I critically analyze the positive and negative points raised in their work, and finally in Section C, I conclude with some ideas and thoughts about how Music-Defined Networking could be improved moving forward.

A. Summary

In their paper, Hogan and Esposito delve into the idea of turning the metaphor of "network orchestration" into a reality, describing a novel approach to augment or replace various network management operations by *leveraging sounds.* They tested this approach with both a real and virtual network testbed, on several mechanisms and applications and conclude that despite this technology's limitations, sound-based network management has potential to be further explored as an effective and inexpensive out-of-band technique.

B. Critical Analysis

1. Background on Music-Defined Networking

To start, it is important to understand the background behind this technology and to set the context. Delivering management traffic is essential to operate and orchestrate network services, which involves a high level of complexity. To handle such complexity, many Software Defined Network (SDN) solutions have been proposed with various advancements over time, but even so, management traffic is still carried in-band with data plane traffic both inside and outside datacenters. While operators commonly isolate management traffic, this logical separation does not hide the fact that sharing the infrastructure for data and management traffic is risky, because data plane or hardware failures could cut off network management traffic as well, resulting in the abortion of important management tasks.

2. Limitations of Past Methods

To address the growing complexity of datacenter operations, researchers have previously demonstrated how an out-of-band management network could be desirable. However, such approaches have been criticized in view of their deployment being **expensive** and requiring **extensive changes** to the datacenter infrastructure. For instance, the construction of additional parallel networks, reflective surfaces, or extensive equipment for server racks can easily add up, making these approaches less scalable and more difficult to implement.

3. Positive Features Required for Out-of-band Management Networks

At minimum, out-of-band management networks should be focused on being reliable, scalable and deployable. Hogan and Esposito further assert that a management network should also be *simple*, that is, being "able to run without major interventions to the existing (datacenter) infrastructure", and *inexpensive*. At first glance, these might seem like obvious positive qualities to have, but on deeper thought, we can actually analyze the relationship between the three main design criteria and the additional two proposed by Hogan and Esposito. Firstly, these features are not necessarily isolated and independent. For instance, something that is scalable and deployable may be more likely to be simple. Something that is simple and easily deployable may be more likely to be inexpensive. The question then is, to what extent is being *simple* and *inexpensive* necessary for a "good" out-of-band management network, or are they simply a result of being able to achieve the three main requirements; being reliable, scalable and deployable?

We can make our analysis on each of the two features separately. First, while being simple could be a byproduct of the three requirements, that is not necessarily so. Arguably, there is some overlap with scalability and deployment, but perhaps a key nuance here about simplicity is that it makes a solution more maintainable. As an illustration, say if we do not need to scale up the network but only need to ensure that it stays reliable over time, a system that is simple would be highly useful as changes or updates can be made with ease and confidence, as compared to a system that is more complex. Hence, Hogan and Esposito do have a case for arguing for a management network being simple, in addition to the three main requirements.

On the other hand, being inexpensive seems more of a natural outcome of achieving the other requirements, and is a nice-to-have rather than something that is absolutely crucial to a well-functioning management network. Of course, one might certainly be able to come up with examples of systems that are scalable, reliable, deployable and simple, but yet are expensive, but it would be reasonable to believe that these cases are usually the exception rather than the norm. As a general principle, being reliable, scalable, deployable and simple should be more often than not be sufficient for producing a system that is inexpensive. Moreover, perception of cost can be relative and thus difficult to evaluate for different stakeholders. As such, there does not seem to be as strong an argument for a management network to be "inexpensive". Rather, this quality seems more like a good bonus to have.

4. Overview of Pros of Music-Defined Networking

Nonetheless, it is with those above-mentioned features that Hogan and Esposito formulate and present the Music-Defined Network, a "paradigm where several network mechanism can be programmed in response to specific sound sequences". This technology is valuable in a sense because it only requires a low cost; for instance using cheap speakers, microphones and Raspberry Pis, and moreover its implementation is relatively simple by nature of the devices required. Given that if such a network were built in a reliable, scalable, and deployable manner, then it would definitely be able to replace existing management operations, making them more effective and efficient. Furthermore, Hogan and Esposito's work is probably the first attempt to manipulate sound signals in order to trigger or execute a diverse range of network management operations such as load balancing and hardware failure detection, which speaks to this technology's potential for further enhancements in future which makes it a valuable approach to keep in mind.

5. Limitations of Devices Used in Approach

While the concept of MDN sounds rather useful, it is important to also highlight a couple of limitations with the devices Hogan and Esposito where working with in their paper. In particular, the Zodiac FX switches' RAM is limited to 120KB and do not support multi-packet queues. This meant that the researchers had to restrict their implementation of certain use cases on a virtual network, which then leaves their approach less comprehensively tested especially on a physical network. Owing to the device limitations faced, we might be slightly skeptical of the results from this paper and look toward further experimentation and research in order for us to draw more concrete conclusions about the MDN approach.

6. Scalability of MDN Applications

In Hogan and Esposito's methodology, they tested their applications with and without background noise. This is a good aspect of their testing as it simulates a real-world situation where the MDN technology would be practically applied. As the researchers rightly noted however, the level of noise may grow significantly based on other applications. Consequently, an MDN application might be less scalable and practical as increasing its size, even if not to a large extent, could result in even more uncomfortable environments for operators, who are already required to wear noise canceling headphones. That said, this limitation could potentially be resolved in future, as suggested by Hogan and Esposito, but this would require further research in accurately tuning sound parameters to manage sound interference, mitigating operator discomfort and supporting multiple MDN applications.

7. Limitations of Frequency Range in MDNs

A crucial part of Hogan and Esposito's MDN approach is that it relies heavily on sets of frequencies that convey certain information about a network. For instance, each set of frequencies could be mapped to a specific port number or task, and upon hearing a set or sequence of frequencies, the necessary actions will be triggered to be executed. This approach certainly seems reliable; we know of methods to accurately identify frequencies in sound using Fast Fourier Transforms (FFT) which help in ensuring that the correct information is relayed and processed. However, when thinking about scalability, one would also have to consider that frequency ranges are finite. The audible human range is only from 0 to 20kHz, and while machines could certainly process wider ranges of frequencies, the wider the range the higher the cost that could be incurred, which decreases the appeal of the MDN approach. Hence, when integrating the use of frequencies in MDNs, the design of a solution would be crucial.

8. Applications of MDNs

The potential for MDNs is rather significant, and as Hogan and Esposito have shown, can be implemented in areas such as Music-Defined Telemetry, Traffic Engineering, and Server Fan Failure Detection.

8.1 Music-Defined Telemetry

Network telemetry is the process of monitoring traffic to track events ranging from performance limitations to attacks, usually done by operators continuously in real-time. In heavy-hitter detection for example, any application process capable of listening and processing sounds could be used in recognizing when a certain frequency is played above a given threshold in a given time interval. The frequency in question here would be mapped to a source and destination port, as well as a source and destination IP address, and a protocol type. These details would be necessary for heavy-hitter detection.

Unfortunately, MDNs use here is not without flaws. Scalability is a major concern here as there may be thousands of active flows per minute, so much so that even if ultrasounds were used instead of today's microphones which have a smaller frequency range, we would probably still be unable to detect every single flow. Consequently, Music-Defined Telemetry may be more suitable for smaller sized networks rather than a scalable replacement as a solution.

8.2 Traffic Engineering

Hogan and Esposito explain that traffic engineering solutions can be classified according to two main design dimensions; either focusing on the **choice of forwarding paths**, or how **sending rates** are dynamically adjusted to balance incoming traffic flows. As Hogan and Esposito demonstrate in their paper, sound can indeed be used as an effective signal to trigger any traffic engineering approach, such as in other load balancing or switch congestion monitoring. Again, the key idea is to use unique frequencies to encode messages for the MDN controller. For instance, when the controller hears a certain frequency, it would immediately know the range for the number of packets in the queue and execute a congestion response based on this information. Thereafter, once all traffic has been sent to the destination, the queue size decreases below a certain number of packets, at which point the controller is again notified through a different, perhaps lower, frequency.

8.3 Server Fan Failure Detection

In datacenters, server fan failures are a significant financial risk, and the documentation on the efficacy of countermeasures are typically not very promising. Naturally then, this area is a considerably lucrative target for the application of MDNs. The key question posed by Hogan and Esposito was: *Can we detect the failure of a single server despite the typical datacenter* *noise?* One answer at least is that we could identify failures by finding the total amplitude of each frequency in the recorded sounds with a server fan turned on, and turned off. Such amplitudes can be easily found by computing the FFT of each sound sample provided, and then used to determine the state of health of the fan. Notably, the difference in amplitude for certain frequencies is significantly larger in cases where two audio signals of the fan on and off are compared in contrast to cases where two samples of a functioning fan are compared. Hence, passive listening for sounds could be an effective out-of-channel mechanism that could help to minimize sever hardware failures. Only a couple of unanswered questions remain, as Hogan and Esposito highlight. First, how many distinct server anomalies could be possibly recognized? Second, what is the optimal microphone server distance such that we would be able to correctly distinguish multiple fan signals?

C. Future Work

Considering the progress made by Hogan and Esposito, as well as the limitations highlighted and analyzed, there a number of potential avenues for future work. In particular, there are two use cases for Music-Defined Telemetry, namely heavy-hitter detection and port scanning.

1. Multi-hop Sound Transmission

Importantly, Hogan and Esposito have limited their evaluation to close-range applications, where sound signals are transmitted between devices over a single hop. While in practice systems are usually restricted to devices that are near enough to each other so that sounds can be transmitted without significant signal degradation. However, it is possible that sound waves can be relayed, even if with very low throughput. To address this issue, a multi-hop sound transmission would be more efficient and allow greater flexibility for the placement of devices. As such, multi-hop transmission definitely seems to be a promising area for future research.

2. Expanding Usable Frequency Range

Additionally, with Hogan and Esposito's equipment, they could only feasibly use approximately 1000 unique frequencies simultaneously. A potential direction that might improve on this aspect is to coordinate an array of microphones listening to different groups of switches, as well as to integrate both classical and ultrasound speakers and microphones. The advantage of using ultrasound microphones is that a typical one could easily capture frequencies of up to 120kHz, which is 6 times wider than using the human audible range of frequencies. Naturally, with more frequencies available for use for encoding signals and information, more complex and scalable network management operations would become feasible.

3. Improving Practical Implementations

Finally, there have been a number of limitations discussed throughout Hogan and Esposito's paper, as well as in this report which would pose significant challenges for practical implementations. For instance, in heavy-hitter detection, the task may be more complex than simply detecting sound frequencies. In order for MDN to be comprehensively applied as a solution, more research, experimentation, testing and evaluation would be required to develop more complex algorithms, sampling, or sketching techniques that may operate in the data or control plane. Hence, while we can draw the general conclusion that MDNs are useful, their application to specific problems in networking would need to be further analyzed and evaluated in greater detail.