StarLego: Enabling Custom Physical-Layer Wireless over Commodity Devices

Ruirong Chen
University of Pittsburgh
Ruirongchen@pitt.edu

Wei Gao
University of Pittsburgh
weigao@pitt.edu

ABSTRACT

Improvement of wireless networking performance heavily depends on new wireless PHY-layer designs, which use to require modifications on the wireless PHY hardware. Such hardware modifications, however, could be expensive or difficult over commodity wireless devices, and becomes the major barrier between lab prototypes and actual wireless systems in use. In this paper, we envision that most of wireless PHY operations could be represented as varying the wireless signal's constellation point on the complex plane, and such new constellation points could be emulated from a commodity wireless MIMO device by mixing the multiple streams of its wireless signals in the air. Based on this insight, we design and implement *StarLego*, a wireless system that can produce custom wireless signals over commodity devices without hardware modification. StarLego is showcased by implementing a custom WiFi PHY preamble, and exhibits great promise to facilitate penetration of new wireless PHY techniques to existing wireless systems.

CCS CONCEPTS

• **Networks** → *Network protocols*; *Network types*.

KEYWORDS

Physical-layer Wireless; Packet Emulation; Constellation Diagram; MIMO

ACM Reference Format:
Ruirong Chen and Wei Gao. 2020. StarLego: Enabling Custom Physical-Layer Wireless over Commodity Devices. In *Proceedings of the 21st International Workshop on Mobile Computing Systems and Applications (HotMobile '20), March 3–4, 2020, Austin, TX, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3376897.3377852

1 INTRODUCTION

Recent emergence of new mobile applications raises unprecedentedly high requirements on the performance, adaptability and reliability of wireless networks, which can only be satisfied by redesigning the wireless physical layer. For example, HD video streaming requires higher wireless capacity at Gbps, which calls for wider channel bandwidth, new modulation methods and multiple data streams [2]. Reducing the power consumption and avoiding interference among heterogeneous wireless devices are critical to practical deployment of large-scale Internet of Things (IoTs), and both build on swift operations of wireless preambles that well coordinate between wireless devices [1].

New designs of the wireless physical layer, however, require modifications of wireless hardware, which are expensive when being applied to the large population of commodity devices or even impossible due to today's integrated system-on-chip (SoC) designs. Such difficulty results in limited applicability of these new designs on commodity devices, and is the major reason for the gap between lab prototypes and actual wireless systems in use.

Avoiding such hardware modification, on the other hand, uses to be considered as impossible due to the incompatible formats of the new wireless signals being produced. For example, many custom wireless PHY designs add new preambles to the wireless PHY frames for various purposes such as power saving [18], identification [13] and interference cancellation [14], but these new preambles can never be detected or recognized by commodity wireless hardware. Similarly, the wireless signal transmitted from a WiFi Access Point (AP), which operates the new generations of WiFi standards (e.g., 802.11n/ac), cannot be correctly decoded by old 802.11g devices, due to the new standards' different ways of spectrum utilization that changes the time-domain signal.

The key insight of this paper, instead, is that such new wireless signals could be emulated from a commodity MIMO-enabled wireless device, by controlling the individual payloads on its MIMO streams and mixing the transmitted wireless signals from these MIMO streams in the air. More specifically, most of wireless PHY operations on the time-domain signal could be represented as varying the signal's constellation point on the complex plane. These new constellation points, even mismatching any constellation diagram being used in existing wireless systems, can always be produced from a mixture of wireless signals in these existing systems with different amplitudes and phases. For example, wireless signals of two BPSK constellation points with the same amplitude and 180° phase difference, when being mixed in the air, results in a new constellation point with zero phase. This new constellation point could then be used to emulate many 802.11 PHY preambles that are modulated by BPSK, such as the new VHT-SIG preamble used in 802.11ac. The number of new constellation points grows when more MIMO streams or higher-order constellation diagrams are used, enabling emulation of more complicated wireless PHY operations.

Based on this insight, in this paper we present a preliminary design of *StarLego*, a wireless system that is potentially able to produce wireless signals with any arbitrary constellation point on the complex plane. The first step of StarLego is to convert the time-domain signal to be emulated to the corresponding constellation

---

HotMobile '20, March 3–4, 2020, Austin, TX, USA

ACM ISBN 978-1-4503-7116-2/20/03…$15.00
https://doi.org/10.1145/3376897.3377852

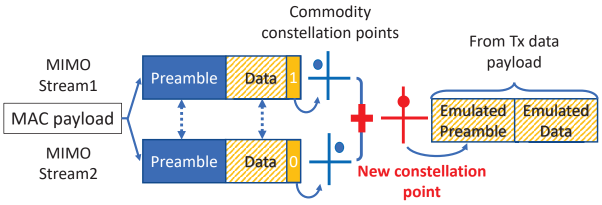


Figure 1: Overview of StarLego

points via FFT, with respect to the number of MIMO streams being used. Afterwards, as shown in Figure 1, the core of StarLego is a payload emulation technique that decides the data payloads transmitted in each of the MIMO stream, in order to produce the desired constellation points when the transmitted signals are mixed in the air. From these new constellation points, StarLego can emulate custom time-domain signals, which could be either new PHY preambles or arbitrary data payloads.

To the best of our knowledge, StarLego is the first that allows a commodity wireless device to enforce custom wireless PHY designs without any hardware modification, and it could greatly facilitate the penetration of new wireless PHY techniques to existing wireless systems. StarLego also advances the existing signal emulation schemes (e.g., WeBee [10] and BlueBee [7]) by being able to precisely produce new wireless signals with custom amplitudes and phases, and could potentially contribute to various application scenarios in emerging cross-technology communication.

In particular, StarLego makes the following contributions:

- We developed analytical models on producing custom wireless time-domain signals by mixing multiple commodity signals in the air, and showed the fine granularity of such emulation over low-cost commodity wireless transceivers.
- We verified the effectiveness of StarLego on producing custom wireless signals over WARP platforms, and demonstrated that StarLego can produce fine-grained constellation diagrams with negligible errors.
- We showcased the practical applicability of StarLego by implementing a custom WiFi PHY preamble (proposed in E-MiLi [18]) over commodity WiFi PHY without hardware modification, and also developed techniques to prevent the commodity WiFi preambles from affecting correct signal emulation in StarLego.

2 MOTIVATION AND BACKGROUND

In this section, we motivate the design of StarLego by discussing how the unique characteristics of modern QAM modulation and MIMO systems could be utilized to emulate new time-domain wireless signals.

2.1 QAM Modulation

Quadrature amplitude modulation (QAM) maps constellation points on the complex plane to time-domain signals with various amplitudes and phases. For example, in Figure 2 that shows a QPSK constellation diagram, the 4 constellation points correspond to signals with the same amplitude but different phases at $\pi/4, 3\pi/4, 5\pi/4$ and $7\pi/4$, respectively. QAM is the most commonly used modulation scheme in wireless systems. It is the technical foundation of most WiFi systems ranging from the old 802.11a/g devices to new 802.11ac/ax systems, which use up to 1024 constellation points. Other wireless technologies (e.g., ZigBee and Bluetooth) use OQPSK and DQPSK for modulation, and are variations from QAM.

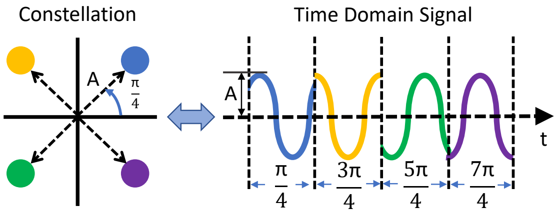
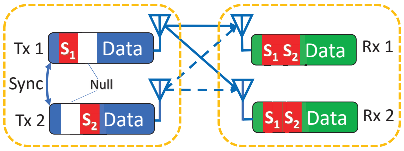
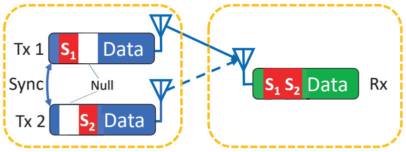


Figure 2: QAM modulation

Figure 2 shows that any time-domain signal in a wireless symbol can be fully represented by its amplitude and phase over the carrier wave, uniquely corresponding to a constellation point on the complex plane. This highlights the possibility of producing new wireless signals by manipulating the QAM constellation points. The major challenge, though, lies in that the desired constellation point may not exist in any constellation diagram used by commodity wireless systems. Such difficulty motivates the design of StarLego that utilizes the multiple data streams from a wireless MIMO transceiver to produce custom constellation points, by mixing multiple wireless signals in the air.



(a) Commodity MIMO



(b) StarLego

Figure 3: Antenna configuration in StarLego

2.2 Wireless MIMO

As shown in Figure 3(a), a wireless Multiple-Input and Multiple-Output (MIMO) system uses multiple Tx and Rx antennas to transfer strictly synchronized data streams in the same spectrum [15]. To do so, each MIMO-enabled wireless device is equipped with an internal clock with nanosecond-level timing accuracy, so that the transmissions over multiple Tx streams can be started at exactly the same time via hardware-driven timing control. By utilizing such timing control in commodity MIMO systems, StarLego ensures that data payloads in different Tx streams are always aligned over time, and such alignment vital to correctly mixing the corresponding wireless signals in the air.

On the other hand, commodity MIMO systems use specialized preambles in each spatial stream for channel estimation, to ensure correct data transmission between the corresponding Tx and Rx. As shown in Figure 3(a), Tx antennas transmit these preambles (S_1

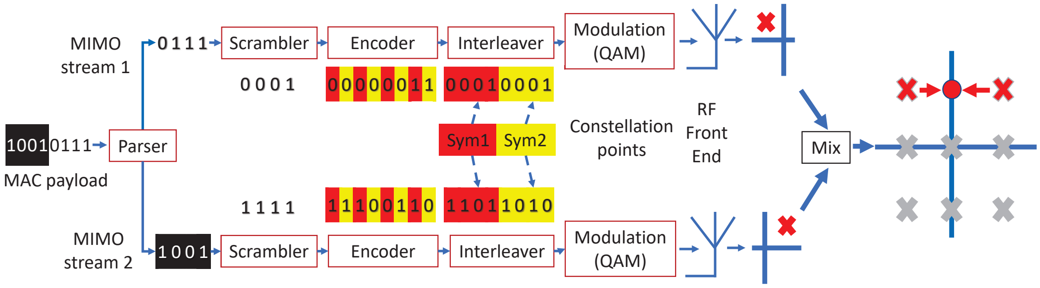


Figure 4: An example of the StarLego's signal emulation process

and S_2) alternatively: Tx 2 puts null power on its RF frontend while Tx 1 is transmitting its special preamble. In this way, both of the Rx antennas can receive all the necessary preambles for channel estimation.

These preambles, however, may affect StarLego's signal emulation by confusing the sole receiver of the emulated signal. As shown in Figure 3(b), the receiver may consider the commodity MIMO preamble S_1 as the start of a wireless packet, and decodes data afterwards. When the emulated signal actually arrives, the receiver will be on the active receiving mode rather than idle listening, and is hence incapable of correctly recognizing the emulated signal. We will address this problem by intentionally applying small shifts to the MIMO preambles, so that the mixture of these commodity preambles will be turned into channel noise. More details will be described in Section 4.

3 PRODUCING CUSTOM WIRELESS SIGNALS

The core capability of StarLego is to create new wireless signals with custom amplitudes and phases, which correspond to new constellation points on the complex plane, by mixing wireless signals from MIMO Tx antennas in the air. On the contrary, existing signal emulation techniques only operate commodity constellation diagrams from a single wireless Tx, and are hence limited to approximating coarse-grained constellation diagrams from high-order QAM (e.g., 64-QAM in WiFi to OQPSK in ZigBee [10]). They are incapable of precisely controlling the wireless signal being produced, nor producing more fine-grained custom constellation diagrams.

3.1 Basic Design of StarLego

Without loss of generality, the time-domain wireless signal with the carrier wave frequency f could be written as

$$S_m(t) = A_m \cos(2\pi f t + \phi_m) \tag{1}$$

where A_m and ϕ_m are the amplitude and phase of the signal, respectively.

Then, we use an example of wireless MIMO with 2 Tx antennas to explain the basic idea of StarLego design. Since the wireless signals from the two MIMO Tx antennas are strictly synchronized and have the same carrier frequency and amplitude, when they are mixed in the air, the mixed signal will be

$$\begin{aligned} S(t) &= A\cos(2\pi f t + \phi_1) + A\cos(2\pi f t + \phi_2) \\ &= A\cos(\frac{\phi_1 - \phi_2}{2})\cos(2\pi f t + \frac{\phi_1 + \phi_2}{2}) \\ &= \tilde{A}\cos(2\pi f t + \tilde{\phi}), \end{aligned} \tag{2}$$

where $\tilde{A} = A\cos(\frac{\phi_1-\phi_2}{2})$ and $\tilde{\phi} = \frac{\phi_1+\phi_2}{2}$. In other words, such mixed signal corresponds to a new constellation point with amplitude $\tilde{A}$ and phase $\tilde{\phi}$.

Eq. (2) can be iteratively extended to more Tx antennas[1]. For a given QAM modulation scheme being used on the Tx antennas that provides a finite collection of signal phases (e.g., 4 possible phases for QPSK as shown in Figure 2), the more Tx antennas being used, the more custom constellation points can be emulated by mixing the transmitted signals in the air. On the other hand, using higher-order QAM modulations also helps improve the granularity of such emulation[2].

No. Tx Antennas	QPSK	16-QAM	64-QAM
1	4	16	64
2	9	49	225
3	16	100	484
4	25	169	841
n	$(n+1)^2$	$(3n+1)^2$	$(7n+1)^2$

Table 1: Number of new constellation points being produced by StarLego

Since the constellation points in standard QAM constellation diagrams are evenly distributed in the complex plane, the emulated constellation points are also evenly distributed. As shown in Table 1, the number of new constellation points that can be produced by StarLego quickly grows with more Tx antennas or higher-order QAM modulations. A low-cost commodity wireless transceiver that supports 2x2 or 3x3 MIMO could be used to easily produce hundreds of new constellation points, hence allowing fine-grained emulation of custom wireless PHY signals.

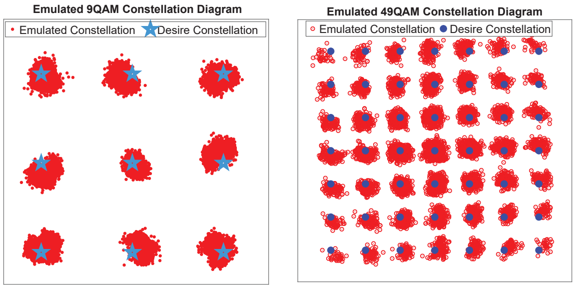
3.2 Deciding Data Payloads

StarLego emulates the desired wireless signal by manipulating the data payloads transmitted from the Tx antennas. As shown in Figure 4, such data payload, while being generated at the MAC layer as a whole, will be first parsed to individual MIMO data streams in a round-robin manner. Afterwards, each data stream will be scrambled, encoded and interleaved before it is being sent to QAM modulation. For example in Figure 4, the parsed data bits 1001 in MIMO stream 1 is scrambled into 1111 by being multiplied with a

---

[1] For OFDM-based wireless systems such as WiFi, the OFDM subcarriers are orthogonal to each other and operate over different frequencies. Hence, StarLego can individually emulate the custom wireless signal in each subcarrier.

[2] In most of commodity wireless MIMO systems, all the Tx antennas are configured to always operate the same QAM modulation scheme.



(a) Emulating 9-QAM (b) Emulating 49-QAM

Figure 5: Emulating custom constellation diagrams

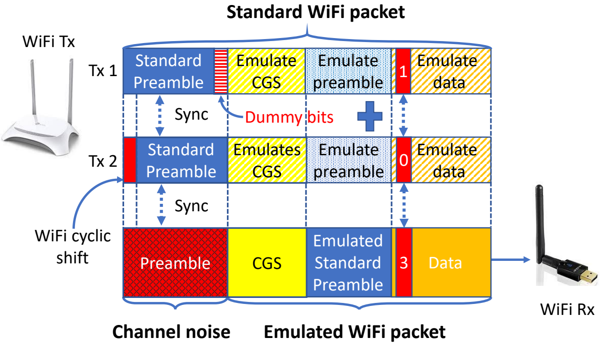


Figure 6: Emulating custom WiFi PHY with StarLego

pre-defined scrambling sequence. It is then encoded with 1/2 code rate and transmitted as two symbols.

Given the desired wireless signal to be emulated, StarLego decides the data payloads by reversely following the emulation process shown in Figure 4. It first decides the time-domain signal for each MIMO stream according to the basic design in Section 3.1, and then reversely converts each time-domain signal to the corresponding constellation points. These constellation points at different MIMO streams are eventually demodulated, decoded and combined to be the corresponding MAC payload on commodity wireless devices, according to the operations of MIMO parser.

3.3 Preliminary Results

To practically evaluate the StarLego's accuracy of producing custom wireless signals, especially with dynamic wireless channel conditions and noise, we implemented StarLego over WARP v3 platforms with standard WiFi PHY and tested StarLego by operating two MIMO streams with QPSK and 14 dB channel SNR. As shown in Figure 5(a), StarLego successfully emulates a custom constellation diagram of 9-QAM with negligible bit errors. If we use 16-QAM on the two MIMO streams and further increase the channel SNR to 20 dB, StarLego can emulate a custom 49-QAM constellation diagram without error, as shown in Figure 5(b). These results demonstrate that StarLego can reliably produce new wireless signals under common wireless channel conditions in practice.

4 A SHOWCASE OF STARLEGO

Based on the design and preliminary results in Section 3, we further use StarLego to implement a custom wireless PHY design, namely E-MiLi [18], over commodity wireless PHY. This custom design allows a WiFi receiver to adaptively downclock itself during idle listening to save power, but the WiFi receiver will be unable to detect standard WiFi PHY preambles when being downclocked. To ensure timely detection of incoming WiFi packets, E-MiLi appends a custom PHY preamble to the beginning of each WiFi packet. This custom preamble is a complex Gold sequence (CGS) that has shifted real and imaginary parts from the standard Gold sequence [6] (e.g., $1 + 0j, 0 + 0j, 0 + 1j, 1 + 0j$, etc), and can be reliably detected by low-frequency WiFi clocks due to its strong characteristics of self-correlation.

We will use StarLego to emulate this custom preamble from commodity WiFi devices, so as to avoid wireless hardware modification at the WiFi Tx that involves an extra PHY-layer block for preamble generation. Hardware modification at the WiFi Rx is still needed to correctly detect the custom preamble, but would be much easier in many practical scenarios such as Internet of Things, where few strong data processing units are used to receive data from large amounts of weak sensing devices.

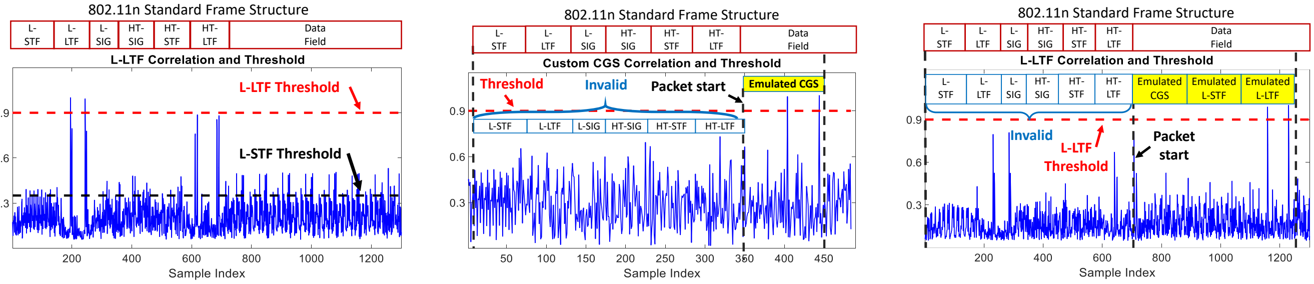
The emulation process over commodity WiFi PHY is shown in Figure 6, where we use two 802.11n MIMO data streams with 64-QAM modulation to emulate the CGS preamble. A standard WiFi packet is also emulated, following the CGS preamble. To ensure that the emulated WiFi packet starts with the emulated CGS preamble, as discussed in Section 2.2, we need to first prevent the WiFi Rx from detecting the standard WiFi preambles transmitted from any of the Tx stream, while still ensuring that data payloads from different Tx streams are aligned. Our approach builds on the fixed duration of WiFi cyclic delay that is applied to one of the Tx streams for MIMO channel estimation and anti-fading [15], and adaptively compensate such delay at the other Tx stream by inserting dummy bits to the beginning of its data payload. The number of such dummy bits is determined by the duration of cyclic delay, which can be obtained by reading the WiFi PHY registers from the adapter firmware. For example, when a 400ns cyclic delay is applied, $400/50 = 8$ dummy bits will be inserted where 50ns is the sample duration of 802.11n Tx.

Because of these dummy bits, the mixture of these preambles from two MIMO streams will be equivalent to channel noise and bypassed by the WiFi Rx. Thus, StarLego ensures correct frame reception from WiFi Rx by recognizing the start of the emulated frame at the emulated preambles.

4.1 Emulating CGS Preamble

We use the StarLego technique described in Section 3 to build two consecutive CGS preambles of 64 bits and use a WARP v3 board as the WiFi Rx to examine its time-domain signal for detection. The Rx is down-clocked by 50% when idle listening, and detects the CGS preambles by doing self-correlation over the received time-domain samples.

The results of such self-correlation are shown in Figure 7(b), with a correlation threshold of 0.9 to ensure robustness across a wide range of channel SNR. First, being different from Figure 7(a) where standard WiFi preambles can be well detected in a standard WiFi packet, Figure 7(b) shows that the mixture of these standard preambles from the two Tx MIMO streams results in low correlation coefficient, and is hence be invalidated as channel noise as we



(a) A standard WiFi packet (b) the emulated CGS preamble (c) the emulated standard WiFi preambles

Figure 7: Results of emulating custom WiFi preambles

expect. Afterwards, the correlation coefficient over the emulated CGS preamble exhibits two peaks above the threshold, and the two emulated CGS preambles can hence be reliably detected.

4.2 Emulating Standard WiFi Preambles

To ensure correct WiFi data transmission after the CGS preamble, we also use StarLego to emulate standard WiFi preambles. In this section, we use the L-LTF as an example of these preambles to demonstrate the effectiveness of StarLego. In 802.11n systems, the L-LTF is used in every WiFi packet for channel estimation, and the WiFi Rx detects L-LTF by finding the correlation peak that shows the similarity between the received time domain signal and the predefined perfect L-LTF signal.

The results of correlation are shown in Figure 7(c), which shows that the correlation over the emulated L-LTF exhibits two similar correlation peaks as those in Figure 7(a), indicating that this emulated L-LTF can be well detected by the WiFi Rx. Note that, as shown in Figure 7(a), different WiFi preambles may correspond to different correlation threshold for being detected. For example, the L-STF has a lower threshold of correlation to be detected.

5 DISCUSSIONS

Our preliminary design and implementation of StarLego, while promising, still have limitations. In this section, we discuss some remaining research challenges that should be considered and addressed in the future.

Supporting new methods of spectrum use. Our preliminary StarLego design has been focusing on creating new wireless signals with custom amplitudes and phases. Another large collection of wireless PHY operations, however, aims to incorporate more spectrum resources or increase spectrum utilization. For example, new WiFi standards (e.g., 802.11n/ac) expand the channel bandwidth to 160MHz via channel bonding. StarLego could be further extended to emulate these operations over commodity devices, by coordinating more transmitters at multiple frequency bands. For example, simultaneously transmitting emulated signals from eight transmitters that operate 20MHz channels over adjacent frequency bands could emulate an 160MHz channel, but how to strictly synchronizing the transmissions among these different transmitters is challenging and needs further research.

Time-domain signal manipulation. Timing in wireless packets could also be modified at the PHY layer. For example, the preamble duration may be reduced to improve the efficiency of WiFi [12], and idle periods between frames can be modulated to convey control messages [8]. Although such timing changes may not reflect in different constellation points, one approach to emulating such timing changes could build on OFDM-enabled wireless transceivers. In one wireless symbol with N subcarriers, the time domain signal after discrete IFFT could be written as $f_n = \frac{1}{N}\sum_{k=1}^{N} F_k \exp(\frac{j2\pi kn}{N})$, where $n \in [1, N]$ and F_k indicates the data bits being modulated in the k-th subcarrier. Each f_n, hence, corresponds to the n-th time slice of the symbol. By controlling the custom constellation points in different subcarriers, we could possibly emulate any timing changes with a granularity of T/N, where T is the duration of wireless symbol.

Distortions in emulation. The showcase of StarLego in Section 4 focuses on making custom preambles detectable by the receivers. However, emulating a discrete set of new constellation points cannot ensure the emulated preamble's time-domain waveform to be identical with that of the ideal preamble. In practice, as shown in Figure 8, when the desired signal does not exactly correspond to any of the emulated constellation point, the emulated waveform of the WiFi preamble could be different from the desired waveform. As a result, a higher SNR is required for the receiver to correctly decode the data payload, because such preambles (e.g., Long-Training Sequence (LTS) in WiFi systems) are usually used for channel equalization during data decoding.

On the other hand, the received signal power in StarLego could be stronger when multiple signal streams from the MIMO Tx are mixed in the same spectrum, augmenting the SNR at the receiver. For example, the cumulative signal power could 2dB higher when two MIMO signal streams are mixed together, and we will further investigate the possibility of using such mixed signal to meet the extra SNR requirement. Furthermore, using higher-order QAM modulations for emulation creates a denser constellation diagram, which helps emulate more new constellation points with less deviations from the desired signal.

Implementation over off-the-shelf devices. Intuitively, the design of StarLego could be realized over any commodity wireless transceivers with controlled MAC payload. However in practice, many engineering details of such commodity wireless devices may still need to be addressed, due to the heterogeneous hardware implementations from different manufacturers. For example, knowing the configuration of the scrambler seed will be critical to deciding the data payloads being used for emulation, but the information

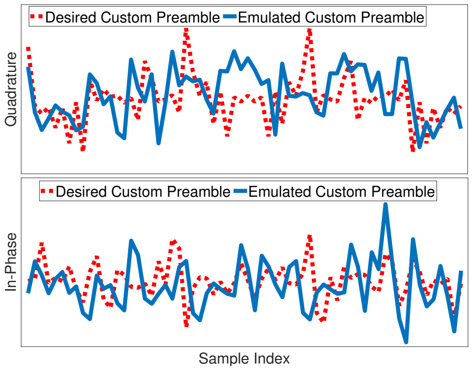


Figure 8: Comparing the time-domain signal between the emulated and the desired WiFi preambles

about such configuration is hard be obtained over some wireless hardware (e.g., the Atheros ath9k series of WiFi chips). Most of these engineering efforts, nevertheless, could be conducted by modifying the device firmware and driver at the wireless device.

Computation overhead. According to Section 3, successful signal emulation in StarLego relies on conversion from the desired time-domain signal to the appropriate MAC payload. Such computation can be performed offline when the desired signal is fixed and pre-defined (e.g., the LTF and STF preambles in the 802.11 standard). The emulating payloads can be pre-converted and stored on the commodity device to preserve the computing power at real-time. On the other hand, such signal usually corresponds to frame preambles with small sizes (e.g., a WiFi LTF preamble only contains 64 bits), and storing the emulating payloads hence requires a small amount of storage space.

Emulating data payloads, on the other hand, involves real-time computation. Such computation, in particular, could be expensive when the emulated data payload is large and requires a large number of symbols to be transmitted. One possible solution to reducing such overhead is to compute the MAC payloads for several data symbols in parallel.

6 RELATED WORK

Cross-technology coexistnece. Research on cross-technology coexistence is the earliest effort that aims to remove the barrier between heterogeneous wireless devices with incompatible formats. Most of these research efforts focus on better coordinating the data transmissions among different wireless technologies, by developing new wireless PHY preambles [19], structures [4] or protocols [11]. However, these approaches require hardware modifications on wireless devices, which are impossible to be deployed over current commodity devices.

Cross-technology communication (CTC). Explicit coordination among heterogeneous types of wireless devices has been proved to be more efficient to avoid interference and achieve coexistence, and such explicit coordination can usually be achieved by transmitting small-sized control messages among these devices. Early research efforts on CTC use specialized gateways to relay such control messages [9, 17], but may involve expensive costs. Others focus on discovering side channels between incompatible wireless technologies by intentionally alternating certain PHY-layer structures or signal characteristics such as packet length [3], timing [8], sequence patterns [16] and dummy traffic [5], but usually result in very low data rates at <1 kbps. Physical-level emulation can improve the CTC data rate [7, 10], but is limited to coarse-grained approximation to pre-defined wireless signals. They are incapable of producing custom wireless signals with arbitrary amplitudes and phases, and hence have little contribution to emulating new wireless PHY designs.

7 CONCLUSION

In this paper, we present StarLego, a new wireless system that can produce new wireless signals on commodity wireless devices without hardware modification. We verified the effectiveness of StarLego over reconfigurable RF hardware, and also implemented StarLego on commodity WiFi PHY to showcase emulation of a custom WiFi preamble.

ACKNOWLEDGMENTS

We thank the anonymous reviewers for their comments and feedback. This work was supported in part by the National Science Foundation (NSF) under grant number CNS-1617198, CNS-1812399 and CNS-1812407.

REFERENCES

[1] Wireless lan medium access control (mac) and physical layer (phy) specifications. *IEEE Std. 802.11ac Draft 1.0*, 2011.
[2] B. Bellalta. Ieee 802.11 ax: High-efficiency wlans. *IEEE Wireless Communications*, 23(1):38–46, 2016.
[3] K. Chebrolu and A. Dhekne. ESense: communication through energy sensing. In *Proceedings of ACM MobiCom*. ACM, 2009.
[4] R. Chen and W. Gao. Enabling cross-technology coexistence for extremely weak wireless devices. In *IEEE INFOCOM*, 2019.
[5] Z. Chi, Y. Li, H. Sun, Y. Yao, Z. Lu, and T. Zhu. B2w2: N-way concurrent communication for IoT devices. In *Proceedings of ACM SenSys*, 2016.
[6] P. Fan and M. Darnell. *Sequence design for communications applications*, volume 1. Research Studie, 1996.
[7] W. Jiang, Z. Yin, R. Liu, Z. Li, S. M. Kim, and T. He. Bluebee: a 10,000x faster cross-technology communication via phy emulation. In *Proceedings of ACM SenSys*. ACM, 2017.
[8] S. M. Kim and T. He. Freebee: Cross-technology communication via free side-channel. In *ACM MobiCom*, 2015.
[9] Y. Li, Z. Chi, X. Liu, and T. Zhu. Chiron: Concurrent high throughput communication for iot devices. In *Proceedings of ACM MobiSys*, 2018.
[10] Z. Li and T. He. Webee: Physical-layer cross-technology communication via emulation. In *Proceedings of ACM MobiCom*. ACM, 2017.
[11] H. Lu and W. Gao. Supporting real-time wireless traffic through a high-throughput side channel. In *In Proceedings of ACM MobiHoc*, 2016.
[12] E. Magistretti, K. K. Chintalapudi, B. Radunovic, and R. Ramjee. WiFi-Nano: Reclaiming WiFi efficiency through 800ns slots. In *ACM MobiCom*, 2011.
[13] H. Rahul, H. Hassanieh, and D. Katabi. Sourcesync: a distributed wireless architecture for exploiting sender diversity. *ACM SIGCOMM Computer Communication Review*, 41(4):171–182, 2011.
[14] S. Sen, R. R. Choudhury, and S. Nelakuditi. CSMA/CN: Carrier sense multiple access with collision notification. *IEEE/ACM Transactions on Networking (ToN)*, 20(2):544–556, 2012.
[15] R. Van Nee, V. Jones, G. Awater, A. Van Zelst, J. Gardner, and G. Steele. The 802.11n MIMO-OFDM standard for wireless LAN and beyond. *Wireless Personal Communications*, 37(3-4):445–453, 2006.
[16] Z. Yin, W. Jiang, S. M. Kim, and T. He. C-morse: Cross-technology communication with transparent morse coding. In *IEEE INFOCOM*, pages 1–9, 2017.
[17] Y. Yubo, Y. Panlong, L. Xiangyang, T. Yue, Z. Lan, and Y. Lizhao. Zimo: Building cross-technology mimo to harmonize zigbee smog with wifi flash without intervention. In *In Proceedings of ACM MobiCom*, 2013.
[18] X. Zhang and K. G. Shin. E-MiLi: energy-minimizing idle listening in wireless networks. In *ACM MobiCom*, 2011.
[19] X. Zhang and K. G. Shin. Gap sense: Lightweight coordination of heterogeneous wireless devices. In *IEEE INFOCOM*, 2013.