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Supercharging Bluetooth Performance with Machine Learning

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We live increasingly in a "sensorized" world. Everything is connected to everything else. Connectivity is key to smart cars, smart cities, smart hospitals, smart armies, and more. As a result, connectivity reliability is crucial.

In addition, spectrum sharing by multiple technologies is making wireless connectivity more unreliable and more prone to dropouts. Traditional wireless receivers don't have the in-built intelligence to function in such crowded environments. Traditionally wireless communications have been built on a foundation of human-intuition-based behavior models and analytically tractable channel approximations. The real-life behaviors and channel conditions, however, can be quite different. While there is an abundance of data that is readily available and collectible about the real-life parameters, there is no existing mechanism by which the traditional wireless communications can be modified and optimized by using this real-life data

Machine learning improves wireless performance exponentially

Machine learning techniques, powered by real data, can be one such mechanism to provide radical improvements in wireless communications, like improvements made by ML in speech

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recognition and image detection. Not only can ML allow wireless receivers to improve reliability in the presence of wireless congestion, but there is also enormous potential to improve range, battery life, data rates and latency.

Bluetooth, WiFi, cellular, satellite communications and sensor networks are some of the types of wireless networks that can benefit from ML. Each of these are constantly expanding markets and there are already billions of connections that can be improved. In Bluetooth alone, there are billions of ear buds, headsets, car audio, hearing aids and many other types of endpoints already in use by consumers worldwide.

Improving wireless connectivity is of paramount importance, driving numerous startups to innovate and deliver solutions in this space. What has emerged is that by adding machine learning Bluetooth can be supercharged. An AI/ML-based feedback system quadruples Bluetooth range, doubles battery life, and multiplies reliability ten times over.

Below are a few examples of performance results from Aira Technologies. Consider music playing on a phone and streaming to your Bluetooth earbud or headset. Figure 1 below shows a representation of the Bluetooth audio across a few seconds when wireless link quality is good.

Figure 1: Bluetooth audio with good wireless link quality

Can you hear me now?

To understand a simple example of how ML has been harnessed to achieve such impressive results, it’s important to understand that wireless communication channels are inherently noisy and as a result, a large percentage of packets that are transmitted arrive with errors. Figure 2 shows a representation of the same Bluetooth audio stream when about half the packets are being lost.

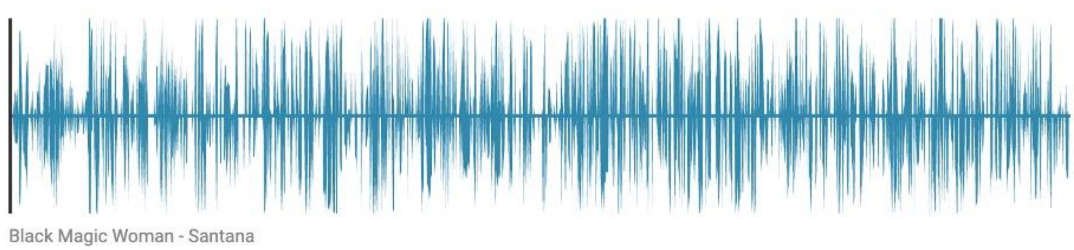

Figure 2: Bluetooth audio with packet loss

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Traditional wireless systems use coding schemes that introduce a degree of redundancy to correct these errors. However, Bluetooth uses the uncoded mode to maximize energy efficiency. So, when packets cannot be recovered, the receiver sends an indication back to the transmitter in the form of what's called a *NACK*. This can be thought of as the opposite of an *ACK* or an acknowledgement that a packet has been successfully received, and the transmitter would then resend the entire packet and do so repeatedly until the receiver receives the message correctly.

In noisy environments, this can be extremely inefficient and result in many retransmissions that end up reducing overall system throughput, increasing power consumption and overall packet latency. In many cases, even multiple retransmissions can't transfer packets across and users simply lose their music stream entirely. Figure 3 demonstrates this scenario wherein the number of packets making it through are so few that there is virtually no music playback possible in a traditional system.

Figure 3: Bluetooth audio with significant packet loss

Are blind retransmissions the only option? Can the transmitter do better? What additional information will it need to do this? Machine learning is an intrinsic part of these solutions. Multi-bit feedback technology provides additional information to the transmitter regarding the failing packets. This allows the transmitter to tailor the retransmissions to correct the failing packets more reliably. What additional information is needed and how it is used in the retransmissions is optimized using data-driven machine learning techniques.

Using machine learning, even the poor reception that is shown in Figure 3 can be corrected to deliver clean music audio. Figure 4 shows a real-world example of how the audio looks after ML-based corrections.

Figure 4: Bluetooth audio with ML-based corrections

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Diving under the hood and looking at over-the-air real-world packet transmission and reception, Figure 5 shows how ML helps Bluetooth maintain wireless link performance even as the environment changes.

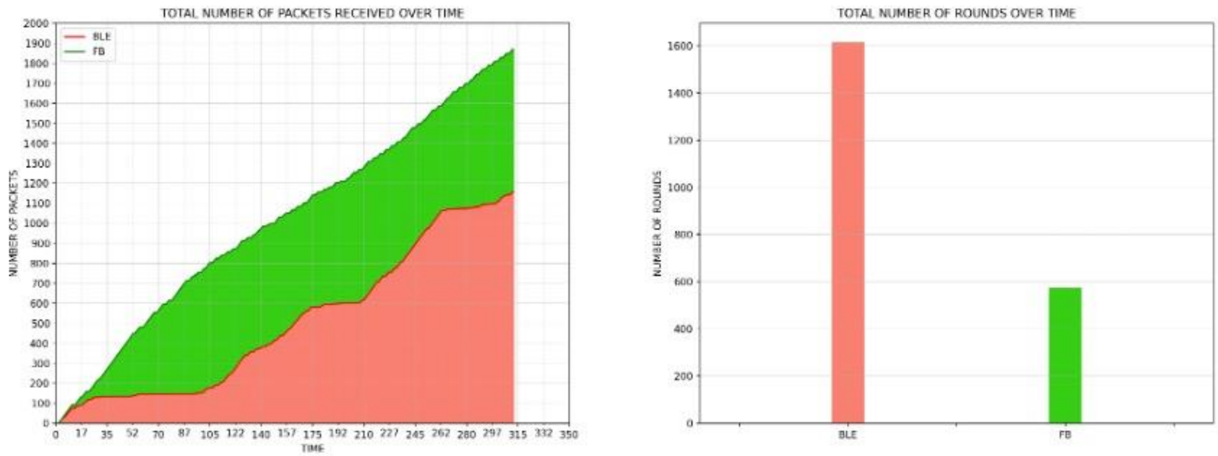

Figure 5: ML helps maintain wireless link performance
click to enlarge

To understand Figure 5, let's first look at the graph on the left. This shows the cumulative number of packets successfully received on the y-axis and time on thex-axis. As a user is walking around the room with their Bluetooth headset on and enjoying music streaming to their headset, packets are being continuously transmitted from their phone, Alexa or similar, to their headset. If there is a large amount of sporadic packet loss, the music experience is not very enjoyable. This is what happens in many instances with standard Bluetooth as shown by the area under the pink on the graph on the left, which shows that the rate at which packets are received varies widely as the user walks around. With ML enabled—the area under the green line—the packet reception rate is constant, thus maintaining music quality.

In addition, as the right part of the graph in Figure 5 (see page 2) shows, the total number of rounds that are consumed by the link to deliver packets across is much higher for Bluetooth without ML (pink) as opposed to Bluetooth with ML (green).

When the left and right side are considered together, this shows that without ML, not only are fewer packets received, but also that there are more total retransmissions needed. This is a classic "double whammy" that ML helps alleviate.

Not only can efficiency be improved, but the ML algorithms also learn on their own to arrive at the best performance under different channel conditions and evolving interference environments. For example, when WiFi and Bluetooth are active in the same room, they interfere with each other because they both operate in the same 2.4GHz band in many cases. ML has been demonstrated to reduce the impact of such interference by a factor of two to four times so that both WiFi and Bluetooth can continue to maintain good performance.

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Energy per bit of information sent is another important consideration for a wireless system, as most wireless devices are battery-powered. Some Bluetooth devices like hearing aids are even more power-constrained compared to phones or headsets. For such devices, energy efficiency is critical. As a hearing aid or earbud gets closer to its range limit, as when a user walks a few feet away from their phone, the energy required to transmit one bit of information on Bluetooth may increase from one to two nano Joules to 100nJ or more. ML-based systems have been shown to extend the range where Bluetooth continues to operate power efficiently by two to four times.

Machine learning improves cybersecurity

Machine learning also helps in keeping wireless links more secure. Because today's wireless protocols re-transmit packets that are not received, these retransmissions increase the probability that an intruder can sniff the packet. Once the packet is sniffed correctly, the intruder has access to ciphertext, which can then be used for sophisticated crypto-analysis. ML-based feedback systems provide better ciphertext security when compared to current systems. Unlike current systems, ML-based multi-bit feedback never re-transmits packets, which reduces the probability of sniffing a ciphertext. This reduces the probability of crypto-analysis.

Exploration continues on the function of multi-bit feedback in multiple applications. Its technology works especially when there is power asymmetry between the transmit and receive directions, for example when the transmitter is more power-constrained than the receiver. This power asymmetry often arises in cellular, WiFi and satellite communications. While these transports are more sophisticated than Bluetooth and have advanced methodologies and protocols to combat packet loss (such as modern codes, HARQ, block ACKs, and more), they will still benefit from the efficiency improvement provided by the AI/ML-based technology.

Bluetooth is merely the most obvious entry point for this technology. New applications will also benefit from the enhanced security benefits. These innovative developments are indispensable in an increasingly machine-to-machine world.

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