When they go low, we go lower (power): Exploiting Geographical Diversity in Low-Power WANs

Paper # XXX

ABSTRACT

Low-Power Wide Area Networks (LP-WANs) are an emerging wireless platform which support battery-powered devices lasting 10-years, while communicating at low data-rates to base stations several miles away. Set-top box manufacturers are adding support for LP-WANs like LoRa, enabling a rapid proliferation of Internet-of-Things devices based on these technologies. Multiple LP-WANs such as LoRaWAN, SIGFOX and RPMA allow users to deploy their own base stations operating on unlicensed spectrum. Despite the expected high-density of gateways, all devices will not experience the promised 10-year battery life, particularly in urban spaces. A large number of devices, such as those in basements, deep inside buildings, or in remote neighborhoods would suffer from severe battery-drain as their signals remain too weak even at the closest base station. This paper presents Charm, a system that enhances both battery life and coverage of LP-WAN clients in large urban deployments. Charm allows multiple LoRaWAN gateways to pool their received signals in the cloud, coherently combining them to detect even the weakest signal that is not decodable at any individual gateway. Charm achieves this through a novel hardware and software design at the gateway that carefully selects chunks of the received signal to be sent to the cloud, thereby saving uplink bandwidth. We demonstrate how our solution scales to decoding weak transmissions at city-scale by identifying signals from which subset of gateways need to be coherently combined over time. A pilot implementation and evaluation of Charm on a network of eight LoRaWAN gateways serving a large neighborhood of a major U.S. city demonstrates significant gain in range and client battery-life.

ACM Reference format:
Paper # XXX. 2018. When they go low, we go lower (power): Exploiting Geographical Diversity in Low-Power WANs. In *Proceedings of IPSN, Porto, 2018,* 8 pages.
DOI: None

FINAL STORY LINE....

(1) Introduction:
- Motivation:
  - LPWAN is awesome and catching up
  - Range and battery life problems (e.g. long battery life is conditional)
  - LoRa networks are planned (UGWs are disorganized)
  - Can we leverage UGWs to collate a decode weak signals?
  - Should lead to improvement in client power and improvement in network range
- Why is it hard?
  - is a SIMO/ joint decoding problem
    - needs detection
    - large amount of data transfer
  - Problems:
    - Inefficient
    - Not scalable
  - Need efficient local decoding scheme
  - Need software architecture to enable this
    - How to avoid wasted computations (e.g. through short circuit)
    - Joint decoding
    - Software architecture
    - Result: improved scalability (due to shorter messaging times)
- Contribution:
  - Leveraging diversity with unplanned UGWs
  - A hardware platform and underlying algorithms for IQ processing and local detection of LoRa preambles
  - Software infrastructure for joint detection and improving scalability

(2) Related Work:
- LPWAN
- SIMO (?) and diversity
- Cloud-RAN (but our system has short and infrequent messages)

(3) Background:
- SIMO Primer
- LoRa
- LoRaWAN

(4) Architecture:
- The goal: decode weak transmission by collating information from multiple base-stations
- Flow diagram (picture with cloudy and edgy stuff)
- The strawman comparison: stream everything
- Strawman limitations
  - Weak signals and limited bandwidth (problems at gateways (could use joint decoding of preambles but cant afford to stream everything))
  - Scaling issues (problems at the cloud)

(5) Gateway:
- Hardware + block diagram + capability + how to decode IQ streams
- Local detection algorithm
- Optional: (LoRa-aware) compression

IPSN, Porto

DOI: None

(6) Cloud:
- Q. How to solve scaling issues in the cloud?
- Avoid wasted computations
  - Short circuit
  - Leverage locality of gateways (only use a subset of gateways for decoding)
- Spatial partitioning helps correctness and performance
  - Leverage locality
  - Leverage timing
- Shorter transmissions help scalability

(7) Implementation
- OC Arch + additions over regular LoRaWAN
- Drive and Penetration test results around campus for earlier deployment

(8) Evaluation:
- Local packet detection: Error CDF vs SNR
- Diversity gain: Usable spreading factors vs distance/SNR
- Impact on client power: Device power trace, Battery life vs distance
- Increased capacity due to sensitivity gain (in simulation)

(9) Conclusions and Future Work:
- Extensions to MU-MIMO, tomography
- Other stuff

1 INTRODUCTION

Low Power Wide Area Networks (LP-WANs) are increasingly seen as an attractive communication platform for city-scale Internet-of-Things (IoT) deployments. They offer the ability to wirelessly connect energy-constrained devices to gateways over distances of many kilometers. LP-WANs also have power and cost advantages over alternatives like cellular networks, particularly in deploy-once, low-maintenance and low throughput sensing applications

While far from pervasive, the capabilities of LP-WANs like LoRaWAN [1, 14], SigFox [3] and Ingenu's RPMA [6] have attracted investment and have spawned early deployments. These technologies operate on unlicensed spectrum, allowing businesses and consumers alike to deploy their own base stations. With the recent announcement by Comcast [] to integrate LP-WAN radios into future set-top boxes in the U.S., LP-WANs are likely to scale rapidly. Indeed, major cities in the U.S. are likely to see fast-paced LP-WAN coverage, given that each LP-WAN base station promises a range of up to ten kilometers [1].

Yet, the maximum range of LP-WAN base stations of 10 kilometers comes at a cost – battery-drain. Specifically, the further an LP-WAN device is from a base station, the more power it is likely to expend to transmit the same amount of information []. (Sudden jump from LP-WAN to LoRaWAN... What is the knob that enables jumping from 1 year to 10 years?) In practical terms for instance, this reduces the battery life of a LoRaWAN device from 10-years when in close proximity of the base station to just 1 year at maximum range []. (The suburban argument is not convincing (and may not even be true). Focus on battery and more uniform coverage.) Given that LP-WANs base station deployments will be at their densest in cities, suburban areas are likely to bear the brunt of poor performance and reduced battery life. (Add some actual power numbers.) More fundamentally, LP-WANs unlike cellular deployments are unlicensed and unplanned, meaning that the outermost suburban neighborhoods may simply be beyond the range of LP-WAN coverage, while cities remain over-provisioned.

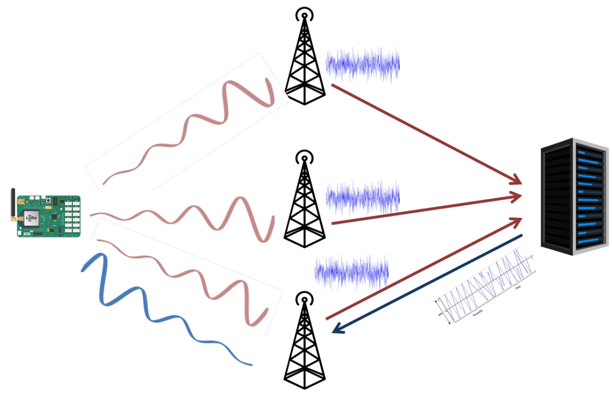

Figure 1: Charm: A Distributed LP-WAN communication system

This paper presents Charm, a system that enhances the battery-life and coverage of LoRaWAN clients in large urban deployments. Charm exploits the observation that while signals from a distant and hard to reach clients may attenuate significantly, they are still likely to be received by multiple base stations. Charm develop a collaborative joint-decoding system that coherently combines weak signals heard across multiple city base stations to decode the underlying information. As a result, it both expands the decoding range of the LP-WAN network and improves battery-life for nodes already in range. Charm is implemented in a first-of-its-kind low-power wide-area pilot deployment of joint decoding serving a large neighborhood of a major U.S. city and demonstrates increased coverage and battery-life for nodes in surrounding neighborhoods.

LoRa is an emerging LP-WAN technology from Semtech that uses chirp spread-spectrum that trades off low bit rate for long range. An important parameter is the spreading factor: different spreading factors can be independently received and end up affecting the transmission time, bit rate and sensitivity of the transmission. LoRaWAN defines the higher levels of the networking stack that enable device-centric unidirectional or bi-directional communication. LoRaWAN gateways are typically inexpensive, simple forwarders that send all decoded packets to a server in the cloud over a regular internet connection, the cloud-server then decides which gateways should respond. LoRaWAN also allows and encourages clients to deploy their own unplanned gateways (which we call *user-deployed gateway* or *UGW*) to expand the coverage of the network.

(Intuitively, explain how does Charm's approach actually leads to client power savings) Charm allows users who are in range to transmit at faster data rates that would not have been decodable using a single gateway receiver. This allows for more air time for weaker transmissions from further away clients.

The main challenges in designing a city-scale joint-decoding system stem from three main causes: 1. very weak receptions, 2. limited bandwidth from the gateway to the cloud server and 3. challenges in scaling at the cloud.

Challenges at the Gateway: Gateways receive transmissions from distant clients which are far below the noise floor. These transmissions are not only difficult to detect but also cannot be decoded independently. (Add actual numbers?) Using an approach similar to [] (Cloud RAN?) would require continuously streaming all the raw received signals to a cloud-based decoder for both detection and decoding. Such an approach places a heavy cost on the internet bandwidth between the gateway and the cloud, which is particularly infeasible for UGWs.

Although LoRaWAN gateways are very capable, they do not provide the raw baseband quadrature signals which are required for joint decoding. We developed a low-cost auxiliary platform, called RFTAP that uses a similar radio frontend combined with a FPGA and Raspberry Pi for local signal processing. This auxiliary hardware behaves like a software-defined radio in the 900 MHz ISM band, generating processed quadrature streams and computing local parameters (like spreading factor and center frequency which are necessary inputs for the cloud-decoding algorithm).

Our solution to the bandwidth limitation problem leverages the structure of LoRaWAN LP-WAN packets. We develop a solution that detects LoRaWAN packets even if they are 37 dB below the noise floor and therefore remain completely non-decodable. Our solution exploits the presence of a large number of repeated preambles in LoRaWAN (up to 16 in the standard). Specifically, we correlate the received sequence with long-sequences of LoRaWAN chirps to detect the locations of packets. We repeat this process across gateways and quickly alert neighboring base stations, should a preamble be detected. The base station also does this for correctly decoded packets – eliminating the need for base stations to upload weak signals for packets already decoded. Owing to the lenient latency constraints for acknowledgement of a packet in LoRaWAN (one to two seconds), our approach readily scales to a large-scale network. In effect, our approach therefore only streams to the cloud signals that correspond to valid packets.

Scalability at the Cloud: (This section still needs lots of work) Another challenge Charm must deal with given its expanded coverage, is the problem of processing a large number of streams to be combined and decoded.

Points to cover:

- How to avoid wasted computations through our distributed algorithm (short-circuiting, selectively combining streams based on location, frequency and time)
- How is this scalable? i.e. why can we support more nodes in the network now? (transmit time decreases)
- What is the software/cloud infrastructure required to support these operations?

(Add some introduction about the nature of experiments.) In our evaluations, we demonstrate the following:

- We improve the range at SF 7 by XXX m, SF 10 by YYY m , and SF 12 by ZZZ m.
- With 8 base stations, we can add X m^2 more area to our coverage area.
- We can achieve gains of J dBW,K dBW and LdBW for the signal using 3, 6 and 8 base stations, respectively.
- We require overheads of K MBps and provide a latency of T ms for detection and decoding of a packet with 8 base stations.

Contributions: In this paper we present the following novel contributions.

- A technique that leverages the geographical diversity of unplanned user-deployed gateways to enable joint decoding of weak transmissions. This improves the quality-of-service for all users and increases the coverage area.
- A hardware platform and the underlying algorithms for processing quadrature streams and detection of LoRa preambles in weak transmissions, both done locally. To reduce gateway internet bandwidth requirements, we also introduce a scheme that selectively forwards a subset of probable candidates to a cloud-based joint decoder.
- A software architecture that builds on top of LoRaWAN to enable joint-decoding of transmissions in a scaleable manner.

2 RELATED WORK

Low-Power Wide-Area Networks: Recent years have seen much interest in Low-Power wide area networks (LP-WANs), including the development of new hardware and standards. Private enterprises such as Semtech [1, 14] and SigFox [12] have developed LP-WAN chips that use extremely narrow bands of unlicensed spectrum. In contrast, cellular standardization bodies have developed two standards for LP-WAN communication for cellular base stations to communicate with low-power IoT devices over licensed spectrum: LTE-M [5] and NB-IOT [11]. Unlike LoRa and SigFox, these technologies require devices to periodically wake up to synchronize with the network – a burden on battery life.

Several recent measurement studies have been conducted to evaluate the performance and range of LP-WAN networks [7, 9, 15] and perform theoretical capacity analysis [8]. Early pilot deployment efforts are also underway with SigFox deploying their hardware to connect security alarms to the cloud in Spain [12], smart blood refrigerators in the Democratic Republic of the Congo [10] and smart city applications [2]. These efforts motivate the challenge of scalability of LP-WANs, particularly in dense urban scenarios. While recent trends such as the opening up of the TV whitespaces [4] has resulted in increased spectrum, there remains the need to study the scaling limits and spectrum management strategies for city-scale LP-WANs. Our paper addresses this lacuna in literature by exploring LP-WAN spectrum and network management over unlicensed spectrum including the TV whitespaces.

Single input, multiple output and diversity: Some related papers about SIMO, diversity used. Could also mention array telescopes like VLBA

Cloud Radio Access Networks (Cloud-RAN):

Discuss how we overcome some of cloud-RAN challenges due to short and infrequent messages

3 BACKGROUND

3.1 Single-Input Multiple-Output

Wireless devices have transitioned to using multiple antennas to leverage gains from on both client devices and access points. These are known as multiple-input multiple-output (MIMO) systems and their design involves using simultaneous transmissions and receptions from different antennas to obtain higher throughput, than what would be possible using any given pair of antennas on a transmitter and receiver. MIMO systems can provide higher throughput and resilience due to their ability to coherently combine signals both at the transmitter (known as *beamforming*) and the receiver (known as *diversity*). In traditional MIMO system such as those found in 802.11n, the various receiver antennas are a part of the same device which makes it easier to synchronize and combine the different receiver channels. However, distributed MIMO systems allow the receivers to be completely independent devices and still be able to coherently combine the received signals. Single-input multiple-output (SIMO) as shown in Figure 2 is a subset of distributed MIMO systems where the transmitter only uses a single antenna. The LoRaWAN scenario we explore in this paper is based on SIMO systems.

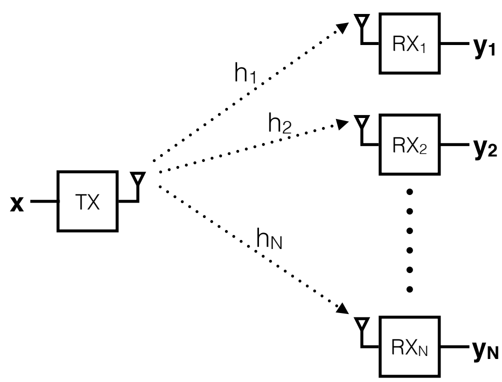

Figure 2: A single-input multiple-output (SIMO) wireless system

Let the transmitted signal be x and each of the gateways receive a signal y_i through an AWGN channel that introduces noise n_i at the receivers. Since LoRa modulated signals are narrowband (up to 500 kHz) and their symbol periods are large (Add number) to remain unaffected by inter-symbol interference, we get the following simplified channel model.

$$y_i = h_i x_i + n_i \tag{1}$$
$$\therefore h_i^* y_i = h_i^* h_i x_i + h_i^* n_i \tag{2}$$
$$= |h_i|^2 x + n_i' \tag{3}$$

3.2 LoRa Modulation

3.3 LoRaWAN

4 ARCHITECTURE

Points to cover:

- The goal: decode weak transmission by collating information from multiple base-stations
- Flow diagram (picture with cloudy and edgy stuff)
- The strawman comparison: stream everything
- Strawman limitations
  - Weak signals and limited bandwidth (problems at gateways (could use joint decoding of preambles but cant afford to stream everything))
  - Scaling issues (problems at the cloud)

5 GATEWAY

Points to cover

- Hardware + block diagram + capability + how to decode IQ streams
- Local detection algorithm
- Optional: (LoRa-aware) compression

6 THE CLOUD

Points to cover

- Q. How to solve scaling issues in the cloud?
- Avoid wasted computations
  - Short circuit
  - Leverage locality of gateways (only use a subset of gateways or decoding)
- Spatial partitioning helps correctness and performance
  - Leverage locality
  - Leverage timing
- Shorter transmissions help scalability

7 IMPLEMENTATION

Points to cover:

- OC Arch + additions over regular LoRaWAN
- Drive and Penetration test results around campus for earlier deployment

8 EVALUATION

Points to cover:

- Local packet detection: Error CDF vs SNR
- Diversity gain: Usable spreading factors vs distance/SNR
- Impact on client power: Device power trace, Battery life vs distance
- Increased capacity due to sensitivity gain (in simulation)

We implemented our system using 8 <name of the board> boards as base stations distributed across a university campus. We used a Semtech SX1276 LoRaWAN transmitter as the client device. We use Charm as the software platform at the backend to support backhaul. We evaluate our system both through proof-of-concept experiments and large-scale trace-driven simulations. We perform our experiments in various environments(both indoors and outdoors) to ensure the viability of the approach in different situations.

9 CONCLUSION AND FUTURE WORK

Need new conclusions....

REFERENCES

[1] 2015. *LoRaWAN – What is it? A Technical Overview of LoRa and LoRaWAN.* Technical Report November. LoRa Alliance. 1–20 pages. https://www.lora-alliance.org/portals/0/documents/whitepapers/LoRaWAN101.pdf
[2] Marco Centenaro, Lorenzo Vangelista, Andrea Zanella, and Michele Zorzi. 2015. Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios. *arXiv preprint arXiv:1510.00620* (2015).
[3] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi. 2016. Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios. *IEEE Wireless Communications* 23, 5 (October 2016), 60–67. DOI: https://doi.org/10.1109/MWC.2016.7721743
[4] FCC. 2010. Second Report and Order and Memorandum Opinion and Order. *Tech. Rep.* (2010). DOI: https://doi.org/ETDocketNo.08-260
[5] GSM Association. 2016. 3GPP Low Power Wide Area Technologies (White Paper). (2016).
[6] Ingenu. 2015. *How RPMA Works.* Technical Report. Ingenu, San Diego, CA. 1–5 pages. http://www.ingenu.com/get-started/resources/
[7] K. Mikhaylov, .. Juha Petaejaejaervi, and T. Haenninen. 2016. Analysis of Capacity and Scalability of the LoRa Low Power Wide Area Network Technology. In *European Wireless 2016; 22th European Wireless Conference.* 1–6.
[8] Konstantin Mikhaylov, Juha Petäjäjärvi, and Tuomo Haenninen. 2016. Analysis of capacity and scalability of the LoRa low power wide area network technology. In *European Wireless 2016; 22th European Wireless Conference; Proceedings of.* VDE, 1–6.
[9] Tara Petrić, Mathieu Goessens, Loutfi Nuaymi, Alexander Pelov, and Laurent Toutain. 2016. Measurements, Performance and Analysis of LoRa FABIAN, a real-world implementation of LPWAN. (2016).
[10] Gowri Sankar Ramachandran, Fan Yang, Piers Lawrence, Sam Michiels, Wouter Joosen, and Danny Hughes. μPnP-WAN: Experiences with LoRa and its deployment in DR Congo. (????).
[11] Rapeepat Ratasuk, Benny Vejlgaard, Nitin Mangalvedhe, and Amitava Ghosh. 2016. NB-IoT system for M2M communication. In *2016 IEEE Wireless Communications and Networking Conference Workshops, WCNCW 2016.* DOI: https://doi.org/10.1109/WCNCW.2016.7552737
[12] Ramon Sanchez-Iborra and Maria-Dolores Cano. 2016. State of the Art in LP-WAN Solutions for Industrial IoT Services. *Sensors* 16, 5 (2016), 708.
[13] Semtech. 2016. SX1301 Datasheet. (2016).
[14] N. Sornin, M. Luis, T. Eirich, T. Kramp, and O. Hersent. 2015. LoRaWAN Specification. (2015), 1–82. https://www.lora-alliance.org/portals/0/specs/LoRaWANSpecification1R0.pdf
[15] Viktor Toldov, Meijers Jp, Román Igual, Riaan Wolhuter, Nathalie Mitton, and Laurent Clavier. 2016. Performance evaluation of LoRa radio solution for PREDNET wildlife animal tracking project. In *LPWAN.*

10 OLD STUFF: MOTIVATION

A quick introduction to LoRa.... Check if we need more details about a particular aspect.

LoRa offers a unique collection of features for dynamic data-rate selection and concurrent reception of packets on the gateway. In the U.S., LoRaWAN standardized 64 channels of downlink ($125khz$) and 8 channels of uplink ($500Khz$) per base station. Current gateways use the Semtech SX1301 base band processor which can listen on up to 8 channels at the same time. Most gateway hardware pairs the SX1301 with two radio frontends that each have four programmable reception channels. Each radio front-end listens across $800kHz$ of bandwidth which supports up to four independent $125kHz$ channels or a single $500kHz$ channel (usually used for uplink). The two radios can be configured independently such that one operates on the $433MHz$ band while the other at $900MHz$ which allows for both a large bandwidth span as well as whitespace coverage. LoRaWAN specifies 7 spreading factors per channel (SX1301 supports 6) that in a similar spirit to CDMA, allows for multiple packets at different rates to be received simultaneously on the same channel. Each increase in spreading factor leads to a doubling of transmission time but a $3.5dB$ increase in link budget (i.e. range). FCC regulations allow LoRa radios to operate in *hybrid-mode* where they can hop across a reduced subset of the total LoRaWAN channel set (8 sequential channels instead of 64). We refer the reader to [13] for a more detailed description of LoRa radio hardware capabilities.

Some whitespace discussion would follow...

Since LoRa radios can span a wide frequency range, we can also access available whitespace depending on the region and usage schedules. Whitespace access requires location information for registering with spectrum databases and requires an out-of-band mechanism (like LoRa) as part of the join processes. This makes it an ideal mechanism for offloading traffic in support of scale.

10.1 Base-Station Management

Section is relevant but content needs to be updated

Most current LoRa base-stations only support traffic on 8 out of the 64 total LoRaWAN channels simultaneously. Each base-station has the freedom to select which set of 8-channels to operate on. Ideally, neighboring base-stations should operate on different channel sets if any of their coverage regions overlap. In practice, this can be difficult to estimate without collecting propagation information in the field or without adopting pessimistic unit-disc models.

One approach for assigning frequencies is to solve the graph coloring problem where each base-station is a node and a link is added if its region of coverage overlaps with any other base-stations nearby. Each of the eight sets of frequencies represents a color. Unfortunately, solving the graph coloring problem is NP-complete, but multiple heuristics perform quite well in practice. Our approach selects the node with the highest degree in the graph (or an arbitrary high-degree node in case of a tie) and then perform a breadth first search (BFS) traversal across the graph where at each node a color is selected using a least recently used (LRU) policy that does not conflict with any neighboring nodes. If there are no available colors, the least recently used color is placed in conflict. This would occur in extremely dense networks like apartment complexes that could have hundreds of set-top boxes with LoRa gateways. This heuristic tends to spread the colors apart across the network.

Base-stations can periodically scan the RF environment around them. If they detect significant interference on their current channel, they could potentially change to a different frequency set. Unfortunately, changing channels at runtime imposes an energy penalty on clients that may sporadically attempt to connect and find that the network is unreachable and be forced to rejoin. This process can be optimized if several 64-channel gateways are deployed across a region to help manage this join process. If all gateways use 64-channel hardware then graph coloring would no longer be required, but fine-grained power control would become increasingly critical.

11 OLD STUFF: IMPLEMENTATION

This section is relevant but needs major revisioning!

We implemented and evaluated our system extensively both through proof-of-concept experiments and trace-driven simulations

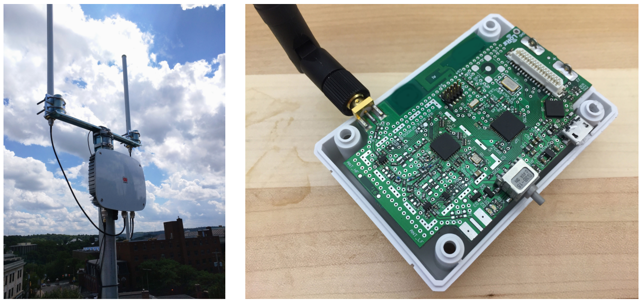

Figure 3: Photo of our gateway (left) and a custom client node (right)

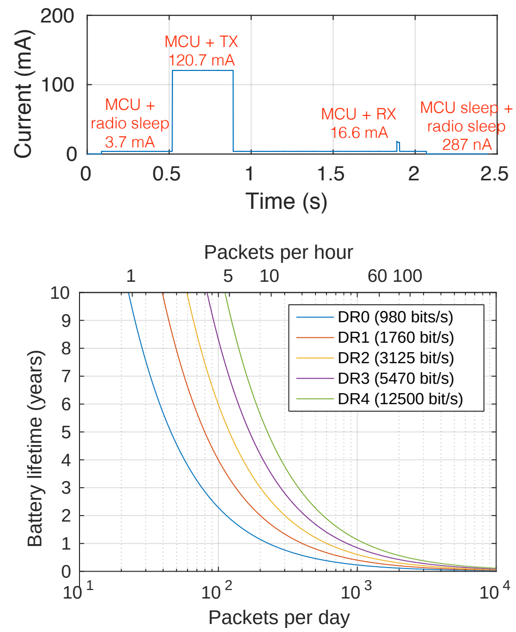

Figure 4: (above) Custom LoRa client current consumption over time for transmitting a packet and then checking for an ACK from the gateway. (below) Lifetime of a custom LoRa client powered by two AA batteries at various operating points based on a measured energy profile.

to evaluate performance at scale. Our simulations were performed using traces gathered through a university campus-scale deployment of LoRaWAN base stations. We describe our hardware, testbed, measurements gathered, simulations and experiments below.

Infrastructure Software Architecture: Add a description of the OC architecture. Refer to website for the problems it solves...

Base Station Hardware: Our pilot deployment gateways used a standard single concentrator chipset that is able to receive on 8-channels simultaneously. Though ideal for low-cost deployments like what a user might deploy in their home, this does not exploit the entire LoRa spectrum. For this purpose, we developed a more capable second-generation gateway, shown in Figure ?? that is able to operate on all 64-channels simultaneously. Similar to the 8-channel gateway, the 64 channel gateway is controlled by a single Raspberry Pi 3. Eight LoRa concentrator cards are used to interact simultaneously with 64 125kHz and 8 500kHz uplink (receive) channels and 8 500kHz downlink (transmit) channels. This spans the complete US LoRaWAN specified channel list from 902.3 to 914.9MHz for uplink and 923.3 to 927.5MHz for downlink. The radio cards are stacked in rows of four to optimize space inside the gateway enclosure. A Ublox GPS timing module is onboard to supply precise timestamps for incoming packets, synchronize time slots in LoRaWAN Class B, and to localize the gateways in the network. For future research, the board-to-board interface facilitates board stacks past that of dual 4 radio boards, while maintaining only a single USB connection to the Raspberry Pi host. This allows the radio board stack to be used with more powerful or generic machines that may not have GPIO and SPI peripherals. Additionally, the radio cards are secured into PCI Express Mini connector that expose many common wire protocols, which ensures upgradeability. We include an RTL software-defined radio for sensing of white spaces and listen-before-talk (LBT) functionality. For extended use in rough outdoor environments, we hardened the deployed hardware (weather-resistant design) and software (watchdog resets). The gateway is fully network connected and power using Power-Over-Ethernet(POE). Figure 3a shows one of our four pilot rooftop gateways.

Most of the custom client arguments like other platforms lacking BLE are not relevant anymore

Custom LoRa Client: We found that many existing LoRa client implementations were not aggressively able to power down peripherals and few lacked BLE support which is extremely valuable for device provisioning. For this reason, we developed an open-source, low-cost, low-power, and extensible LPWAN end-node hardware platform shown in Figure 3b. The custom client is powered by a Texas Instruments CC2650 microcontroller (MCU) with integrated 2.4 GHz IEEE 802.15.4 and Bluetooth Low-Energy (BLE) radios. It communicates to LoRa networks through a Semtech SX1276 LoRa radio. The node can be augmented with expansion modules for a variety of applications (e.g. environmental sensing, GPS localization and actuation). In addition to typical sleep states, the MCU has an ultra low-power sensor co-processor for sensor sampling and data aggregation, and a cryptographic accelerator that enhances the performance of security functions and reduces code-size. The custom client hardware is housed in a small plastic enclosure that accommodates two AA batteries.

Both our MCU and LoRa radio have multiple sleep and function states that consume varying amounts of power. In Figure 4a we look at the current consumed by these devices while sending out 8 bytes of data and receiving an acknowledgment. The radio was configured for uplink communications with 125 kHz channel bandwidth, data rate of 980 bits/s, spreading factor of 10 and coding rate of 4/5. Based on a simple power model, we estimate the lifetime of these devices in Figure 4b while operating on two 2000 mAH AA batteries (we make a conservative estimate of 60 % usable energy and maximum shelf life of 10 years). Thus, with proper duty-cycling, the custom client can function and communicate for multiple years on simple batteries.

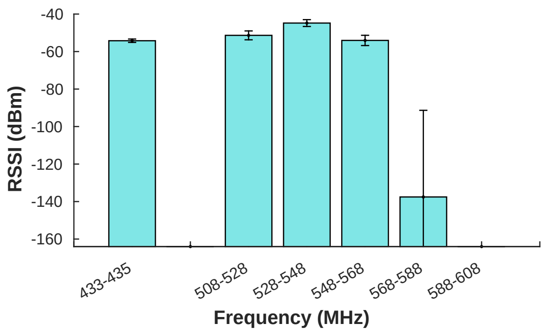

Figure 5: Depicts the RSSI and signal-to-interference plus noise ratio (SINR) for two LoRa devices 3 m apart across frequencies, including the unlicensed and TV whitespace bands. Demonstrates commercial LoRaWAN radios can receive and transmit on the TV whitespaces.

12 OLD STUFF:EXPERIMENTAL RESULTS

This section presents experimental results and benchmarks used to drive large-scale simulations in Section 13

12.1 Link Performance at the Whitespaces

While the above experiments were performed on the open ISM frequencies (the 433 MHz band and 902-928 MHz), our approach can benefit from the opening up of additional frequencies in the TV whitespaces. Fortunately, commercial LoRa radios are capable of operating on the 512-572 MHz whitespace frequency bands. Figure 5 plots the RSSI gathered by transmissions from one LP-WAN radio to another at a distance of three meters in a sealed anechoic chamber (for regulatory reasons). We observe that LoRa radio experiences a gradual drop in performance in the whitespace band, as frequencies withdraw from the 433 MHz band. This is quite natural given that the radios are designed for the ISM bands, and no low-cost radio can be expected to perform optimally across a wide range of sub-GHz frequencies. However, this shows the promise of deploying large-scale LP-WAN testbeds using current LoRa technology in the whitespaces, particularly in dense low-range scenarios, such as apartment complexes, where spectrum shortages are commonplace.

12.2 Campus-wide deployment

We currently have a campus-wide LoRaWAN system available to the student body deployed at a large university campus. The system consists of four rooftop gateways that support a variety of custom and commercially available sensing devices. Our base stations were deployed to support coverage of the complete geographical area as well as signal penetration inside buildings. After installing our four gateways, we perform a set of coverage tests. The tests are performed with a LoRa end-node configured for uplink communications with 125 kHz channel bandwidth, data rate of 980 bits/s, spreading factor of 10 and coding rate of 4/5. Downlink communications from the gateway used 500 kHz channels at 3900 bits/s. Figure 7 shows the coverage heatmap based on the average received signal strength indicator (RSSI) of ~ 12 messages sent from each location. Though some regions may not be covered using one gateway (due to shadowing, attenuation, etc.), a combination of

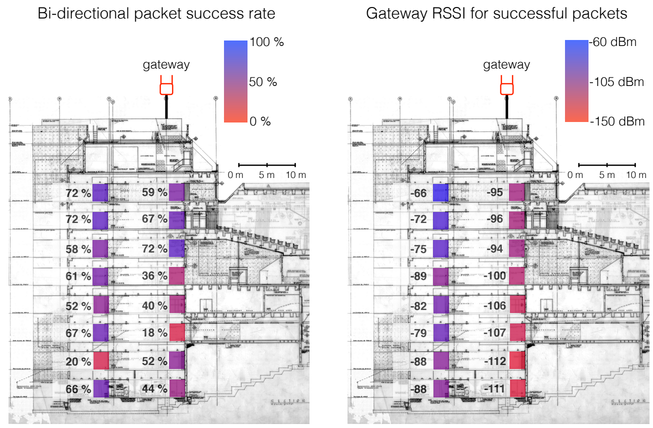

Figure 6: RF signal penetration experiments performed in a large poured-concrete building on campus. (left) shows the success rate for bi-directional packet exchange between end-node and gateway and (right) shows the RSSI at the gateway for successful transfers.

four gateways can successfully cover all major campus regions (>6 square km). We also explored the penetration inside of buildings. Figure 6 shows the signal penetration across multiple floors of a large 250,000 sq.ft. 9-story poured concrete building with a single gateway located on the roof. The packet success rate on the left is computed based on the number of complete bi-directional transfers (~ 60 points in each left corridor, ~ 15 points in each right corridor). The image on the right shows the gateway RSSI of successful transfers. The traces obtained from this testbed were used to drive the trace-driven simulations described below.

13 TRACE-DRIVEN SIMULATIONS AT SCALE

Based on our micro-benchmarking experiments, we perform a set of trace-driven simulations to demonstrate the trends of our various approaches as the system scales. Figure 8 shows a baseline experiment simulating a week of time for a single base station in the middle of a 10km by 10km area with uniformly distributed nodes. The plot shows the effective throughput of the network as the number of clients increases using our additive interference model (spreading factor aware) as well as our more realistic capture effect model. The 8-channel base-station represents the standard capacity of most current LoRa gateways. The 64-channel base-station represents the capacity of our custom hardware which as one would expect servers approximately 8x more devices. The 8-channel with a single white space band shows the potential of taking a normal gateway and equipping it with a white space radio system. We see that each white space band provides about 80% of the capacity of a 64-channel base station. It is common for cities to have 1-3 of these bands free at any given time.

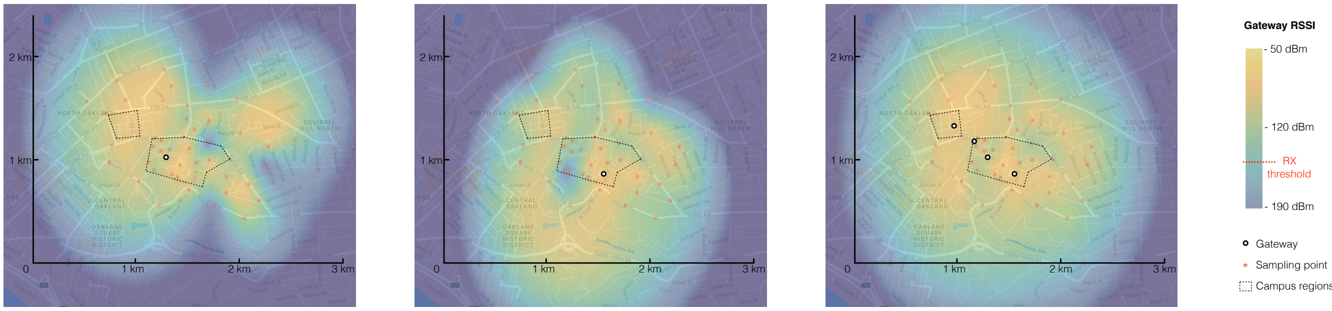

Figure 7: Network coverage in and around a large university campus campus with rooftop base stations. (left) and (middle) show coverage areas of two candidate gateways and (right) depicts that of the combination of all gateways.

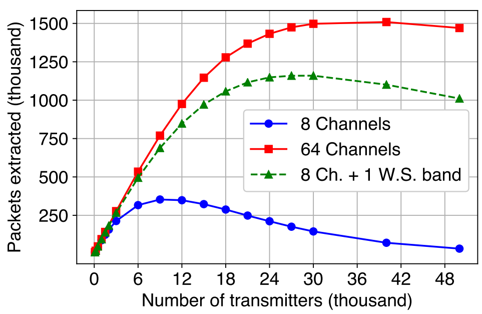

Figure 8: Network throughput under increasing clients transmitting 20 byte packets every 15 minutes. We see typical Aloha performance with a significant boost in capacity from a single White Space channel nearly matching the capacity of full 64-channel LoRaWAN gateway.