Cosmic Backscatter: New Ways to Communicate via Modulated Noise

Zerina Kapetanovic†, Shanti Garman‡, Dara Stotland‡, Joshua R. Smith‡
†Stanford University, ‡University of Washington

ABSTRACT

New methods of passive wireless communication are presented where no RF carrier is needed. Instead, data is wirelessly transmitted by modulating noise sources, from those found in electronic components to extraterrestrial noise sources. Any pair of noise sources with a difference in noise temperature can be used to enable communication. We discuss using the Earth, the Moon, the Sun, the coldness of space, and Active Cold Load circuits as sources of thermal contrast. We present Cosmic Backscatter and demonstrate that wireless connectivity can be enabled by switching an antenna connection between the "cold" Sky and a "hot" 50Ω resistor. Furthermore, we present Noise Suppression Communication, where data is transmitted by controlling an Active Cold Load to selectively reduce emitted noise below ambient temperature levels.

CCS Concepts: • Hardware → Wireless devices; • Networks → Cyber-physical networks

Keywords

Thermal Noise, Backscatter, Wireless Communication

1 Introduction

Cosmos, or the universe, includes all of space and the energy that space contains, which of course includes the Earth, the Sun, the Moon, the Sky, other planets, asteroids, and much more [11]. Radio astronomers observe celestial objects and characterize them in terms of their brightness (or noise) temperature. They can also be considered cosmic microwave noise sources that thermally generate noisy electromagnetic signals. In addition to observing (or sensing) these cosmic noise sources, this paper demonstrates that they can be used to enable passive wireless communication. We can backscatter thermal noise sources by switching an antenna connection between two noise sources that have a high temperature contrast (e.g., the Earth and the Sky). Consider a transmitter that switches its transmit antenna connection between two states, similar to traditional backscatter techniques. Cosmic noise sources can be modulated using this same transmitter design by having an antenna pointing towards the Earth as one connection state, while the other being an antenna pointing up towards the sky. Figure 1 shows an example of the case where the antenna is pointing up towards the sky to perform measurements. These methods can be thought of as generalizations of modulated Johnson noise communication [7], where data is transmitted by selectively connecting and disconnecting an impedance matched resistor to an antenna.

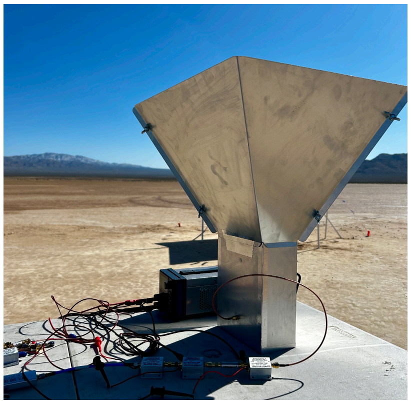

Figure 1: Measuring the Noise Temperature of the Sky. A horn antenna connected to a receive chain used to measure the noise temperature of the sky at 1.4GHz.

We start with the observation that the essential requirement for Modulated Johnson Noise (MJN) communication is thermal contrast: somewhere in the system it is necessary to have two noise sources with different noise temperatures, which we can refer to as hot and cold. First, this paper summarizes MJN communication and identifies the non-obvious source of cold in this communication scheme. Next, we propose two new methods of communication: (1) Cosmic Backscatter and (2) Noise Suppression Communication, which make use of different cold sources. We compare the expected properties of these three communication methods.

Many of these methods work by switching between an ambient temperature microwave noise source and one that

HotNets '23 The 22nd ACM Workshop on Hot Topics in Networks, November 28–29, 2023, Cambridge, MA, USA
ISBN 979-8-4007-0415-4/23/11
https://doi.org/10.1145/3626111.3628203 ..$15.00.

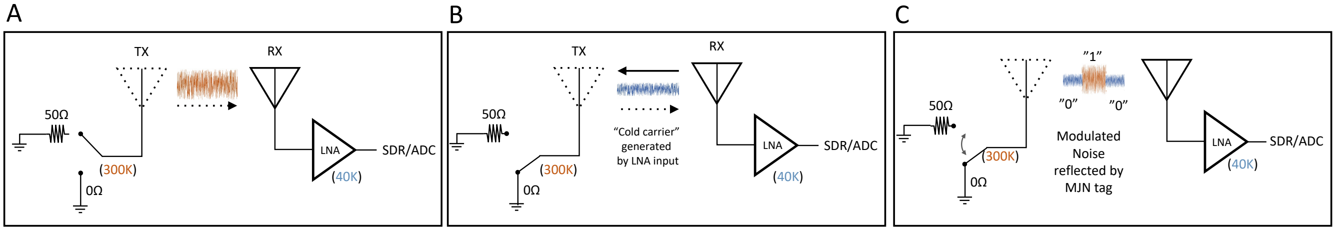

Figure 2: Modulated Johnson noise: Receive LNA as Active Cold Load. **(A)** Johnson noise at ambient temperature (300K) is emitted with a matched 50Ω load is connected. **(B)** The TX antenna is grounded (reflective state) and the cold radiation field from the receive LNA is reflected. In this state, the receive LNA observes a low temperature. **(C)** The switch in the MJN transmitter changes states and the received signal changes between 300K and 40K.

is below ambient temperature. Such methods work not by emitting power, but by suppressing or reducing it. For that reason, they are intrinsically low emission, low interference, and stealthy (i.e. hard to detect). These techniques, compared to MJN, use different cold sources. In MJN the receive LNA input is the cold source, whereas in Noise Suppression Communication a powered LNA on the transmit side is the cold source and Cosmic Backscatter uses the sky as the cold source. The properties of the three methods differ in various ways, which makes them suitable for different applications depending on power and emissions requirements.

Compared to other passive and active communication techniques, modulating noise sources has unique advantages. A conventional wireless communication transmitter generates radio waves. In backscatter communication, one device generates radio waves and a different device can send information by reflecting those radio waves. This paper describes a family of alternative approaches to communication in which data is transmitted in a distinct way: by switching the transmit antenna between ambient temperature ("hot") thermal microwave noise and a lower temperature source of thermal microwaves.

As an example, we can consider applications related to enabling co-existence between space and terrestrial wireless communication and sensing systems. There are over 5,500 active satellites in orbit and it is expected that there will be 58,000 by the year 2030 [14]. This increase introduces new challenges that need to be addressed such as minimizing radio frequency interference (RFI) that disrupt other critical technologies. For example, terrestrial observatories use extremely sensitive RF equipment and are significantly impacted by RFI introduced by satellites.

The proposed communication techniques can enhance the co-existence between space and terrestrial wireless communication systems. While these techniques cannot fully replace existing methods, they can be used to mitigate interference and improve spectrum efficiency for ground-to-satellite, satellite-to-ground, and intersatellite communication. A benefit to modulating noise to convey information is that it would cause significantly less RFI, and as previously mentioned, can be viewed as a form of noise suppression since the maximum signal ever generated would be the power level of ambient noise. Moreover, these techniques have many similarities with a microwave radiometer. A radiometer could be used to detect modulated noise signals. There is potential for both space and terrestrial radiometers to be used as hybrid systems for sensing and communication.

In this paper we explore various methods of modulated noise communication and present our vision on how they can benefit a variety of applications. We summarize our key contributions: **(1)** We present Cosmic Backscatter and demonstrate that data can be wirelessly transmitted by modulating cosmic noise, **(2)** We present Noise Suppression Communication and demonstrate that data can be wirelessly transmitted by reducing the emitted noise power, **(3)** We implement a prototype system to evaluate each communication technique and potential noise.

2 Modulated Noise Communication Overview

This section introduces concepts and related work necessary to understand the research described in this paper. It describes Johnson Noise and noise temperature, some of the fundamental physical concepts the paper relies on. It describes Microwave radiometers, which use related methods for sensing rather than communication. It introduces the concept of the Active Cold Load (ACL), a circuit that generates "cold" noise, and which ordinarily is used to calibrate a radiometer. It describes the naturally occurring cold microwaves that can be observed in a clear sky. This paper demonstrates that by modulating between a hot load (300K resistor) and either an ACL or the cold sky, data can be transmitted using signal power levels that are below the ambient thermal noise.

2.1 Noise Temperature

All objects emit electromagnetic radiation that depends on their temperature and emissivity. A black body (with maximum emissivity), emits radiation whose power as a function of frequency is accurately described by Planck's law. In other words, Planck's law predicts the spectrum of the emitted light given the temperature of an object. This is

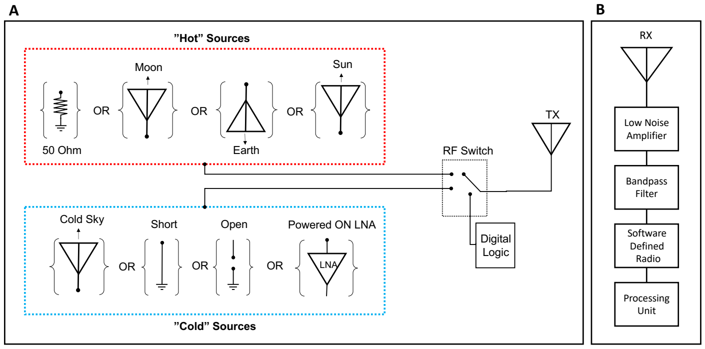

Figure 3: Modulated Noise Communication System. **(A)** a transmitter switches antenna connection between hot and cold source. **(B)** receiver includes LNA, filter, SDR, and processor.

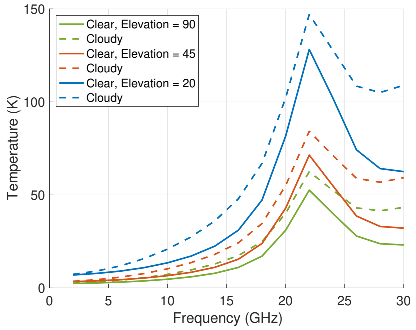

Figure 4: Sky Noise Temperature. Sky noise temperature with respect to frequency at varying elevation angles and weather conditions.

why objects glow red and then blue as the emission peak shifts through the visible range as temperature rises. At low frequencies (including all microwave frequencies), Planck's law simplifies to predict that the noise power is white (independent of frequency) and proportional to absolute temperature. Nyquist's formula describing Johnson Noise is essentially a one-dimensional, low-frequency special case of Planck's law [3]. Given a resistor at temperature T, over a bandwidth B, the total noise power it delivers to another matched load resistor is given by $P = kTB$, where k is Boltzmann's constant [17]. In a circuit, the noise temperature means the temperature at which a matched resistor, with the same bandwidth, would have to be to produce the observed noise power. In a radiometric setting, a microwave radiation field's temperature means the temperature that a black body would need to produce the same amount of thermal microwave power.

2.2 Microwave Radiometers

Due to the dependence of microwave radiation on temperature and emissivity, it is possible to remotely estimate the properties of an object by measuring the microwave noise power that it emits. Microwave radiometers flown on satellites or airplanes are used to create detailed maps of soil temperature, ocean salinity, plant coverage, snow and moisture, and other geophysical properties [19, 10].

In MJN communication, a microwave radiometer is the data receiver, and an electronically switchable ambient thermal noise source is the data transmitter. It turns out that MJN works by changing the emissivity of the transmitter; the physical temperature of the transmitter is always the same. It also turns out to be important that the system is not in thermal equilibrium: the powered receive LNA is essential because it enables the change in transmitter emissivity to produce a detectable change in temperature at the receiver. In other words, in order to detect or observe Johnson noise there must be some thermal contrast (e.g., the LNA input at the receiver is cold, in contrast to the transmitter).Radiometers must be calibrated, using noise sources of two different temperatures. Sometimes liquid nitrogen is used as the cold source. Alternatively, a clear sky zenith measurement can be used as a cold source [8]. In recent years researchers have created purpose-built Active Cold Load (ACL) circuits for radiometer calibration. ACLs are discussed in more detail in the next section.

2.3 Active Cold Loads

An ACL is a circuit that presents a low noise temperature in the microwave frequency range [4, 2]. Physically, the ACL's signal-carrying degrees of freedom (i.e., the carriers responsible for electrical conduction) are cold, but the system's other degrees of freedom (the state of the metal's crystal lattice) are at ambient temperature. In other words, if one were to touch an ACL or measure its emissions at infrared wavelengths, it would appear to be at ambient temperature; its microwave emissions, however, correspond to that of a cold object. There are no commercially available ACLs; however, the input of a LNA functions as an Active Cold Load [18].

2.4 Temperature of the Sky

Compared to other extraterrestrial noise sources (e.g., the Earth or Moon), the sky can be used as a cold source. The noise temperature of the sky is dependent on frequency, weather conditions, and elevation angle (angle of antenna pointing towards the sky). It is known that weather conditions, such as rain and clouds, can significantly impact the noise temperature of the sky, and above 10GHz become the dominant noise source [6]. Under certain weather conditions, the noise temperature can become nearly the same as the ambient physical temperature. In [6] they evaluate the sky noise temperature across a broad frequency range and weather conditions. Using data from [6], Figure 4 shows the sky noise temperature for frequencies ranging from 2-30GHz under clear and cloudy sky conditions. At frequencies below 2GHz the sky temperature ranges from approximately 2-10K depending on elevation and weather conditions. At much higher frequencies, such as above 20GHz, the sky noise temperature is shown to be as high as 150K.

3 Modulated Johnson Noise Communication

In [7, 5], connecting and disconnecting the load impedance from the transmit antenna changes the temperature measured by a microwave radiometer on the receive side. The connected (matched) state is easy to understand: the receiver sees a microwave radiation field at the temperature of the resistor (i.e. ambient temperature). In the disconnected (mismatched) state, the receiver sees a noise temperature that is much lower than the ambient temperature. This is not as easy to understand. It turns out that the LNA in the receiver functions as an Active Cold Load (ACL) [4, 2]: it behaves like a refrigerator, using power to lower the temperature of the signal-carrying degrees of freedom in the LNA input. The powered receiver emits microwave radiation corresponding to a temperature lower than the ambient temperature. The disconnected state of the transmitter is impedance mismatched; in this state, the transmit antenna functions as a reflector. In this state, a cold radiation field originates at the receiver, is reflected by the transmitter, and then propagates back to the receiver where it is amplified. This explains why the receive radiometer measures a low temperature when the transmitter is in a reflective state. Consistent with this theory, the temperature that the receiver measures in the mismatched state is almost the same as the directly measured temperature of the LNA input. The two-way propagation that makes MJN communication possible, thus it is also appropriate to call it Thermal Backscatter. What is actually being backscattered (in the mismatched state) is the cold radiation field produced at the receive LNA's input, as illustrated in Figure 2.

4 Cosmic Backscatter

Cosmic backscatter involves switching an antenna connection between hot and cold sources to modulate bits of information. There are many options for a hot source such as an impedance matched 50Ω load, the Earth, or even the Sun. The Earth, similar to a 50Ω terminator, has a noise temperature of around 290K. The Sun is a noise source that can be observed across a broad frequency range and the brightness temperature varies depending on whether an active or quiet Sun is being observed [12]. A reliable cold source for cosmic backscatter is the Sky. At lower frequencies (< 5GHz) the sky on a clear day is few degrees Kelvin, as shown in Figure 4. Because there is a large temperature contrast between the sky and other hot sources (e.g, Earth), we can enable wireless communication. Using the hardware design shown in Figure 3, we (1) evaluate different noise sources and (2) implement a system to wirelessly transmit data packets using cosmic noise sources.

4.1 Results

To evaluate cosmic backscatter we implement a transmitter that uses an RF switch and Raspberry Pi 3 to control the switch [1]. The RF switch can be configured to switch between different loads. On the receive side we use two low noise amplifiers (LNAs), an RTL-SDR dongle, and a laptop PC as the processing unit [9, 13]. The system is designed to operate at 1.42GHz and both the transmitter and receiver use pyramidal horn antennas [20]. Designing the system to operate 1.42GHz is advantageous for Cosmic Backscatter for several reasons. For example, when using the sky as the cold source, the noise temperature is very low and weather does not significantly impact the noise temperature at lower frequencies, which was shown in Figure 4.

Evaluating Noise Sources. We focus on comparing three different noise sources: a 50Ω terminator, the Earth, and the sky. To perform the evaluation we use a wired setup where a receive antenna is connected directly to the receive chain. The evaluation is performed by collecting approximately 30 million data samples for each noise source observation. Figure 5 shows the observed noise distribution of the real component for each measurement. First, Figure 5A shows the distribution for a 50Ω terminator connected directly to the receive chain.Figures 5B-D show the antenna pointing down towards the Earth, towards the horizon, and up towards the sky, respectively. The observed noise distributions illustrate how temperature plays a role in measured noise power. For example, the 50Ω terminator and the Earth have a much higher temperature compared to the sky, and sky distribution shows a much lower variance which also indicates that the thermal noise power would be much less. This is also shown in Figure 5E, which presents the average measured power after amplification of each noise source. There is approximately a 9.5dB difference between the sky and the Earth, and a 7dB difference between the Sky and the 50Ω terminator. This indicates that data can be wirelessly transmitted by switching an antenna connection between a cold and hot source. Lastly, in Figure 5F we show a thermal image that shows the drastic temperature contrast between the sky and forest shown in the image[1]. **Wireless Data Transmissions.** To demonstrate cosmic backscatter, we implement a system to transmit information by switching between a 50Ω terminator and an antenna pointed towards the sky. This transmitter design is shown in Figure 5G. We configure the transmitter to send data packets using a data rate of 4bps with a distance of approximately 5 feet between the transmitter and receiver. The data packets consist of a 13-bit Barker code used as the preamble, followed by 17 data bits. The packets are transmitted by performing ON-OFF keying. A 1-bit is transmitted by continuously switching between the two states, while a 0-bit is transmitted by staying in the cold state. The receiver demodulates the data packets by performing heterodyne detection and it is assumed that the receiver knows the switching frequency used on the transmit side [7]. Figure 5H shows the resulting demodulated data packet. We believe similar results can be achieved by switching between an antenna pointing down towards the Earth and another antenna pointing up towards the sky.

---

[1] The FLIR E4 IR camera senses from 7.5-13um. The temperature at this wavelength is not generally the same as the temperature at 1.4GHz. Nevertheless, the temperatures at different frequencies tend to be correlated.

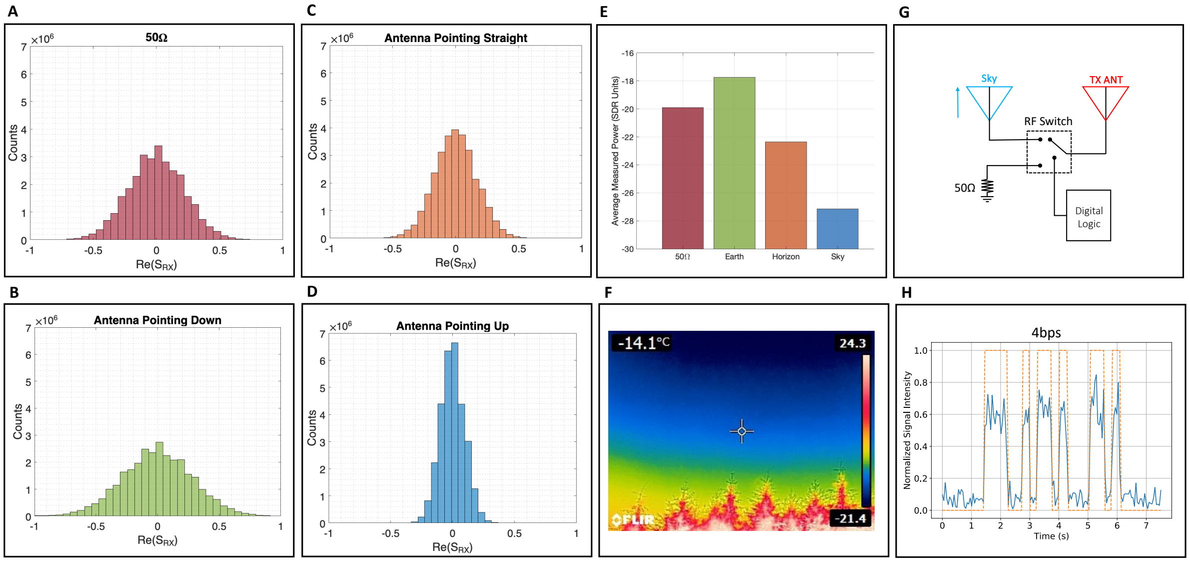

Figure 5: Cosmic Backscatter Results. Distribution of the real part of the received 1.4GHz signal for **(A)** an antenna pointing down towards the Earth, **(B)** a 50Ω terminator, **(C)** antenna pointing towards the horizon, and **(D)** antenna pointing up towards the sky. **(E)** shows average measured power of each load after amplification. **(F)** shows the thermal image of the sky and tree line, illustrating the drastic temperature contrast. **(G)** shows the transmitter implementation used to evaluate cosmic backscatter. **(H)** shows a demodulated data packet that was transmitted wirelessly by switching between cold sky and a 50Ω terminator.

5 Communication by Noise Suppression

Data can be wirelessly transmitted by *reducing* the emitted noise power of a transmitter. This can be done by selectively connecting and disconnecting the input of a powered-on LNA. An LNA may have a physical temperature close to room temperature, but its noise temperature is cold. For example, the ZHL-1217HLN+ LNA has a noise temperature of around 39K when it is powered on, which puts it below that of the ambient thermal noise [7]. In this method, data is sent by selectively connecting an LNA input (cold) or a 50 Ω resistor (hot) to the transmit antenna, as shown in Figure 6. Data is received by measuring the observed noise power at the receiver LNA. While this method is not low power, it is low emissions and stealthy, since the maximum power output is that of an ambient temperature resistor.

5.1 Results

We implement the transmitter design shown in Figure 6 and use the receiver design shown in Figure 3. On the transmit side a ZKL-33ULN-S+ LNA is used as the cold source. All other hardware components are identical to the setup described in Section 4.

Data Transmissions via Noise Suppression. Similar to Cosmic Backscatter, the system is designed to transmit information bits by performing ON-OFF keying. We evaluate the performance of this scheme by comparing the distribution of demodulated 0 and 1-bits, in both wired and wireless experiments. The wireless experiment is conducted in an anechoic chamber, with the transmitting and receiving antennas separated by a distance of 10 cm. 0-bit data and 1-bit data transmissions are recorded and the distribution of demodulated bits are compared. Figure 6B shows the results for the wired experiment with data rates of 10bps and 5bps. Figure 6C shows the results for the wireless experiment at 1bps. In all cases, the difference in signal intensity between the two bit states indicate that data can be transmitted reliably using NSC. As expected, signal intensity in the wireless case is lower than in the wired case, which results in a lower data rate. However, the successful demonstration of wireless functionality is an important step. Another key takeaway from the results is that the distribution comparison provides insight on coding gain using this scheme and how performance varies with respect to data rate.

6 Ongoing and Future Research

We have presented several new techniques for performing passive wireless communication by modulating thermal noise sources. While our initial results are promising there are several ongoing and future areas of research:

Range Scaling Predictions. Measuring the range scaling for Cosmic Backscatter and Noise Suppression Communication will provide more insight on how these techniques compare to modulated Johnson noise. We predict that MJN scales as $\frac{1}{r^4}$ since a cold signal must propagate from the LNA (functioning as Active Cold Load), back to the transmitter which modulates it, after which it propagates forward to the receiver for amplification. We further predict that Cosmic Backscatter and NSC will scale as $\frac{1}{r^2}$ since the cold signal propagates from transmitter to receiver only. **Performance Evaluation and Optimization.** We have presented

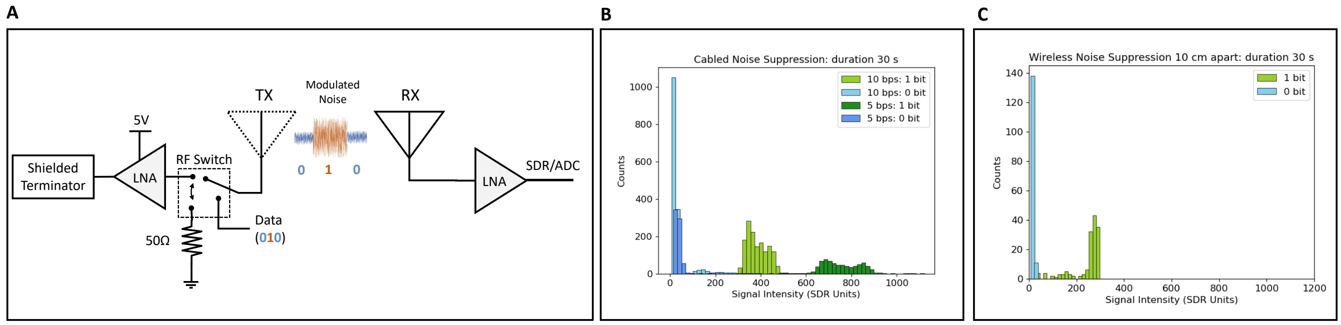

Figure 6: Noise Suppression Communication (NSC). **(A)** An LNA input serves as a cold load. While the NSC apparatus may appear similar to the MJN scheme, its mechanism of operation is different. **(B)** shows the contrast of demodulated 0 and 1-bits for different data rates using NSC. Similarly, **(C)** shows the same for a wireless transmission using NSC.

initial results for Cosmic Backscatter and NSC. There are several areas of optimization that should be focused on to improve each technique. These areas of optimization include implementing signal processing techniques to improve the robustness of the data transmission, further evaluating different noise sources (e.g., for cosmic backscatter), optimizing the system for varying conditions (e.g., weather), and much more. For example, the current implementation of Cosmic Backscatter and NSC use a simple ON-OFF keying approach to modulate information. More sophisticated modulation schemes can be implemented and multiple bits per symbol can be transmitted by designing hardware to switch between several different loads that have contrasting noise temperatures. Implementing these techniques and evaluating the performance in terms of achievable throughput and communication range are important next steps. Moreover, a fundamental challenge with Cosmic Backscatter is the impact of weather on the performance of the system. Techniques can be implemented to strategically switch between certain loads depending on the conditions of the surrounding environment. While the data rates present in this work are low, we believe the performance can be significantly improved with a more sophisticated implementation. A benefit to using thermal noise sources is that the system is not limited to operate at any specific frequency range. This characteristic can be leveraged to minimize the interference caused by other RF technologies as well as enabling simultaneous communication amongst multiple thermal noise transmitters.

Applications. Both Cosmic Backscatter and NSC are inherently low RFI and considered passive communication techniques. Cosmic Backscatter can also be designed to operate at very low power. Because of these characteristics, there are many potential applications for modulated noise communication techniques. The original MJN method could be advantageous for implantable devices because there is no need to generate an RF signal, which can cause tissue heating. Cosmic Backscatter and NSC communication could potentially be leveraged to enable satellite connectivity, particularly for applications that have low-power and low bandwidth requirements (e.g., IoT devices). Back-of-the-envelope calculations suggest these techniques could support ranges on the order of hundreds of kilometers, which is appropriate for LEO or inter-satellite links. Previously we described how radiometers are used for sensing, but they could also be used to enable communication. There are many satellites equipped with radiometers as are several ground stations (e.g., observatories). Recent work has demonstrated that passive radar can be enabled by using the Sun as a source [15] and how these techniques can be expanded satellite remote sensing [16]. Such techniques could also be expanded to enable very low-power and low RFI satellite connectivity. We note that communicating from Earth to space and space to Earth are entirely different situations. For a receiver in space getting data from a terrestrial transmitter, the hot Earth is the background, whereas for a receiver on Earth collecting data from a satellite, the cold sky is the background. An important area of future work is to fully evaluate these two scenarios by developing a testbed to emulate the different communication links and gain a better understanding of the performance scaling. Other potential applications include using modulated noise communication for emergency scenarios (e.g., SOS signals). The methods could also be used in sensitive scientific, military, or intelligence applications in which communication channels that are unobtrusive and difficult to detect are needed.

7 Conclusion

This paper presents Cosmic Backscatter and Noise Suppression Communication. Instead of relying on a generated or ambient RF signal, we demonstrate that we can wirelessly transmit information by modulating noise sources. By switching the transmit antenna between a hot thermal noise source (e.g., 50Ω resistor or the Earth) and a lower temperature cold source (e.g, the sky or an active LNA input) data bits can be transmitted. The methods presented in this work will open up new avenues of research, particularly for applications that require data transmission in RFI-sensitive settings.

Acknowledgement This work was supported by the Milton and Delia Zeutschel Professorship.

8 References

[1] Analog Devices. Adg919, 2023. `https://www.analog.com/en/products/adg919.html`.

[2] X. Bi, Z. Feng, S. Guan, Z. Cao, Y. Mei, J. Li, Z. Zhang, and Q. Xu. An L- and C-band radiometer utilizing distributed active hot and cold loads with 156 % fractional bandwidth. *IEEE Transactions on microwave theory and techniques*, 70(3):1841–1855, month =.

[3] R. Dicke. The measurement of thermal radiation at microwave frequencies. *Review of Scientific Instruments*, 17(7):268–275, July 1946.

[4] R. Frater and D. Williams. An active "cold" noise source. *IEEE Transactions on microwave theory and techniques*, MTT-29(4):344–347, April 1981.

[5] S. Garman, A. Saffari, D. Kobuchi, J. R. Smith, and Z. Kapetanovic. odulated noise communication: Reading uhf rfid tags without a carrier. In *IEEE International Conference on Radio Frequency Identification (IEEE RFID)*, pages 19–24, 2023.

[6] K. Gritton. Atmospheric noise temperature induced by clouds and other weather phenomena at shf band (1-45 ghz). 2005.

[7] Z. Kapetanovic, M. Morales, and J. R. Smith. Communication by means of modulated Johnson noise. *Proceedings of the National Academy of Sciences*, 119(49):e2201337119, 2022.

[8] N. Küchler, D. T. Turner, U. Löhnert, and S. Crewell. Calibrating ground-based microwave radiometers: Uncertainty and drifts. *Radio Science*, 51(4):311–327, 2016.

[9] MiniCircuits. ZHL-1217HLN+ low noise amplifier, 2022. `https://www.minicircuits.com/pdfs/ZHL-1217HLN+.pdf`.

[10] NASA. Advanced microwave scanning radiometer (amsr) sips, 2023. `https://www.earthdata.nasa.gov/eosdis/sips/amsr-sips`.

[11] NASA. What is the universe?, 2023. `https://exoplanets.nasa.gov/what-is-an-exoplanet/what-is-the-universe/#:~:text=It%20includes%20all%20of%20space,the%20planets%20orbit%20the%20Sun`.

[12] National Radio Astronomy Observatory. Solar observing, 2023. https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/solar-observing: :text=Observations

[13] NooElec. NESDR SMArt XTR, 2023. `https://www.nooelec.com/store/sdr/sdr-receivers/nesdr-smart-xtr.html`.

[14] U. S. G. A. Office. Large constellations of satellites: Mitigating environmental and other effects. *Report to COngressional Addresses*, 2022.

[15] S. Peters, D. Schroeder, W. Chu, D. Castelletti, M. Haynes, P. Christoffersen, and A. Romero-Wolf. Glaciological monitoring using the sun as a radio source for echo detection. *Geophysical Research Letters*, 48(14):e2021GL092450, 2021.

[16] S. T. Peters, D. M. Schroeder, M. S. Haynes, D. Castelletti, and A. Romero-Wolf. Passive synthetic aperture radar imaging using radio-astronomical sources. *IEEE Transactions on Geoscience and Remote Sensing*, 59(11):9144–9159, 2021.

[17] D. M. Pozar. *Microwave Engineering*. John Wiley & Sons, Inc., 2012.

[18] S. S. Súbjcerg, J. E. Balling, and N. Skou. Performance assessment of an LNA used as active cold load. In *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pages 4742–4745, 2015.

[19] The European Space Agency. Sentinel-1, 2023. `https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1`.

[20] West Virginia University Radio Astronomy Instrumentation Laboratory. Building horn telescope overview, 2023. `https://wvurail.org/dspira-lessons/BuildingHornTelescope_Overview`.