Glaze: Overlaying Occupied Spectrum with Downlink IoT Transmissions

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Existing Internet of Things (IoT) solutions require expensive infrastructure for sending and receiving data. Emerging technologies such as ambient backscatter help fill this gap by enabling uplink communication for IoT devices. However, there is still no efficient solution to enable low-cost and low-power downlink communication for ambient backscatter systems. In this paper we present Glaze, a system that overlays data on existing wireless signals to create a new channel of downlink communication for IoT backscatter devices. In particular, Glaze uses a new technique that introduces small perturbations to existing signals to convey data. We evaluate the performance of Glaze and show how it can be used across wireless standards such as FM, TV, or Wi-Fi to communicate with devices with minimal impact on existing data transmissions.

CCS Concepts: • **Hardware → Wireless devices; Communication hardware, interfaces and storage; Power and energy.**

Additional Key Words and Phrases: Internet of Things, backscatter communication, cross-technology communication, low-power systems

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1 INTRODUCTION

Over recent years there has been a rapid growth in the deployment of IoT devices. These devices are used in home, cities, even large industries such as agriculture. However, deploying current solutions for IoT systems at large scale has two key drawbacks: cost and maintenance.

Mainstream IoT solutions require the setup of additional equipment, such as a base station to transmit data. Setting up the antenna, tower hardware, tower space and management for the base station quickly increase the cost of the IoT deployment. Furthermore, many of these IoT devices have high power consumption and rely on single use batteries, making it difficult to maintain at a large scale. Imagine deploying a large network, tens of

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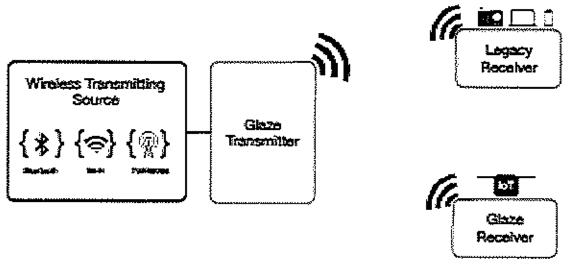


Fig. 1. **Glaze System.** The Glaze module connects to the antenna port of a preexisting wireless transmitter to overlay data. The transmitted signal is then received by a Glaze receiver and legacy receivers.

hundreds of devices, to collect data. These devices would require routine maintenance just to replace batteries, negatively impacting productivity and increasing overall cost.

Recent breakthroughs in ambient backscatter technology make improvements in reducing the cost and power consumption of IoT systems by enabling both peer-to-peer and uplink communication for IoT devices by utilizing existing wireless signals. For example, devices can communicate peer-to-peer by backscattering TV broadcast signals or Wi-Fi signals can be modulated by a Wi-Fi tag to send uplink data to a base station [14] [10]. Other examples such as FM backscatter, demonstrate that devices can communicate by backscattering FM broadcast signals as well [23]. These techniques have been used to develop devices that can even operate at ultra low power, allowing them to be completely battery-free [19] [17] [18]. While these ambient backscatter solutions are very promising they still lack reliable downlink communication to enable a fully end-to-end IoT system.

To enable downlink communication with existing ambient backscatter solutions, the setup of an additional base station would be required, which could not rely on backscatter techniques. For instance, ambient backscatter tags that rely on TV broadcast signals for peer-to-peer or uplink communication would need a separate base station for downlink communication. This is true for FM or Wi-Fi signals as well, which in most cases would quickly drive up the cost. A more promising solution that has been proposed for Wi-Fi backscatter, is using the presence and absence of Wi-Fi packets to convey downlink data [10]. However, this solution is constrained to Wi-Fi systems and requires modifications to the Wi-Fi access point.

In this work we bridge the gap by introducing a new system called Glaze, a general paradigm for downlink communication that can be applied to any preexisting wireless signal to enable downlink transmissions to IoT endpoint devices. Since TV transmissions already exist, they could carry downlink data for IoT endpoint devices. Similarly, FM transmissions, Wi-Fi or Bluetooth signals could carry this information as well. If this data can be decoded at low-power at the endpoint device, it can be used to enable an end-to-end ambient backscatter communication system. However, there are three main challenges in directly reusing existing wireless signals and infrastructure. First, requiring backscatter devices to have TV, FM, Wi-Fi or other receivers would be very power consuming and expensive. Second, it is non-trivial to modify the hardware, firmware, or encoding pipeline of existing transmitters to overlay additional IoT data. Lastly, we must not degrade the performance of the existing communication channels. We solve these challenges as follows.

To transmit additional data using existing wireless signals, for example Wi-Fi, without requiring a Wi-Fi receiver at the backscatter device to decode the signal, we overlay a low rate data transmission on top of the existing wireless signal. The IoT backscatter device then needs only a very simple low-power radio to decode the low rate Glaze downlink message.

To avoid making changes in the transmitting radio hardware or firmware, we propose connecting a Glaze module to the antenna port of wireless radios to overlay data on top of the RF signal. For instance, a Glaze module can be connected to the antenna port of a Wi-Fi access point to encode downlink data transmissions for ambient backscatter devices, while Wi-Fi packets are still being transmitted and received by legacy receivers, as shown in Figure 1.

Lastly, to minimize interference towards existing communication channels our data embedding technique stems from the domain of digital watermarking and information hiding. There have been several proposed techniques to hide messages in media such as images or audio, with minimal distortion impact. One example is additive spread spectrum modulation, where many small increases and decreases in pixel brightness are introduced in an image to embed additional data while being imperceptible to the human eye [20]. We extend some of these concepts to wireless communication to send additional data while introducing minimal interference. We propose an encoding scheme that introduces small amounts of attenuation to the existing wireless signals to overlay additional data. The key insight to this approach is that most wireless receivers are built to tolerate a small amount of noise in the wireless signal, allowing us to convey additional data to the IoT endpoint devices.

In the remainder of this paper we will explain how downlink communication can be enabled for ambient backscatter systems by leveraging existing wireless signals and infrastructure. Specifically, we go over the following key contributions,

- *We present Glaze, a data overlay system for preexisting wireless signals that enables downlink communication for ambient backscatter systems.* Glaze uses a data encoding scheme that can be applied to most wireless signals to convey additional data to IoT endpoint devices, without disrupting existing communication links. The Glaze module can be added to an existing wireless transmitter without modifying hardware or firmware components.
- *We show that Glaze can be applied to packetized data networks, such as Wi-Fi.* Such networks do not continuously transmit data and the module would need to predict the Wi-Fi downlink activity to successfully embed data.
- *We design and implement hardware prototypes for the Glaze module and receiver.* The Glaze module and receiver operate at low-power and are compatible with existing backscatter uplink solutions. Specifically, we show that downlink communication can be achieved at rates up to 10 kbps and distances of up to 3.5 meters for Wi-Fi signals. Moreover, we demonstrate that with FM and TV broadcast signals the Glaze system can achieve rates of up to 10 kbps at distances of 9 meters when the transmit power is set to 20dBm.

2 MOTIVATION AND CHALLENGES

Ambient backscatter communication is a promising approach to enable communication for IoT systems because it is a low-cost and low-power solution, however current implementations are still limited to uplink or peer-to-peer communication. While most IoT data is uplink, for instance sensor data sent to the edge or base station, all control and signaling data is downlink. This includes information such as the reporting rate (e.g. how frequently the sensor should send data), updates (e.g. a latest version of the firmware), acknowledgements, diagnostic data, among others. In order to enable an end-to-end IoT system using ambient backscatter communication techniques there must be a downlink channel as well. For example, ambient backscatter leverages existing infrastructure to send data from tag to tag. However, sending any downlink data still requires dedicated infrastructure. With these limitations, IoT endpoint devices are unable to take full advantage of the cost benefits offered by backscatter techniques since they would still need an expensive IoT radio receiver for downlink communication.

Glaze solves this problem by removing the need for dedicated infrastructure or high power receive radios and instead, overlays downlink IoT transmissions on existing RF signals that can be received by backscatter devices. Furthermore, because of its modular design Glaze can be used with any wireless transmitter without requiring modifications to the hardware or firmware. To bring Glaze to fruition there are several challenges that need to be addressed and can be broken down into two categories: broadcast and data networks.

2.1 Broadcast Networks

Broadcast networks account for signals such as digital TV or FM and AM radio, that stream data continuously. Applying the Glaze system to such signals is challenging for two reasons. First, it is inevitable with any data overlay technique that the embedded message will cause distortion towards the wireless signal. While small amounts of distortion are acceptable, we do not want to exceed a threshold that will cause channel degradation. The Glaze system must adapt to these constraints depending on the wireless signal and optimize the performance of the embedded message. In particular, for broadcast signals, the modulation scheme used by the broadcast transmitter plays a key role in defining the data overlay technique parameters.

The modulation scheme of the wireless signal used to encode its own data will also determine how resilient the signal will be to distortion caused by the data overlay technique. We mentioned previously that the Glaze system introduces small amounts of attenuation to embed data on top of the wireless signals. This can be viewed as introducing small shifts in amplitude, which means a signal that uses frequency modulation will be more resilient in comparison to a signal that uses amplitude modulation. A specific example would be that a digital TV broadcast signal would be more susceptible because it uses 8-VSB (a form of amplitude modulation) in comparison to analog FM broadcast signals, which would be much more robust.

Lastly, since the major appeal of ambient backscatter communication techniques is the capability of being a low-cost and low-power solution for IoT systems, the Glaze system must also maintain these characteristics. In particular, the Glaze receiver needs to operate at very low-power and be compatible with existing ambient backscatter uplink solutions. To enable this, we must design hardware that can decode the additional embedded data without the need for power consuming component such as ADCs or RF oscillators. Moreover, we need a low complexity data overlay scheme that is also resilient to channel noise in order for the Glaze receiver to decode the transmitted data without expensive computation.

2.2 Data Networks

Integrating the Glaze system with data networks is even more challenging. Data networks account for wireless signals such as Wi-Fi or BLE, which instead of continuously transmitting, send data intermittently. Take Wi-Fi as an example, which uses packetized protocols to transmit data to clients. In order to reliably overlay data on top of Wi-Fi or other signals using packetized protocols, the Glaze system must be aware of incoming packet transmissions and the duration of the packets. These two insights will determine when the Glaze module should begin to overlay data and if an entire Glaze packet can be overlaid during the duration of the packet transmission. Specifically, if the packet transmissions are very short, then the Glaze system might need to overlay data across several packets. Thus, not only do we need to know the aforementioned parameters, we also need an adaptive data overlay scheme to accommodate the varying signal characteristics.

Another challenge with applying Glaze to data networks is that the distance between the wireless transmitter and receiver plays a role in how much distortion can be introduced to a wireless signal. In the case of Wi-Fi, clients can be very close or much further away from the Wi-Fi access point (AP). A client that is further away from the AP cannot tolerate as much distortion introduced to the signal in comparison to a client that is closer in proximity. Thus, the Glaze system must be aware of an APs associated clients along with their proximity to adapt the data overlay technique and in turn avoid channel degradation.

3 GLAZE SYSTEM OVERVIEW

Glaze is a novel communication system that enables a new channel of communication for ambient backscatter devices by overlaying data on existing wireless signals. By utilizing existing infrastructure and spectrum, we envision Glaze to be used as a low-power and low-cost modular solution for downlink backscatter communication. As shown in Figure 1, Glaze has two key components: a Glaze module and receiver. The module is connected

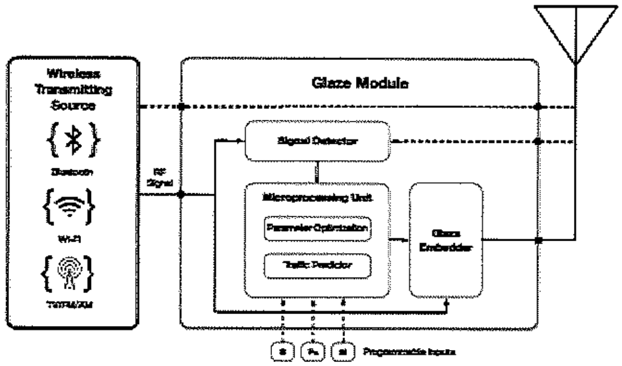


Fig. 2. **Glaze Module Design.** The Glaze module connects to the antenna port of wireless transmitters to overlay additional data.

to the antenna port of a wireless transmitter, which can be anything from a Wi-Fi AP to FM or TV broadcast tower. It overlays data on top of wireless signals and outputs a composite signal to be transmitted and received by legacy receivers and Glaze receivers. In the remainder of this section, we describe the components of the Glaze module and receiver necessary for the system to be compatible with both broadcast and data networks.

3.1 Glaze Module

The Glaze module overlays data by introducing small amounts of attenuation to the wireless signals. For example, it can modify a Wi-Fi transmission by changing the signal in a way that Wi-Fi receiver's performance is not affected, yet the signal carries additional data for ambient backscatter devices.

Achieving the above is non-trivial. One approach to add additional data to an existing signal is to modify the firmware of existing radios. For instance, a Wi-Fi transmitter could be modified to carry additional information in the guard bands or pilot tones. Although this can be implemented on software defined radio platforms, implementing such techniques on commercial off-the-shelf Wi-Fi radios would require hardware changes. Furthermore, modifying guard bands and pilot tones might affect the reception of existing signals. Instead, we use a different approach in Glaze, which does not require hardware or firmware changes to the radio platforms. Our system operates as a module that is added to the antenna ports of existing transmitters. It does not need to decode the original signal, yet it is able to overlay data to enable downlink transmissions for IoT endpoint devices. This is accomplished by using the following components in the Glaze module:

- **Signal Detector:** The Glaze module should only overlay data when there is a signal being sent by the wireless transmitter. A FM transmitter always transmits a signal, while a Wi-Fi transmitter might only transmit a packet when it has something to send. Instead of trying to decode the transmissions, the Signal Detector monitors for incoming signal transmissions and activates the rest of the Glaze module pipeline.
- **Parameter Optimizer:** Before overlaying the data, the Glaze system must define the data encoding parameters to avoid degrading the original wireless signal. The Parameter Optimizer takes into account the modulation scheme, channel power and bandwidth of the wireless signal. Moreover, it considers the

distance between the wireless transmitter and its associated clients for data network scenarios. All of these inputs are used to optimize the data embedding parameters. For instance, how much attenuation can be introduced to the wireless signal or the rate of embedding.

Traffic Predictor: Since some wireless transmitters, for instance Wi-Fi APs, use packetized protocols, the Glaze module must be aware of the start of a packet transmission and its duration. The Signal Detector can detect the packet transmissions, however having some knowledge of packet duration is needed because the Glazed data might not always fit in a single transmission. For example, if a low bit rate is being used to overlay the additional data it would need to be embedded across several Wi-Fi packets. The Traffic Predictor is used to estimate the likelihood of signal transmissions for a select unit of time. In turn, the Glaze module can make intelligent decisions when overlaying data, such as optimizing data rate and choosing the ideal time to begin embedding.

Glaze Embedder: Finally, the data is overlaid by the Glaze Embedder. It overlays the Glaze data on the RF signal based on the parameters determined by the Parameter Optimizer. At a high level, the Glaze Embedder introduces small perturbations to the RF signal in the form of attenuation, but in a way that does not degrade the reception of the preexisting wireless signal. All the while, being able to be received by the IoT endpoint devices.

3.2 Glaze Receiver

The Glaze receiver needs to be very low-power and yet should be able to receive and decode the Glaze signal transmissions. Typically in wireless systems, data is encoded in the frequency domain and in turn, receivers require power hungry components to perform high complexity tasks needed to decode. One approach to avoid power consuming components would be to overlay data on the baseband of the wireless signal in the time domain. This would enable the Glaze receiver to decode without needing power consuming hardware components to perform tasks such as Fast Fourier Transforms. However, this would instead increase complexity at the Glaze module. That is, the module would need to downconvert the wireless signal to the baseband frequency, overlay the Glaze data, then upconvert back to the RF frequency. While this approach is possible, it would not be a very practical implementation. Instead, overlaying data directly on the RF signal avoids these changes to the Glaze module and enables the Glaze receiver to have a low-power design.

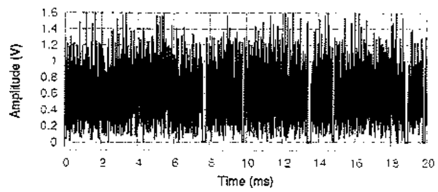
4 GLAZE PHYSICAL LAYER

To realize the Glaze system described in the previous section, we need to implement the network physical layer. This includes two key components. First, defining an encoding and decoding algorithm used to overlay data on the existing wireless signals. Second, defining a scheme to detect Glaze packets, perform synchronization, and decode data at the receiver.

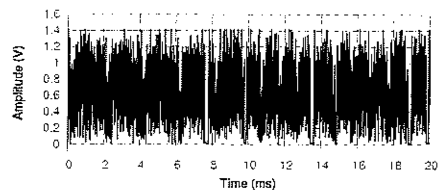
4.1 Modulation and Bit Encoding

We define Glazing, a data embedding technique for RF signals. It introduces small amounts of attenuation to RF signals to encode additional data. The technique is built upon the key intuition that most receivers are designed to withstand some amount of noise in the signal. As long as we can convey data in the noise we can send downlink transmissions to ambient backscatter devices, and as long as we add very little noise to the RF signal we can reduce the impact on receiver performance. To understand the Glazing technique, we first start by defining the data embedding function,

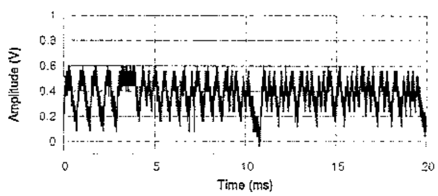
$$X(s) = s \cdot \alpha_m \quad \text{where,} \quad \alpha_m = \begin{cases} \frac{1}{10^{\frac{\Delta}{10}}} & \text{if } m = 0 \\ 1 & \text{if } m = 1 \end{cases} \tag{1}$$



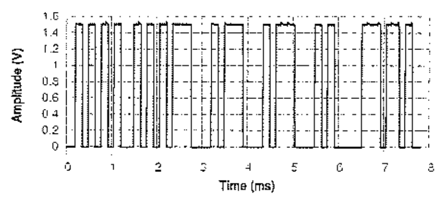
(a) **Wi-Fi Packet Transmissions.** The envelope of Wi-Fi packet transmissions before applying the Glazing technique.



(b) **Glazed Wi-Fi Packet Transmission.** The envelope of Wi-Fi packet transmissions after applying the Glazing technique.



(c) **Signal at the Glaze Receiver.** The signal seen at the Glaze receiver after passing through an envelope detector.



(d) **Decoded Glaze signal.** Data decoded by the Glaze receiver

Fig. 3. **Glazing technique.** An example of the Glazing technique applied to Wi-Fi packet transmissions at the Glaze module and decoding at the Glaze receiver.

where *s* is the RF host signal (eg. Wi-Fi, TV, or FM) and Δ is the amount of change introduced to the signal in the form of attenuation to overlay a data message, *m*. Specifically, if we want to overlay a 0-bit then Δ will equal the maximum amount of attenuation allowed for any particular host signal. Moreover, if we want to overlay a 1-bit then no change will be made and Δ=0. The maximum amount of attenuation allowed for data embedding can be determined by taking into account the minimum signal strength seen at an associated client device, $P_{\boxtimes}$ and the typical client receiver sensitivity, $P_{\boxtimes\boxtimes\boxtimes\ \boxtimes\boxtimes}$, for any particular wireless signal and protocol. Thus, Δ $P_{\boxtimes}$ $P_{\boxtimes\boxtimes\boxtimes\ \boxtimes\boxtimes}$. Furthermore, to improve the robustness of the overlaid data we implement a Manchester encoding scheme where a 0-bit is represented as a zero to one transition and vice versa for a 1-bit. Lastly, to decode the overlaid data the Glaze receiver compares the received signal with and average of itself to distinguish between two data levels.

An example of the above data overlay mechanism is shown in Figure 3, where the encoding and decoding scheme are applied to Wi-Fi packet transmissions. First, Figure 3(a) shows Wi-Fi packet transmissions over 20ms and Figure 3(b) shows those same Wi-Fi packets after applying the Glaze embedding technique with Δ=4dB attenuation. The Wi-Fi signal is then transmitted and received at the Glaze receiver. Figure 3(c) shows the received signal after passing through an envelope detector. The Glaze receiver decodes the the overlaid data and outputs the estimated message shown in Figure 3(d).

4.2 Packet Detection and Synchronization

To be able to decode a Glaze packet transmission the receiver must perform a series of tasks to identify an incoming packet, which includes synchronization and extracting important parameters needed for decoding. The Glaze system uses the packet structure shown in Figure 4 to perform packet detection and synchronization. There are three main fields: short training field (STF), long training field (LTF), and data. The short training field includes

9 bits	13 bits	25 bits
Short Training Field	Long Training Field	Data

Fig. 4. **Packet Structure for Glaze Embedding.** The Glaze system uses a short and long training field, followed by data, to overlay packets on top of existing signals.

a 7-bit wake-up signal that is a bit sequence of redundant 1s and 0s used to trigger the Glaze receiver to wake-up from sleep mode. The last two bits of the STF carry the bit rate used to encode data, which has four possible values. For instance, in a Wi-Fi scenario the bit rate can be 3bps, 200bps, 5kbps, and 10kbps corresponding to the binary representation 00, 01, 10, and 11. The second field is the LTF, which is a 13-bit Barker code preamble. The preamble is used for synchronization and enables the Glaze receiver to identify the start of the data in the received packet and begin decoding. Finally, the last field is data and can carry up to 25 bits. To enable coexistence of multiple receivers associated with one Glaze module, a device ID field can be added to the packet structure as well. In other words, each device will have a unique ID, which would be included as a header in the packet.

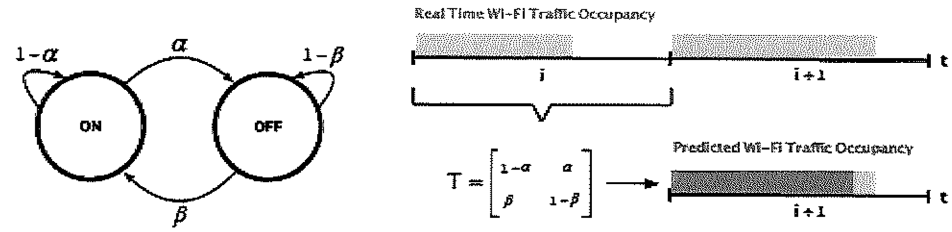
5 GLAZE SYSTEM DESIGN

In Section 3 and 4 we described the Glaze system and the components necessary to overlay data on existing wireless signals. Moreover, we detailed challenges with ensuring there is minimal distortion impact on the wireless signals all the while being able to decode the overlaid data at the IoT endpoint devices. In the following subsections we go over the design of the Glaze module and receiver needed to realize the Glaze system.

5.1 Glaze Module Design

The Glaze module consists of several components all needed to enable overlaying data with minimal distortion towards the wireless signal. First, the module must be able to detect a signal transmission to know when to start overlaying data. Second, it needs to optimize the data overlay parameters to ensure that the Glaze data does not interfere with the existing communication channel. Lastly, the module needs to adapt the Glazing technique when overlaying data on wireless signals that use packetized protocols (eg. Wi-Fi). We address each requirement as follows.

- **Signal Detector:** The Signal detector is used to to detect incoming signal transmissions and trigger the remainder of the Glaze module pipeline. This can be achieved by using a simple energy detector. The energy detector is always measuring the signal strength of the wireless signal and when the signal strength exceeds a predetermined power threshold the rest of the Glaze module pipeline is enabled. The Signal Detector can be implemented by using an off-the-shelf energy detector.
- **Parameter Optimizer:** The solution to achieve parameter optimization is twofold. Input parameters such as modulation scheme, channel power, and bandwidth can be programmed in software for the Glaze module. However, we also need to know the distance between the wireless transmitter and associated clients to determine the maximum amount of distortion that can be introduced without disrupting any communication link. We address this by using the energy detector to sense both incoming and outgoing packet transmissions. The Glaze module uses the output of the energy detector to measure the signal power of incoming packets. Each time the module senses a received packet, it immediately begins to sense for an outgoing packet transmission as well. The key intuition with this approach is that every time a Wi-Fi access point receives a packet from an associated client it will always send an acknowledgement within a fixed time frame. We use this Wi-Fi characteristic to determine if the client is associated with the AP. If so, the signal strength of the received packets are used to determine how much distortion can be introduced when overlaying data.



(a) **Markov Model.** A two state Markov model for Wi-Fi traffic prediction. The ON and OFF states represent packets being transmitted or not.

(b) **Occupancy Prediction.** An example of Wi-Fi traffic occupancy prediction using the Markov model.

Fig. 5. **Wi-Fi Traffic Occupancy Model.** A two state Markov model shown on the left is used to predict short-term Wi-Fi traffic occupancy. On the left, an example is illustrated of how Wi-Fi occupancy prediction is implemented.

- **Traffic Predictor:** As mentioned above the energy detector is used to sense incoming and outgoing signal transmissions. The detection of an outgoing signal transmission is also used to trigger the rest of the Glaze module pipeline when using the Glaze system in data network scenarios. However, challenges with data networks (eg. Wi-Fi) still persist. That is, since Wi-Fi packets are transmitted in bursts, the Glaze module needs to have an idea of when to begin overlaying data and determine the optimal data embedding rate for any given unit of time. A simple approach would be to embed each bit using a very low data rate (few bps), spanning many Wi-Fi packets, to ensure that there is always enough energy per bit to be decoded at the Glaze receiver. However, this approach would greatly limit the performance of Glaze. If there is a way to know the total Wi-Fi downlink traffic occupancy in a short time frame, then we can optimize the data embedding rate to improve throughput and choose the optimal time to begin overlaying data.
A useful characteristic of Wi-Fi traffic that can help address this challenge is that it is very persistent. That is, typically if Wi-Fi traffic occupancy is high, then it is likely to stay high for a very long time. Similarly, if it is low then it is likely to stay low. This has been modeled in several studies by using the Hurst exponent [3, 5]. At a high level the Hurst exponent is a calculated value used to measure the long-term memory of a time series. The exponent can be used to classify the predictability of a time series. Specifically for Wi-Fi time series data, studies have show that the Hurst exponent ranges from 0.75 to 0.90 and data is considered persistent if it has a Hurst exponent greater than 0.5 [15]. The key takeaway from the mentioned results is that in most cases Wi-Fi traffic has a high Hurst exponent and in turn we should expect very persistent traffic flow. We leverage this trait and develop a promising approach to estimate short-term downlink Wi-Fi traffic occupancy by using a two state Markov model. In fact, using Markov models to forecast time series data has shown to be a promising approach in the wireless networking domain. For instance, improving the estimation of expected transmission count (ETC) in wireless links or a slight variation by using Interrupted Poisson Processes to model Wi-Fi traffic [2] [12].
Figure 5 shows the model where the two states represent a Wi-Fi AP transmitting packets (ON) or not transmitting (OFF). Using this method we can predict the likelihood of having a very long OFF period and also the average downlink Wi-Fi traffic per unit of time. With this knowledge, the data embedding rate can be optimized when using the Glazing technique. For example, when the downlink Wi-Fi traffic occupancy is predicted to be very high we can use a higher bit rate when overlaying data. On the other hand, if the

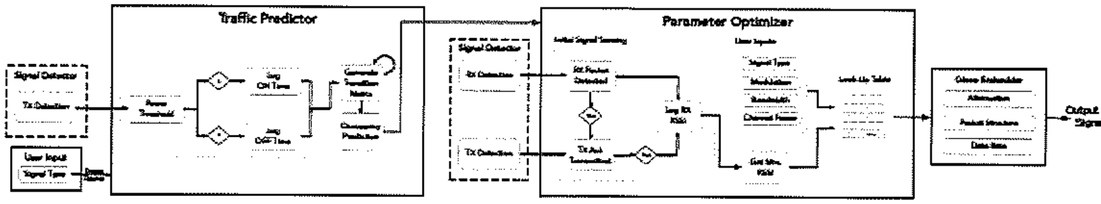


Fig. 6. **Glaze Module Pipeline.** The Glaze module pipeline goes through a process of performing occupancy prediction and parameter optimization before beginning to embed data.

Wi-Fi traffic is expected to be low we wait to overlay data. If the low Wi-Fi traffic occupancy persists for a predetermined time frame (eg. 100ms) then we switch to low bit rate to overlay the next Glaze packet.
To implement the Traffic Predictor, the energy detector is used to determine the total ON and OFF time of the Wi-Fi AP for a select unit of time. The data is then used to generate a transition matrix that gives the probability of staying in each state or transitioning,

$$T = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix} \qquad where, \qquad \begin{matrix} \alpha = P_{ON} \rightarrow P_{OFF} \\ \beta = P_{OFF} \rightarrow P_{ON} \end{matrix} \tag{2}$$

where α is the probability of transitioning from ON to OFF and β is the probability of transitioning from OFF to ON. With this, the probability of staying in each state is represented by 1 - α or 1 - β. We use the transition matrix, T, to estimate the total amount of Wi-Fi packet transmissions in the next unit of time. To perform the data processing and occupancy prediction a low-power microcontroller (MCU) can be used. Figure 5(b) shows an example of this process. The time unit i is used to generate the transition matrix. The MCU keeps track of total ON and OFF times during the select time unit by using a power threshold. If the power of the incoming signal exceeds the threshold, this is considered ON, otherwise it is treated as OFF. After monitoring the incoming signal transmissions, the transition matrix, T, is generated and used to predict the Wi-Fi downlink traffic activity of the next time unit, $i + 1$.
Using the Traffic Predictor, the Glaze module can make intelligent decisions for the data embedding scheme. However, there still may be scenarios where the predicted Wi-Fi traffic occupancy is greater than what is actually seen during the time of data embedding. In these cases, the Glaze receiver might not be able to decode the packet and would result in increased error rates. To supplement the Wi-Fi traffic occupancy model, we also use the energy detector monitor the total amount of energy per unit of time during the data overlay process. If it senses that the total occupancy per time unit is less than what was predicted the Glaze module will re-transmit the packet and update the data embedding rate.

- **Glaze Embedder:** The Glaze Embedder is the last component in the Glaze module pipeline, which is used to perform the Glazing technique. The design consists of a microcontroller and digital attenuator. The microcontroller controls the digital attenuator by defining how much attenuation to apply to the wireless signal as well as the data rate. The output of the Parameter Optimizer and Traffic Prediction blocks define how much attenuation is acceptable for the wireless signal at hand and also what data embedding rate should be used for the packet that is to be overlaid.

Figure 2 shows the Glaze module implementation. The energy detector is connected to monitor outgoing and incoming signal transmissions. The output of the energy detector goes to the MCU. The MCU uses the power measurements from the energy detector to perform parameter optimization, packet prediction, and adaptive rate embedding. Moreover, the MCU makes decisions using a look up table to pick the best data rate and the attenuation amount that can be used given the input parameters. The look-up table is generated by having prior

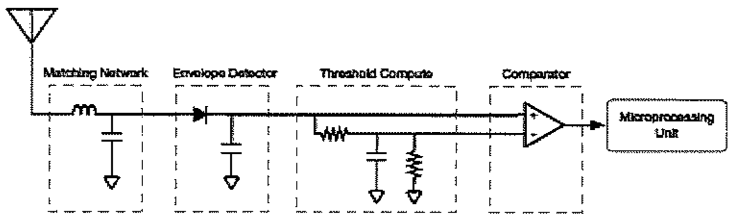


Fig. 7. **Glaze Receiver Design.** A high level circuit diagram of the Glaze receiver.

evaluation of the impact of Glaze embedding for different signal characteristics. In Section 7 we demonstrate this by evaluating the impact of the Glaze system on Wi-Fi, TV, FM signals. Lastly, the digital attenuator takes input from the MCU and performs the data embedding. Depending on the wireless signal that the Glaze module will be overlaying data on, certain components of the Glaze module would be disabled. For example, the signal detector, adaptive rate embedding, and occupancy prediction are only necessary for intermittent signals. Figure 6 illustrates the the process that each component of the Glaze module performs.

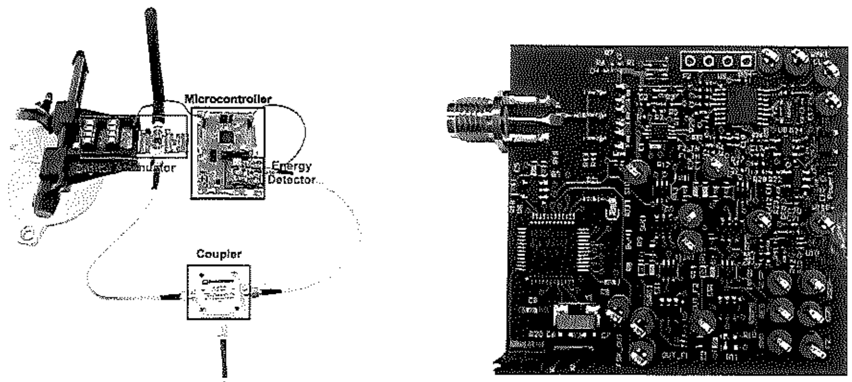
5.2 Glaze Receiver Design

Next we describe how the Glaze receiver achieves a low-power design and decodes the Glazed data. Figure 7 shows the design of the Glaze receiver, which has four stages: 1) impedance matching 2) envelope detection 3) threshold compute and comparator 4) microprocessing unit.

- **Impedance Matching:** An impedance matching circuit is passive and consists of inductors and capacitors used to tune the receiver to a specific radio frequency. For each wireless system that Glaze is integrated with, the Glaze receiver must be tuned to the appropriate frequency to have optimal performance. For instance, if we are overlaying data on TV broadcast signals then the Glaze receiver should be tuned to one of the channels in the UHF or VHF bands. Similarly, for Wi-Fi or FM the matching network of the receiver would need to be modified.
- **Envelope Detector:** The task of the envelope detector circuit is to remove the high frequency carrier from the received signal (eg. 2.4GHz for Wi-Fi). It is completely passive by using only diodes and capacitors, in turn allowing it to operate at very low-power. We choose specific values for each one of the circuit components to remove the carrier frequency and only the amplitude of the signal remains.
- **Threshold Compute and Comparator:** In principle, an ADC can sample the output of the envelope detector and distinguish between two signal levels. However, to enable a low-power receiver, we should not use the ADC to decode data. Instead, we design a RC circuit to compute a dynamic threshold based on the input signal. Then a comparator compares this threshold with the input signal and outputs the embedded data. The RC circuit is equivalent to a single-bit ADC that has a dynamic threshold based on the input signal.
- **Microprocessing Unit:** Similar to the Glaze module, the Glaze receiver also uses a microcontroller (MCU). In this case, the MCU performs only one task. It takes the output of the comparator and decodes the received data. Then based on the data tasks can be performed. This can be anything from provisioning the IoT endpoint device or triggering a sensor to collect data.

6 PROTOTYPE IMPLEMENTATION

In order to perform an evaluation of the Glaze system we implement prototypes of the Glaze module and receiver described in Section 5. The Glaze module is implemented using off-the-shelf components as shown in Figure 8(a).



(a) **Glaze Transmitter Prototype.** Off-the-shelf components used to implement the Glaze module.

(b) **Glaze Receiver Prototype.** The Glaze receiver printed circuit board.

Fig. 8. **Prototype Implementations.** The Glaze module and receiver prototype hardware.

Specifically, an LTC5505 Analog Devices energy detector, MSP432 microcontroller (MCU), and an HMC1119 Analog Devices digital attenuator. The energy detector is used to enable the Signal Detector and Traffic Predictor. The microcontroller enables the Parameter Optimizer and coupled with the digital attenuator to enable the Glaze Embedder.

A 4-layer printed circuit board (PCB) was developed to prototype the Glaze receiver design using off-the-shelf components. The receiver is implemented using a MSP430F5310 microcontroller and NCS2200 TI comparator. The prototype receiver board is shown in Figure 8(b). To receive data, the MCU needs to sample the output of the comparator, perform cross-correlation to find the preamble, and finally, decode the Manchester encoded data. The maximum achievable throughput with this receiver is limited to 10kbps, a constraint set by the MCU and its power consumption. That is, the MCU needs to sample the output of the comparator, performs an if-else statement and saves the results in the memory. This process can be done for data rates less than 10kbps . However, running the MCU with higher frequency crystals would increase this limit but also the power consumption. By increasing the frequency, the MCU would be able to sample the output of the comparator and save the results in the memory faster and as result the data rate could be higher. The Glaze receiver prototype uses an 8MHz crystal and this limits the data rate to 10kbps.

Fundamentally, there is a trade-off between power consumption and performance. For the Glaze receiver to operate at low-power, we use less power consuming components such as the completely passive envelope detector and comparator to decode data. However, these design choices also limit the sensitivity of the Glaze receiver to -25dBm. To improve sensitivity, other design approaches can be taken. For instance, we can add a Low Noise Amplifier (LNA) to the Glaze receiver to amplify the input signal. Another approach to improve the sensitivity is by using the ADC of the MCU rather than the comparator and threshold compute components. Since the ADC has better sensitivity or in other words it is able to detect signals with lower signal strength, we would be able to achieve a higher communication range at the receiver. While these approaches improve sensitivity they also increase the power consumption of devices and would not be practical for low-power or battery-free systems. With the current topology of the Glaze receiver, we achieve very low-power consumption. The Glaze receiver consumes only 50μW in listening mode and 800μW when decoding data at 5kbps. This amount of power consumption allows us to have a battery-free design that can harvests the required energy from ambient light or ambient RF signals.

7 EVALUATION

In this section, we focus on evaluating the Glaze system for three different RF signals: Wi-Fi, TV, and FM. Specifically, we first evaluate the impact that the Glaze system has towards each wireless signal, followed by the performance of the Glaze system itself.

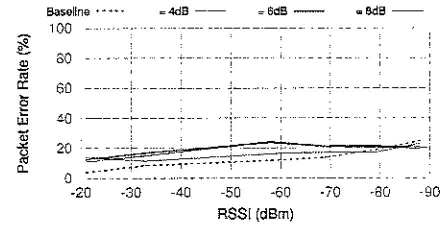
7.1 Impact towards the Wireless Signals

We are interested in the impact that the Glaze system has on the original wireless signals to determine the upper bound for introduced distortion and to ensure that we do not degrade any communication links when overlaying Glaze packets. Distortion impact towards Wi-Fi packet transmissions is evaluated by measuring packet error rate for different amounts of attenuation used for Glaze embedding. Moreover, the impact towards FM signals is gathered by measuring the quality of audio. Similarly, for the TV signals the distortion impact is measured by evaluating video quality. For each evaluation we setup bench-top experiments, where a software defined radio (SDR) is configured as the wireless transmitter, the Glaze module is connected to the antenna port of the SDR to overlay data, and off-the-shelf legacy receivers are used to receive the transmitted signals. The distortion impact for each RF signal was evaluated for Δ = 4, 6, and 8dB attenuation used to embed data. Lastly, the insights gathered from this evaluation are used to formulate the look-up table stored at the Glaze module. The Glaze module uses the look-up table to tell the Glaze embedder how much attenuation can be used to embedded date and a what rate. For instance, the maximum amount of attenuation that can be used per signal type. Moreover, for data networks such as Wi-Fi, how much attenuation can be used depending on the RSSI of associated clients.

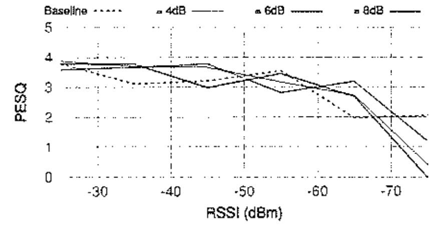
7.1.1 Wi-Fi Packet Transmissions. To evaluate distortion impact for Wi-Fi signals we overlay Glaze data on top of Wi-Fi packet transmissions and analyze the PER as a function of RSSI. A USRP X300 is configured as a Wi-Fi AP to send 802.11g Wi-Fi packets with a data rate of 9Mbps and packet length of 346 bytes. We transmit 200 consecutive packets with an interarrival time of 25μs. A Dell laptop PC is used as a Wi-Fi receiver to receive the Wi-Fi transmissions. Finally, the total packets received are used to determine the PER. Figure 9(a) shows a plot of PER versus RSSI ranging from -20 to -90dBm with different amounts of attenuation applied. For a fair comparison, we also plot the baseline of the PER for our experimental setup.

Intuitively, we expect that as the RSSI decreases the PER will increase and as more attenuation is introduced to overlay data, we expect the PER to increase further. This trend is evident when the attenuation is Δ=6 dB or greater, however, the distortion impact is still minimal. For instance, when Δ is greater than 4 dB the average deviation from the baseline is approximately 8%. The key takeaway from this experiment is that when the Glaze module uses Δ 8dB the system does not need to be concerned about degrading the Wi-Fi packet transmissions, even at low RSSI. However, if a larger Δ is to be used, the RSSI of associated clients must be taken into account.

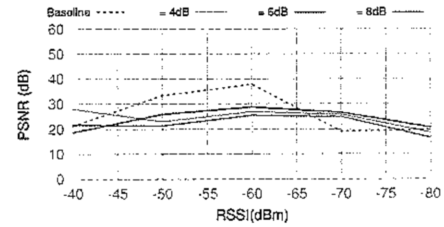
7.1.2 Analog FM Broadcast Signals. The distortion impact towards FM broadcast signals is evaluated by using the Perceptual Evaluation of Speech Quality (PESQ) metric to measure the quality of audio after data embedding. The PESQ metric models a mean opinion score (MOS) that ranks the quality of speech from 1 being very bad to 5 being excellent. As a reference, a PESQ score greater than 1 is considered sufficient for human hearing [7]. A real FM broadcast signal was recorded using a USRP at 91.7MHz for 15 seconds. The signal recording was retransmitted using the USRP, with the Glaze module connected to the antenna port to embedded data. The signal is received by a FM radio and the audio was recorded to then calculate PESQ as a function of RSSI. Figure 9(b) shows the results for PESQ versus RSSI ranging from -25 to -75dBm. The PESQ results show that FM broadcast signals are resilient towards Glaze embedding for attenuation ranging from Δ=4-8dB, even at very low RSSI.



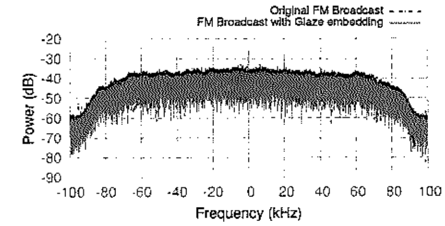
(a) **Impact on Wi-Fi Signals.** The PER as function of RSSI for Wi-Fi transmissions with Glaze embedding.



(b) **Impact on FM signals.** The PESQ of demodulated FM audio as function of RSSI with Glaze embedding.



(c) **Impact on TV signals.** The PSNR of video quality from demodulated digital TV with Glaze embedding



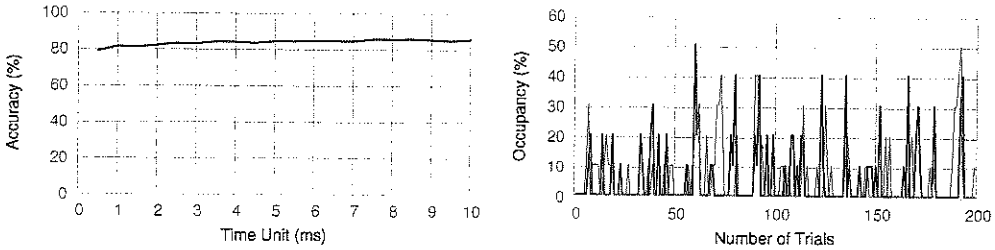
(d) **Impact in the Frequency Domain.** FM broadcast signal spectrum before and after Glaze embedding.

Fig. 9. **Distortion impact of Glaze on wireless signals.** The distortion impact on Wi-Fi, FM, and TV signals was evaluated for different amounts attenuation used for Glaze embedding.

Furthermore, the PESQ maintains a value greater than one up until -80dBm, even using very high amounts of attenuation.

7.1.3 Digital TV Broadcast Signals. We evaluate the impact Glaze has on digital TV signals by measuring the quality of audio using the Peak Signal-to-Noise (PSNR) ratio. PSNR is the ratio of the maximum power of a signal to the power of the distorting noise [22]. Typically in wireless systems a PSNR ranging from 20-25dB is considered sufficient for image quality [22]. Similarly to FM, a real TV signal was recorded at 539MHz for 10 seconds. The signal recording was re-transmitted using a USRP with the Glaze module connected to the antenna port to embedded data. The signal was received using an off-the-shelf TV tuner. We recorded 10 second videos for different Glaze embedding scenarios as function of RSSI. Figure 9(c) shows the measured PSNR versus RSSI for a TV broadcast signal. We see the impact that the Glaze embedding has on the video the TV signal was carrying almost immediately. At an RSSI of approximately -45dBm the PSNR begins to deviate from the baseline results. However, when applying attenuation ranging from Δ=4-8 dB the PSNR maintains a value greater than or equal to 20 dB, even at very low RSSI.

7.1.4 Impact in the Frequency Domain. Evaluating the impact that the Glaze system has on an RF signal in the frequency domain in necessary to ensure spectral mask requirements are maintained. Figure 9(d) shows an FM signal before and after overlaying data using 4dB attenuation. We can see that the the FM signal with overlaid data is attenuated uniformly across the entire 200kHz bandwidth. This resulted is expected because the digital attenuator at the Glaze module is designed to apply attenuation across the entire channel bandwidth. Moreover, a minimum of 25dB is maintain between the main and side lobes of the signal.



(a) **Wi-Fi Traffic Occupancy Model.** Accuracy of the model for different units of time in milliseconds

(b) **Predicted Occupancy.** An example of predicted occupancy in comparison to the actual Wi-Fi traffic occupancy from the collected data set.

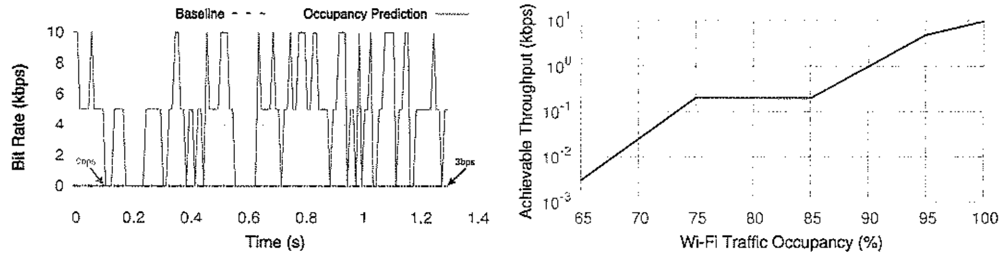
Fig. 10. **Markov Model Evaluation.** The accuracy of the two state Markov model to predicted Wi-Fi traffic occupancy.

7.2 Glaze System Performance

To evaluate the performance of the Glaze system, we first look at how well the Glaze module can optimize the Glazing technique for Wi-Fi signals. We discussed in previous sections that the module can adapt the bit rate for data embedding and optimize parameters to achieve the best performance. To gather the feasibility of this implementation, we first evaluate the performance of the two state Markov model to predict Wi-Fi traffic occupancy and discuss how the Glaze module can use these inputs, among others, to optimize performance. Lastly, we evaluate the performance of the Glaze receiver. In particular, we are interested in the bit error rate at varying distances from the Glaze module. Moreover, we evaluate the bit error rate for the overlaid Glaze data when using different amounts of attenuation to overlay data. In the following sections, we detail the results of each evaluation.

7.2.1 Modeling Wi-Fi Traffic Occupancy. A two state Markov model is used to predict the total Wi-Fi traffic occupancy per unit of time, as described in Section 5.1. These insights can help the Glaze module determine the best bit rate per packet and in turn enable adaptive rate embedding. To evaluate the accuracy of the model, we collect Wi-Fi traffic data in a home setting where there is a single Wi-Fi AP using 802.11b/g/n protocols and four active clients. The clients are all performing different tasks ranging from simple web browsing to video or music streaming. We use the Wi-Fi traffic data to generate transition matrices and make predictions for expected Wi-Fi traffic occupancy in the next time frame. For example, the first 5ms seconds of Wi-Fi traffic data is used to generate a transition matrix, and this set of probabilities are used to predict the total Wi-Fi traffic occupancy in the next 5ms and so on. To evaluate the model we run 7500 trials and compare the predicted occupancy to actual occupancy in the Wi-Fi traffic data set collected and calculate the accuracy percentage.

Figure 10(a) shows the accuracy of the model when predicting occupancy for units of time ranging from 0.5-10ms. Furthermore, Figure 10(b) shows an example of the actual occupancy and predicted occupancy for a 10 ms unit of time and for 200 trials. The accuracy of the model ranges from 80-85%, where predicting occupancy for very short units of time, for instance 0.5ms, is not as accurate in comparison to longer units of time, 5-10ms. Intuitively, it makes sense that units of time that are 0.5ms or less have lower accuracy. The reasoning is that typically the duration for Wi-Fi packet transmissions are very short. For instance, high throughput protocols (eg. 802.11g/n/ac) have packet durations that are in the μs range. In this case, if we continue to decrease the time unit used for the occupancy model then the accuracy would eventually be equivalent to a coin toss. In other words, decrease towards 50%.



(a) **Adaptive Rate Embedding.** The performance improvement of Glaze when using the Traffic Predictor

(b) **Wi-Fi Achievable Throughput.** The maximum achievable throughput for the Glaze system as a function of downlink Wi-Fi traffic occupancy.

Fig. 11. **Achievable throughput for data overlay on Wi-Fi transmissions.** The achievable throughput for Glaze embedding for Wi-Fi scenarios using adaptive rate embedding.

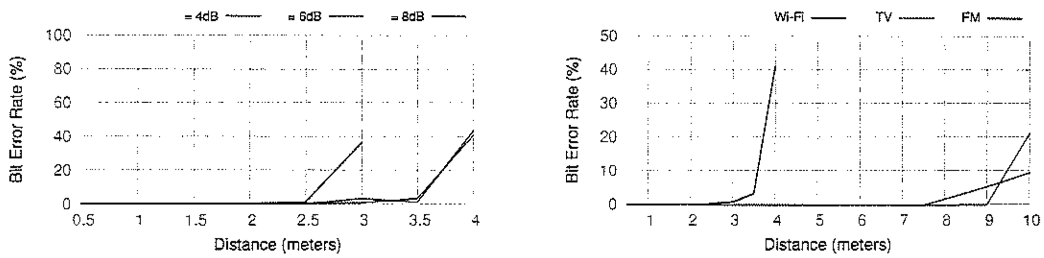
These results show that using the two state Markov model to predict short-term Wi-Fi traffic occupancy can help the Glaze transmitter choose the optimal parameters to begin embedding and also the best data rate to use for any given unit of time. Figure 11(a) shows an example of bit rate as a function of time with and without occupancy prediction for real Wi-Fi traffic. If occupancy prediction is enabled at the Glaze transmitter the bit rate used to overlay data can be adapted to higher rates when there is high occupancy. However, without having any knowledge of the channel occupancy the Glaze transmitter would need to fall back to the baseline data rate of 3bps.

7.2.2 Achievable Throughput. In order for the Glaze module to optimize data overlay parameters, it also needs to know the achievable throughput for different amounts of Wi-Fi traffic occupancy during a select unit of time. To gather this information we applied the Glaze data overlay technique to Wi-Fi transmissions for occupancy varying per 1ms unit of time. For each occupancy we overlaid Glaze data using data rates ranging from 0.03-10kbps and attenuation of Δ=8 dB. Figure 11(b) shows a plot of the achievable throughput as a function of Wi-Fi traffic occupancy ranging from 65-100%. We can see that at 100% Wi-Fi traffic occupancy we can achieve the maximum data rate of 10kbps and as the occupancy decreases the achievable throughput decreases to the baseline data rate of 3bps. It is important to note that the upperbound on achievable throughput of the Glaze system is limited by the prototype implementation. Specifically, the MCU used at the Glaze receiver can only decode data at rates up to 10kbps. In future implementations, this can be improved by using higher frequency crystals at the MCU. Table 1 compares the performance of Glaze to other backscatter solutions in terms of downlink capability, signal compatibility, modification to the hardware/firmware of existing wireless transmitters, throughput, and range. Solutions such as Ambient and FM Backscatter do not have downlink capabilities. On the other hand, Wi-Fi backscatter enables downlink communication for IEEE 802.11- protocols, but also requires modification to Wi-Fi APs. Wi-Fi backscatter achieves data rates of up to 20kbps at distances 2.2m and 5kbps at 3m, whereas, Glaze reaches data rates of up to 10kbps at 3.3m. Given these results, the two systems are not directly comparable in terms of throughput performance. Moreover, referring back to Section 6, the achievable throughput of Glaze is limited by the 8MHz crystal in the prototype implementation and can be further improved with minor hardware modification to the Glaze receiver.

Lastly, this throughput analysis is utilized at the Glaze module, along with results from Section 7.1 and 7.2.1, to perform parameter optimization and adaptive rate embedding to ensure that we maximize performance while minimizing the interference towards the original wireless signals.

Table 1. **Comparison to other Downlink Backscatter (BS) solutions.** A comparison to other backscatter solutions in enabling downlink communication.

Solution	Downlink	Signal Compatibility	Device Modification	Downlink Throughput	Range
Ambient BS [14]					
FM BS [23]					
Wi-Fi BS [10]		Wi-Fi		20, 5kbps	2.2, 3m
Glaze		Wi-Fi,FM,TV		10kbps	3.5m



(a) **Wi-Fi Overlay Performance.** The BER as a function of distance for the Glaze system in a Wi-Fi scenario.

(b) **Performance Comparison.** The BER as a function of distance for the Glaze system in FM, TV and Wi-Fi scenarios.

Fig. 12. **Performance of the Glaze System.** The achievable throughput and BER performance for the Glaze system when overlaying data on Wi-Fi, TV, and FM signals.

7.2.3 Bit Error Rate versus Distance. Next, we evaluate the bit error rate (BER) as a function of distance between the Glaze module and receiver. We perform our experiments on Wi-Fi packet transmissions in an indoor lab setting and FM and TV broadcast signals outdoors on a university campus. Each wireless transmitter is placed in a fixed position with the Glaze module attached to the antenna port. The Glaze receiver is placed at a varying distance from the transmitter. To evaluate the Glaze system for Wi-Fi signals, we use an 8dBi directional antenna at the transmitter and a 3dBi omnidirectional antenna at the Glaze receiver. The transmit power at the wireless transmitter was set to 20dBm. In the case of evaluating the system for FM and TV broadcast signals, we also used an 8dBi directional antenna at the transmitter and 3dBi omnidirectional antenna at the Glaze receiver. Since it is impractical to emulate FM and TV broadcast tower, we transmit TV and FM broadcast signals at 915MHz with a transmit power of 20dBm.

Figure 12(a) shows the BER as a function of distance for Glaze packets overlaid on Wi-Fi packet transmissions. We performed a controlled experiment with a bit rate of 10 kbps for Wi-Fi traffic occupancy approximately 100% to demonstrate the the maximum performance of the Glaze system. The results show that with an attenuation of Δ=4dB the Glaze system can achieve data rates of up to 10 kbps at a distance of 2.5 meters and when the attenuation is further increased to 6 and 8dB the distance improves to 3.5 meters. Figure 12(b) compares the performance of the Glaze system for all three RF signals. Similarly to Wi-Fi, Glaze packets were overlaid on TV and FM broadcast signals using a bit rate of 10 kbps for varying amounts of attenuation. We can see that FM has the best performance with range up to 10 meters, followed by TV at 9 meters, and Wi-Fi at 3.5 meters.

Fundamentally, Wi-Fi has a shorter communication range in comparison to FM and TV just by considering the carrier frequency. In other words, as the carrier frequency increases the path loss increases as well, in turn

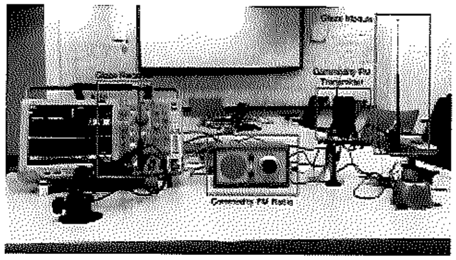


Fig. 13. **Proof of Concept.** The Glaze system integrated with a commodity FM transmitter.

decreasing the communication range of a wireless communication system. We see this in our results, where the communication range for the Glaze system is approximately half in comparison to the FM and TV broadcast signal results, which where transmitted at 915MHz. This makes sense because 915MHz is approximately half of the carrier frequency for Wi-Fi, 2.4GHz. While the evaluation for FM and TV was performed at 915MHz, we would expect in a real-life scenario the communication range for broadcast signals to be significantly larger. The reasoning behind this is twofold. First, digital TV operates in the UHF and VHF band in the United States, which is much lower than 915MHz. Similarly, FM broadcast signals in the United States are transmitted at carrier frequencies ranging from 87.8-107MHz. Second, the transmit power at TV and FM broadcast towers are drastically higher than 20 dBm. An estimate of communication range for real-life FM and TV broadcast scenarios is 125km and 75km, respectively.

7.3 Proof of Concept

For proof of concept, we integrated the Glaze system with a commodity FM transmitter. Figure 13 shows the proof of concept implementation. The Glaze module is connected to a commodity FM transmitter and a laptop PC is used to provide an audio input to the FM transmitter. The FM signal is broadcast at 108MHz and received by a commodity FM radio. Meanwhile, the Glaze receiver is able to decode the overlaid packets. To give readers an intuition of FM audio quality with Glaze embedding and performance of the Glaze receiver we provide a video clip demonstrating the Glaze system in the following web link, https://youtu.be/FIJPrj2Pt04

8 APPLICATIONS BEYOND BACKSCATTER

While this paper focuses on enabling downlink communication for backscatter systems, there are several other IoT applications for Glaze. Many of today's technologies require expensive equipment to enable communication with IoT endpoint devices. Glaze on the the other hand, is a low-cost and low-power solution that can enable downlink communication for devices. In the remainder of this section, we discuss a few potential applications beyond ambient backscatter systems and explain why Glaze is a viable solution,

- **Low-power wake-up signals.** Glaze can be used to send low-power wake-up signals to devices. For instance, when deploying large-scale sensor networks, many of these devices rely on batteries and need to be efficient with power. Glaze can trigger devices to report data only when necessary rather than relying on fixed duty cycling. Recent work in enabling low-cost Internet connectivity for remote regions is another example use case. In Wi-Fly, Internet from commercial planes is leveraged to extend coverage to base stations on the ground [1]. Most of these base stations are power constrained and because connectivity is intermittent, devices should save power by only turning on when a plane is flying by. In this scenario Glaze can be leveraged to send low-power wake-up signals to the base stations when an airplane is present.

Downlink Data Streaming. Glaze can be used to enable downlink data streaming to devices to enable smart city applications. In an urban city environment there are FM, TV, and cellular broadcast towers. These towers transmit signals that travel very long distance, tens of miles. The Glaze module can be retrofitted with these transmitters to stream data to billboards, send traffic announcements, update bus schedules or advertisements to name a few. Furthermore, several cities and homes are already equipped with smart devices. Some examples include devices like doorbells, thermometers, and security cameras and all of these require updates at one point or another. The Glaze system can be used to send updates to devices in a single transmission, rather than sending updates to each individual device.

9 RELATED WORK

Our work is related to efforts in backscatter communication systems [6, 8, 10, 21]. For instance, Interscatter shows how Wi-Fi transmissions can be generated by backscattering Bluetooth signals [8]. Wi-Fi backscatter enables uplink communication by backscattering Wi-Fi transmission and is also capable of downlink communication by encoding bits in the presence or absences of Wi-Fi packets, which achieves data rates of up to 20kbps at 2.2 meters and 5kbps at 3 meters. However, this technique requires modifications to the Wi-Fi AP and only works for 802.11 compliant devices. While Wi-Fi backscatter has shown to have higher throughput at shorter distances, the Glaze system can achieve longer range with slightly lower data rates in Wi-Fi scenarios. This can be an appealing trade-off when deploying backscatter based IoT systems for coverage of larger areas since most downlink transmissions have low bandwidth requirements (eg. acknowledgements, reporting rate).

Recently there have been several emerging techniques in cross-technology communication that relate to Glaze as well. Solutions such as FreeBee and Chiron show how to enable concurrent communication between Wi-Fi and ZigBee devices [11, 13]. Other techniques such as B2W2 enable communication between Wi-Fi and BLE devices [4]. In relation to cross-technology, applying data hiding techniques to wireless communication has been proposed [9] [24]. These techniques analyze the performance of data hiding techniques for wireless signals and show in simulation how additional data can be encoded in RF signals to communicate with IoT devices. Other solutions such as Smart Personal Object Technology (SPOT), developed by Microsoft in 2002, uses FM broadcast subcarrier transmissions to convey data to devices [16], such as smart watches. Similarly, WATCH demonstrates how Wi-Fi transmissions can be sent in active TV channels [25].

All of these techniques are promising approaches to enable downlink communication but they are either limited to low throughput or short range, applicable only to specific wireless standards, or require modification to commodity devices. In contrast, Glaze improves upon this by providing a low-cost and low-power solution for downlink communication that is compatible with a variety of wireless standards. Moreover, the Glaze module does not require hardware or firmware modifications to existing transmitters, but instead connects the antenna port of devices to overlay additional data and enable downlink communication.

10 DISCUSSION AND CONCLUSION

We introduced Glaze, a new communication system that overlays data on existing wireless signals to enable downlink communication for ambient backscatter systems while having minimal distortion impact towards preexisting communication channels. In this section, we highlight several future research directions for the Glaze system.

Improving Throughput and Sensitivity. We have shown that Glaze can be integrated with a variety of wireless transmitters to overlay downlink data transmissions. However, the performance for certain scenarios can still be improved. For instance, the range in Wi-Fi scenarios is currently limited to 3.5m. This can be improved by using better performing hardware, for instance replacing the MCU, but a possibly more power conscious approach would be exploring different coding techniques to increase throughput and sensitivity. In relation to throughput, performing multilevel embedding can be implemented. For instance, multiple states of attenuation can be used to embed multiple bits per symbol. Developing protocols to perform adaptive multi-level embedding based on channel conditions would also help boost performance. This would require the Glaze receiver to have knowledge of the data rate and number of attenuation states used for encoding data, requiring a more complex physical layer implementation.

Forecasting Wi-Fi Traffic. A two-state Markov model was implemented to aid in predicting the short-term downlink Wi-Fi traffic occupancy and in turn optimizing Glaze embedding. While this technique has proven to perform well, there are many other approaches that can be explored to further improve the the performance of Glaze embedding. For instance, recurrent neural networks can prove to provide in-depth insights about Wi-Fi traffic. One example is the long short-term memory model and can be used to forecast Wi-Fi traffic, predict interarrival times, or average packet size with presumably better accuracy.

Multi-band Glaze Receiver. The current topology of the Glaze receiver requires modifying the impedance circuit depending on what wireless signal is being used to overlay data due to the varying carrier frequency. A potential research direction to solve this problem is to explore implementing a multi-band Glaze receiver that could operate at ISM, UHF, and VHF bands.

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