Supporting Information for

Communication by Means of Modulated Johnson Noise

Zerina Kapetanovic, Miguel Morales and Joshua R. Smith

Zerina Kapetanovic.
E-mail: zerinak@uw.edu

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Supporting Information Text

System Validation

We provided additional details of the system validation in the following sections.

Experimental Setup. Fig. S1 shows the experimental setup used to collect data of several different loads connected to the receiver: 50Ω at three different temperatures, short circuit, open circuit, and the input of an LNA. To clarify the meaning of "LNA input" as a load: we take an additional powered up LNA and connect its input to the input of our standard receive signal chain (which consists of two more LNAs, bandpass filter, etc.). The LNA that is used as a load is identical to the LNAs used in the receive chain. The purpose of measuring the LNA input as a load is to measure its effective noise temperature, which will determine the baseline noise that the received communication signals will be added to, and will also determine the properties of the radiation field that the receive LNA emits back toward the transmitter.

To lower the temperature of the 50Ω load to 273K and 77K, we submerged the load in ice water and liquid nitrogen, respectively. The temperature values for room temperature and ice water were measured with a thermal camera. The liquid nitrogen temperature was taken to be the standard value for liquid nitrogen (77K) because its temperature was below the range of the thermal camera. In Fig. S2 we show the thermal images of the cabled experimental setup.

Performance Evaluation

To evaluate the performance of our prototype implementation we used off-the-shelf hardware. The transmitter includes an ADG919 RF Switch, a 50Ω terminator, an open circuit terminator, and a Raspberry Pi 3B was used to control the RF switch. The receiver includes two ZHL-1217HLN+ LNAs, a VBF-1445+ bandpass filter, an RTL-SDR dongle, and a laptop PC (1–3). Both the transmitter and receiver use pyramidal horn antennas that provide approximately 13.6dBi of gain.

SDR Hardware Configuration. We note that the SDR must have a fixed gain value configured. In particular, when working with RTL-SDR devices, the gain is not set to a fixed value by default. Not doing so can results in inconsistent data recordings. Additionally, it is common for certain RTL-SDR devices produce a constant DC 'spike'. This can be suppressed by using the Hampel identifier. In Fig. 1A of the main text, this method was used to remove the DC spike, specifically with number of neighbors, k = 100. Lastly, to interface with the SDR, the Python RTL-SDR library was used (4).

Data Packet Transmission and Detection. To evaluate the performance of the system, data packets were transmitted that are structured to have a preamble followed by data payload. The preamble is a 7-bit Barker code that is used for packet detection and synchronization. The data packet has a total of 20-bits. In Figure S3 we show an example of encoding a data packet. To detect and decode a data packet on the receive side, the receiver first performs heterodyne detection to get the demodulated signal and then synchronizes by cross-correlating for the known preamble. After synchronizing for the preamble, the data bits can be extracted from the data packet.

System Design and Implementation

We provide additional details on the system design and implementation in the following sections.

Selecting an RF Switch. The system was evaluated using an ADG918 RF switch, however, other switches in the ADG family can be used. In Figure S4 we show a comparison of ADG918, 919, and 901 all of which has excellent feedthrough isolation, but the RF load configuration may vary. First off, the ADG918 and 919 are SPDT switches and the primary difference is that the ADG918 is absorptive and the 919 is reflective. Here, the load configuration does not matter and both will have identical performance since the RF1 and RF2 ports isolated from each other.

The ADG901 is an absorptive SPST which can also be used, but requires specific load configurations for the RF1 and RF2 ports. In Figure S4C we show the schematic for the ADG901 where the unselected port is connected to a 50Ω shunt. The ADG901 switches between RF1 being isolated from RF2 and RF1 being connected to RF2. Given this, only specific load configurations will work. Specifically, the system will work if RF1 and RF2 both are connected to an open circuit load or if RF1 is connected to an open circuit while RF2 is connected to 50Ω. This is due to the fact that the RF ports are connected to 50Ω shunts and the aforementioned configurations ensure there is a contract between the two states. For instance, if RF1 is connected to 50Ω and RF2 is connected to an open circuit, then regardless of what switch state you are in, you will always see 50Ω and the receiver would not be able to demodulate any information bits because there is no contrast between the two RF switch states.

Constructing Horn Antennas. The horn antennas used to evaluate the system were constructed using readily available materials and were based off of the designs provided by the West Virginia University Radio Astronomy Laboratory (5). In particular, an empty “F-type” rectangular paint can and metal-coated home insulation board are used to construct the 1.4GHz antenna. The design can be made more robust by replacing the home insulation board with aluminum flashing.

Additionally, antenna stands were constructed by modifying camera tripods to have a square piece of plywood attached as a platform for the antenna to sit on. The antennas were attached using reusable zip ties which loop through the handle of the paint can (e.g., waveguide) and a hole through the plywood.
Power Consumption Comparison

We compare the power consumption of our transmitter to other passive and low-power wireless communication techniques as shown in Table S1. The transmitter power consumption is identical to that of ambient backscatter solutions and is less power consuming than traditional RFID (WISP platform). We also look into low-power BLE solutions (Atmosic ATM33) which is more power consuming than Modulated Johnson Noise and the backscatter solutions. Of course, the achievable throughput must also be considered, and other solutions would outperform modulated Johnson noise in this regard. For example, ambient backscatter has shown to achieve data rates of up to 10kbps, the WISP can achieve data rates of up to 256kbps, and the Atmosic ATM33 can achieve data rates ranging from 125kbps - 2Mbps (6–8). While Modulated Johnson Noise is limited to low data rates, a key benefit is that it is not dependent on ambient or generated RF signals.
Fig. S1. Noise Measurements Experiment. A block diagram of the cabled experimental setup to evaluate the noise temperature and noise power of various loads.
Fig. S2. Experimental Setup. (A) The cabled experimental setup inside of an anechoic chamber and (B) shows the corresponding thermal image. The 50Ω load submerged in liquid nitrogen is shown in (C) and the corresponding thermal image is shown in (D). Note that the measurement range of the thermal imaging camera does not reach liquid nitrogen temperatures.
Fig. S3. Data Packet Encoding. (A) shows a 20Hz square wave subcarrier and (B) shows the data packet to be encoded which includes a 7-bit Barker code as the preamble followed by data bits. (C) shows the resulting encoded signal which is also the control signal for the RF switch.
Fig. S4. Selecting an RF switch. (A) shows the ADG918 switch (B) shows the ADG919 and (C) shows the ADG901. The ADG918 and 919 are SPDT switches while the ADG901 is an SPST switch.
Table S1. Power Consumption Comparison. A comparison of the power consumption of Modulated Johnson Noise to existing low-power wireless communication solutions.

| Solution                  | Power Consumption (TX) |
|----------------------------|-------------------------|
| Modulated Johnson Noise    | 0.25 uW                 |
| Ambient Backscatter (6)    | 0.25 uW                 |
| RFID (7)                  | 2.32 uW                 |
| Low-Power BLE (8)         | 6.3 mW                  |
References

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