Stealthy Signals: Using Ghost Modulation to Watermark Interference

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ABSTRACT

LEO satellite constellations have changed the world for the better through Earth observations, research, and telecommunications. Recent advances, especially in telecommunications, have brought the world closer to global connectivity. While these constellations usually have intra-network communications, they generally lack inter-network communication with other networks which leads to interference and noise. This interference and noise leads to degradation of network performance. We propose Ghost Modulation (GM), a novel protocol, to enable inter-network communication and spectrum coordination between a LEO satellite and any other device that supports the GM protocol. GM changes the transmission timing of key packets to encode data while passing most packets through. We evaluate our protocol and show that it can be used to dynamically coordinate heterogeneous networks with minimal overhead.

CCS CONCEPTS

• **Networks** → *Cross-layer protocols*; **Network protocols**.

KEYWORDS

wireless subprotocol, spectrum sharing, cross-technology communication, satellite

ACM Reference Format:
Ashton Palacios, Chase Bledsoe, Elle Kelsey, Laura Landon, Jon Backman, and Philip Lundrigan. 2023. Stealthy Signals: Using Ghost Modulation to Watermark Interference. In *The 1st ACM Workshop on on LEO Networking and Communication 2023 (LEO-NET '23), October 6, 2023, Madrid, Spain.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3614204.3616105

1 INTRODUCTION

Recently, the costs associated with the production and deployment of satellites have decreased significantly [4, 17]. As a result, many companies, including Starlink and OneWeb, have announced plans to manufacture and launch thousands of low Earth orbit (LEO) satellites [18, 22]. Their mission is to provide high-speed, low-latency broadband Internet to the world, including regions that are traditionally difficult to serve due to the high costs of establishing infrastructure and low market demand. The implementation and deployment of these satellites represents a monumental step toward global connectivity.

As much benefit as these satellites provide, they come at a cost. With the increased deployment of satellites comes the challenge of increased interference and mounting pressure to share the spectrum more efficiently. Given a satellite's position in the sky, it has the unfortunate ability to interfere with many different entities, such as other satellites, terrestrial cellular networks, and radio astronomy observatories. While the interference might not be intentional and efforts can be taken to mitigate it, like using beam forming, unintentional signal leakage and interference is unavoidable. Passive devices, such as radio astronomy observatories, are highly affected by satellite communication. Radio astronomy arrays deploy extremely sensitive receivers which in turn can easily be overwhelmed with a very faint signal from a satellite. Researchers have also explored the potential negative impact satellites have on cellular networks [11].

With the mass deployment of a LEO network, technologies need to be developed to facilitate spectrum coordination

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LEO-NET 23, October, 2023, Madrid, Spain

ACM ISBN 979-8-4007-0332-4/23/10…$15.00
https://doi.org/10.1145/3614204.3616105

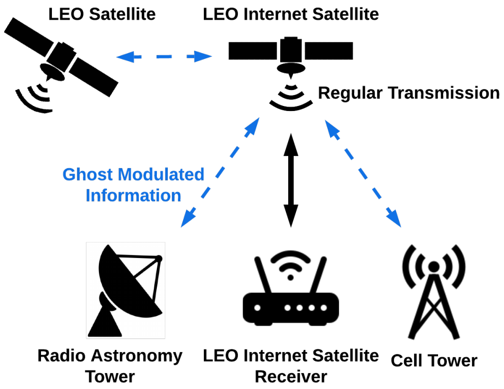

Figure 1: A LEO satellite communicating with a ground receiver. The LEO satellite modulates the timing of the data transmissions to convey secondary information to nodes it is interfering with.

between heterogeneous networks. But with such a diverse set of potential interference points and device capabilities (passive devices, cell phones, cell towers, other satellites), the question becomes, how can a satellite coordinate with so many vastly different systems without negatively affecting its own communication?

To smoothly integrate LEO satellite networks with existing heterogeneous networks, we propose a novel protocol called *Ghost Modulation* (GM). GM provides a stealthy secondary signal (a ghost) in the main communication stream. This secondary signal can be decoded by the devices that are being interfered with, regardless of the device capabilities and modulation scheme used by the transmitter and receiver. GM allows a device to encode information about itself, such as a watermark, that identifies the source of interference. Essentially, we encode data in interference so the source of interference is identifiable.

Figure 1 shows GM's capabilities. In this scenario, a LEO satellite is communicating with a ground node. The communication is interfering with other nodes, such as another LEO satellite, a radio astronomy tower, and a cell tower. In a traditional environment, these devices would have no actionable information about the interference. Using GM, a secondary stream of information is encoded in the transmissions. This allows the other nodes to decode metadata based on the interference pattern without decoding the main stream of data. This provides actionable information to the devices that are being interfered with. For example, an operator can notify the deployer of the satellite that interference is occurring or set up an automated system to stop a satellite from transmitting if a ground node detects interference.

The key innovation that makes GM possible is making slight changes to the timing of key packets of the main data stream to encode secondary information. A device that is being interfered with only needs to look at the timing of the interference to decode the data. Encoding data this way provides substantial benefits. First, it requires *no additional transmissions to encode the extra information* because it is timing based, not transmission based. Second, this method is progressive. If a satellite is not transmitting, then there is no need to send out a GM signal because it is not causing interference. If a satellite is transmitting a lot of data, the GM data will be encoded more often. Third, it makes GM a software-defined protocol, which means it came be implemented completely in software and is independent of the physical layer the transmitter is using. A GM enabled transmitter only needs software to run that purposefully delays key packets. Similarly, the receivers only need to look at the timing of interference to decode the secondary data and are not required to decode the main transmission. GM allows for inter-network communication between heterogeneous networks. Together, these benefits allow a satellite to adopt GM with no packet overhead and operate normally.

Other solutions for spectrum coordination are difficult to implement because they often require additional hardware to be installed on the transmitting satellite and/or receivers. This is labor intensive, costly, and impractical for the vast number of satellites already or about to be deployed. GM provides backwards compatibility with already deployed satellites with a software update, cheaper future satellite implementations, and scalability.

We make several contributions in this paper:

(1) We introduce Ghost Modulation, a novel protocol that uses existing transmissions to deliver informing meta-information, like a watermark, about the transmitter to a interference-affected device without injecting additional packets.
(2) We implement GM using two software-defined radios (SDRs) and evaluate various aspects of GM. We show that it has low bit error rate, minimal impact on primary satellite transmissions, and the ability to receive from multiple transmitters.

In this paper, we share initial proof-of-concept designs and demonstrative evaluations. Ghost Modulation is still in early stages of development, but we believe it provides a promising path forward for LEO satellite spectrum coordination between heterogeneous networks.

2 RELATED WORK

Various studies have been conducted to determine and model the impact that LEO satellite constellations will have on the terrestrial networks [12, 14, 20, 21]. The studies conclude that current and future technologies do not have built in coordination protocols that can help mitigate interference

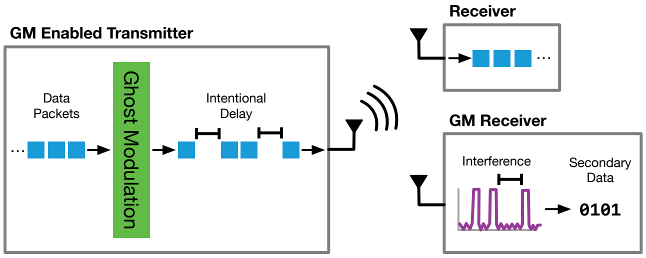

Figure 2: Ghost Modulation architecture. A transmitter adds intentional delay to packets and a secondary receiver can decode secondary data.

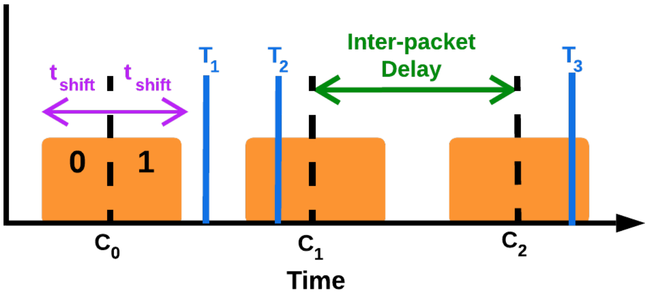

Figure 3: Ghost Modulation's process for encoding data in packet shifts. T_1, T_2, T_3 are interference reception times and C_0, C_1, C_2 are time centers.

and allow efficient primary communication. Several authors have offered potential solutions ranging from additional hardware [1, 7] installed on satellites to custom random access algorithms [1, 6]. The random access protocols [1, 6] are based on time division multiple access, ALOHA, code division multiple access, and many other medium and multiple access schemes. These solutions work well for mitigating interference and increasing fair use of the spectrum. However, these solutions do impact the quality of service of primary transmissions meaning throughput and similar network characteristics will be decreased. GM works in tandem with primary transmissions with minimal impact on primary traffic.

Work has also been done for terrestrial networks to mitigate the interference from satellites using signal processing techniques [2, 15, 24]. These solutions have primarily been created for radio astronomy arrays but could also be applied other networks. The design of these filters and systems have worked in the past, but with constellations becoming larger, interference without additional informing data will become difficult to overcome. GM helps provide the informing metadata to help these techniques.

Much research has been done on developing methods for implicit fingerprinting of a device based on its innate RF characteristics [3, 8]. This implicit fingerprint could be used as a watermark to accomplish a similar goal as GM. Such methods often require the ability to measure minute RF characteristics about the transmitter. Our method take the opposite approach. GM provides a way for explicit fingerprinting, raising the barrier of fingerprinting to any device that detects interference.

3 ARCHITECTURE

3.1 Overview

GM encodes data within its main data transmissions by slightly perturbing the timing of transmissions. This allows for an extra layer of communication available to any device listening, without requiring the demodulation of the actual data transmitted and without any additional transmissions.

Our system consists of three entities, as shown in Figure 2: a GM enabled transmitter, an ordinary receiver, and a GM receiver. The GM transmitter sends data to the receiver over a wireless channel. At the same time, it slightly delays certain packets. The GM receiver is being interfered with by the transmitter. The GM receiver looks at the timing of the interference to extract secondary information about the interference, such as a watermark.

In order for the GM receiver to decode the secondary data, it must know which times to look at for a potentially delayed transmission. It is impossible for the receiver to know if a delay is naturally occurring (e.g., network congestion, multiple access protocol) or intentional. To deal with this, we synchronize the receiver by having the transmitter delay the packets in a known pattern (see Section 3.2). Once the two devices are synced, the receiver will look for specific "time centers". A time center provides a reference point from which to shift packets. The shift value is used to encode the data.

As shown in Figure 3, to send a binary `0`, the transmitter sends a transmission prior to the time center. This is shown as T_2 in the figure. It consists of the time center minus some shift amount, t_{shift}: $T_2 = C_1 - t_{shift}$. To encode a binary 1, the transmitter shifts the transmission after the target time center, as shown as T_3.

A GM receiver decodes the information from the transmitter by interpreting the times at which it experiences interference from the transmitter. Immediately following a time center, the receiver checks the interval before and after the center defined by $(C_n - t_{shift}, C_n + t_{shift})$, where n is an arbitrary time center. Interference experienced outside of a time center interval, such as T_1, is not considered which allows for packet pass through for the transmitter.

We discuss the two parts of decoding the data in the next two subsections.

3.2 Synchronization Phase

The synchronization phase of GM begins with transmitting a known sync word. We use a differentially encoded binary sequence with constant inter-packet delay time centers with bits encoded by the previously discussed method of shifting the packet transmission time to the left or right of the time centers. This scheme allows the receiver to evaluate interference arrival times based on the intervals between interference events rather than pre-shared time centers. Furthermore, differential encoding prevents the inversion of the binary sequence, ensuring that the sync word can be identified without context and interpretation error. After identifying the sync word, the receiver determines the zero time by analyzing the arrival times of the interference in the sync word. The time center of the last packet in the sync word becomes the shared zero time, which completes the synchronization phase.

3.3 Message Phase

Next, the transmitter begins the message phase. As explained earlier, message data is encoded based on a transmission's proximity to a time center. To know which time centers to focus on, the transmitter and GM receiver have a shared pseudorandom sequence of time centers. We use a pseudorandom sequence because it helps minimize the impact of our protocol on the satellite's main stream of data.

Since GM is a general-purpose modulation scheme, arbitrary data can be encoded in the message. The GM message contains an identifier that uniquely identifies a device in a database. This allows a GM receiver to look up information about the interference source to prevent future interference. In the future, we will explore transmitting other types of data, such as transmission duration, geolocation, message priority, etc. This communication fosters and facilitates the coordination of transmission times and frequencies with technologies that see the satellite transmissions as interference. These technologies can perform varying spectrum coordination actions based on the information obtained from the GM message including switching frequencies, beam forming in different directions, establishing a multiple access control scheme, or any other possible action. An example scenario could include a radio astronomy or cellular tower surrounding itself with several GM receivers to outline a no-transmission or change-of-transmission-frequency zone. When one of the receivers syncs with a satellite and learns the satellite will soon cross into the specified area, data could be sent through an out-of-band channel to the satellite requesting it to stop broadcasting, change its frequency, or beam steer away from the area until the satellite has completely passed over. We leave this for future work.

As long as the transmitter has data to send, GM messages will be encoded in the data. If all of the bytes of the message have been sent, the GM protocol will start again. This gives a GM receiver several opportunities to sync with the transmitter in a single pass of the satellite.

4 EVALUATION

We implement the GM protocol using two SDRs, one Ettus USRP N210 [10] and one Ettus USRP X410 [9]. The N210 acts as our transmitter while we receive using the X410. To eliminate uncontrolled interference and noise, the transmitter and receiver are connected with RF cable with 30dB of attenuation. We implement the transmitting and receiving code using a mixture of GNURadio [19], C++, and Python.

To assess GM's performance and resilience, we carry out three evaluations, each focused on a separate area of interest and importance: bit error rate, impact on primary satellite transmissions, and ability to decode multiple GM transmitters.

4.1 Bit Error Rate

In order for the GM receivers to perform their spectrum coordination actions, the bit error rate (BER) must be low enough for the actionable information to be interpreted correctly. Bit error in GM is introduced in three forms: flipped bits from a packet on the opposite side of the time center, mixed bits from one packet on each side of the time center, and dropped bits from no packet within the interval. To evaluate this, we increase the rate at which another transmitter transmits a signal, which we call our interference rate, while a second transmitter is sending a GM message. We send out interference transmissions according to the Poisson distribution with a variety of mean values. A Poisson distribution is used because we want to model realistic interference arrival times. Figure 4 shows the results.

As expected, the BER increases with the amount of interference because there is a higher chance of interference happening during the shift window where bit decisions are made. These results show that using the GM protocol in channels that experience interference and noise, a majority of the bits can be recovered. Additional coding can be used on the message to increase error detection and correction. With the ability to re-transmit the GM message multiple times over a given area, even with some bit error, a satellite can transmit informing metadata to other users of the same or adjacent frequency.

4.2 Impact on Primary Transmissions

Spectrum coordination is important, but arguably the primary communication network is the most important. For

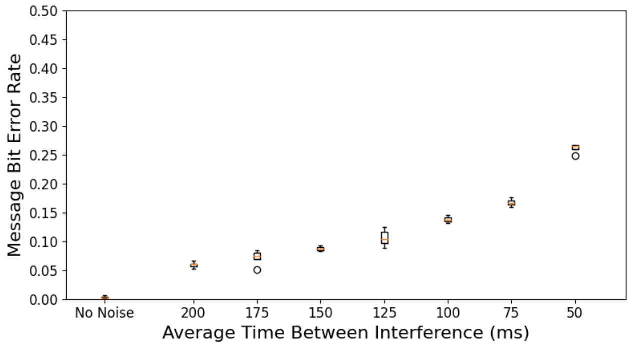

Figure 4: Bit error rate evaluation of a single GM transmitter to receiver under varying interference levels.

the GM protocol to be implemented in any satellite constellation, it should have little to no impact on the primary transmission.

To evaluate GM's impact on the primary transmission, we implement a proof-of-concept design using Netfilter [16]. Netfilter is a Linux framework that allows the manipulation of incoming or outgoing network packets. It allows us to capture and manipulate transmission timing of outgoing traffic to modulate a GM message. We use iperf3 [13] to generate an arbitrary amount data to simulate satellite broadband traffic to a ground node. The GM protocol modulates using the data. We measure the induced jitter from a GM transmitter and report the results in Figure 5. We measure jitter because our protocol affects the spacing between packets leaving the transmitter. Our protocol does not have an impact on the overall data rate because we are not creating or removing any packets.

Using GM increases the jitter of the main stream of data on average from 28 μs to 79 μs. This impact is expected and minimal. As a benchmark for measuring acceptable latency, we use the limits defined for VoIP applications–an application which has demanding timing requirements for uninterrupted operation. The standard VoIP jitter threshold is 30 ms [23]. The induced jitter from GM is far below this threshold. LEO satellites that employ GM will be able to perform their normal operations while coordinating with surrounding networks. This is critical because normal operations of LEO satellites range from broadband internet to critical communications.

4.3 Multiple Transmitters

At any given moment, especially with future deployments of broadband Internet satellites, there may be many satellites overhead a single area at once. GM receivers need the ability to receive messages from multiple GM transmitters simultaneously. We run a single GM receiver and progressively add more overlapping transmitters up to six transmitters. We select six because our current software can only support up to six simultaneous transmitters. Each configuration is run 100 times where detection rate is calculated by how many transmitters the receiver is able to sync with. The results are shown in Figure 6.

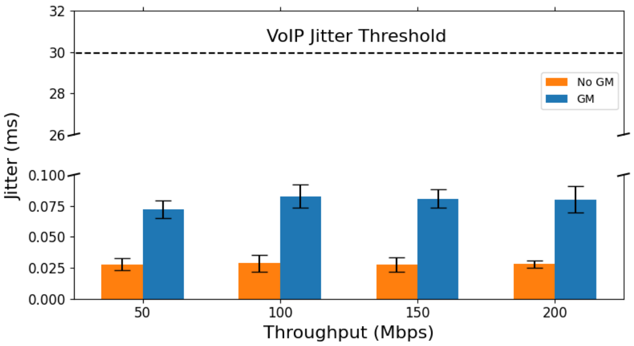

Figure 5: Induced jitter from the GM protocol on primary transmissions.

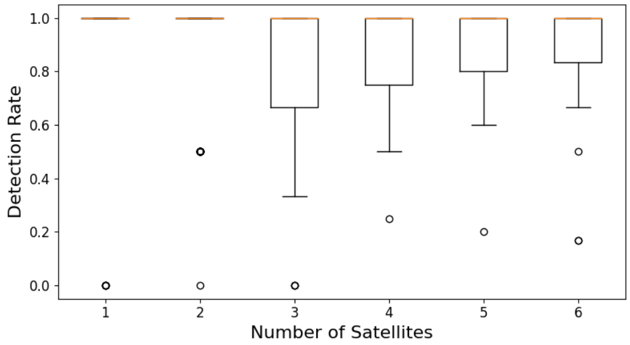

Figure 6: Multiple transmitters to single GM receiver evaluation.

This evaluation shows that a single GM receiver can receive messages from multiple transmitters simultaneously. The box plots in Figure 6 display an asymptotic behavior because the receiver, on any given test, generally misses none or a single transmitter. If only a single transmitter is missed, as the number of transmitters increase, the detection rate will grow asymptotically to one. We note that some of the configurations have outliers at 0.0%. This occurs occasionally when a receiver does not properly detect a GM transmission. This would normally pose a problem, but since LEO satellites will stay over a given area for two and half minutes up to ten minutes [5], there are multiple opportunities to receive the GM message. If a GM receiver misses one of the transmissions, it will catch the next transmission.

As shown in this evaluation and previous subsections, a receiver can successfully receive and decode GM transmissions under varying conditions.

5 CONCLUSION

In this paper, we propose the Ghost Modulation protocol as a additional feature of LEO satellite networks. GM is a protocol that allows actionable metadata to be interleaved within the timing of primary transmissions, informing satellite constellations and terrestrial networks. While we have only discussed encoding a watermark, other information could be encoded as well, such as transmission frequency, geospatial location, heading, etc. Different technologies can take different spectrum sharing actions based on the provided data including switching frequencies, beam forming in different directions, or establishing a multiple access control scheme. In conclusion, LEO satellite constellations have changed the world for the better, and GM can enable these constellations to coordinate and inter-operate more efficiently with other already established networks.

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