

Beartooth Relay Protocol: Supporting Real-Time Application Streams over LoRa

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Abstract. The near-ubiquitous availability of wireless connectivity lets users take advantage of a large variety of mobile applications. This connectivity predominantly comes as cellular and WiFi, limiting users to available infrastructure. At the same time, commercial efforts for infrastructure-less connectivity do not support mobile application traffic. In this paper, we present a new LoRa radio and a relay protocol capable of supporting real-time application traffic on point-to-point and multihop connection. Our solution has the potential to extend mobile application functionality beyond infrastructure coverage areas.

Keywords: LoRa, Mobile, LPWAN, D2D, Multihop

1 Introduction

People have grown used to wireless internet connectivity. They expect to keep up with news, work email, and stay in-touch through a variety of messaging and video apps. Indeed, essential functions of daily life such as transportation, shopping, lodging, and payments rely on mobile applications communicating with cloud backends and, soon, edge computing servers in near real-time. Unfortunately network coverage, or adequate provisioning, is not ubiquitous and areas such as rural roadways and developing regions need means to bridge gaps between cellular and WiFi coverage.

Modern connectivity comes predominantly through two types of technology: cellular and WiFi. While both have evolved over the years to offer impressive throughput and even rapidly decreasing latency [1]. Networks based on these technologies remain reliant on infrastructure which limits their availability and performance outside of major cities [2]. At the same time, infrastructure-less connectivity solutions are not well-suited to fill the gap for mobile applications. Walkie-talkie and amateur (HAM) radios do not offer data services integrated with cellphones primary due to regulatory limitations precluding encryption [3]. Satellite communications, while available on some smartphones, remain expensive and performance-limited, though recently planned new constellations may change that [4]. In the industrial, scientific and medical (ISM) band solutions such as DASH7, Z-Wave, and Sigfox target sensor networks and provide energy-efficient, but low data-rate connectivity [5, 6]. 802.11ah provides

higher data rates, but at a more restricted range [7]. Recently introduced Long Range (LoRA) networks can cover large area due to the long range permitted by the chirp spread-spectrum (CSS) modulation, but lack support for mobile application traffic [8]. Finally, GoTenna offers a Frequency Shift Keying (FSK) ISM network with a flooding protocol focused on short message delivery, but lacks throughput and latency to support mobile applications.

To bridge the gap between coverage limitations of cellular and WiFi networks and the lack of support for mobile applications in the ISM band, we offer the following contributions:

1. We describe a new Beartooth LoRa radio designed to address the limitations of cellular and WiFi coverage and low data rate of existing infrastructure-less networks. Beartooth’s goal is to support throughput and latency of existing mobile application traffic. Indeed, Beartooth is the first LoRa system to deliver real-time voice on point-to-point connections.
2. We present a new scheduled multihop protocol, the Beartooth Relay Protocol (BRP), to extend the system’s support for mobile application traffic beyond point-to-point connections. While multihop connectivity can connect a Beartooth network to cloud servers that support mobile application functionality, we believe that many mobile applications could be adapted to provide much of their functionality with local connectivity only.
3. We experiment with a smartphone-based deployment of BRP and report on the feasibility and limitation of software-based link-layer implementations. Placing link-layer logic on the smartphone reduces Beartooth hardware costs, provide the flexibility for faster experimentation, and simplify protocol updates. On the other hand, a software implementation carries with it the inefficiencies of cross-layer communications. We demonstrate that running the link-layer in software is possible and provides enough throughput to carry voice traffic, although with additional latency.
4. Finally, we present a detailed measurement study of Beartooth radios running BRP. We quantify the overhead of software protocol implementation as well as its performance in terms of latency, throughput, and battery power draw. We extend these results with a discussion on protocol limitations and improvements, including plans for on-chip implementation.

Our results show that Beartooth networks have the potential to form a *third leg* of consumer connectivity to fill in the coverage gaps between cellular and WiFi networks and supporting mobile application traffic. The adoption of Beartooth radios in smartphones, already underway in the Sonim XP8, paves the way to ubiquitous and constant connectivity beyond infrastructure-based wireless networks.

The rest of this paper is organized as follows. In Section 2 we discuss the limitations of existing communication technologies. Section 3 introduces the Beartooth radio and Section 4 its multihop protocol suite. In Section 5 we present a measurement study of the performance within a Beartooth network. Section 6 discusses limitations of our approach and an outline of future work. Finally, we conclude in Section 7.

2 Related Work

To frame the need for an alternative to the cellular/WiFi duopoly, we briefly discuss the limitations of these networks. We then explore the work on infrastructure-less communications within the cellular, WiFi, and ISM bands.

2.1 Limitations of Cellular and WiFi Networks

The 2019 Federal Communications Commission (FCC) mobile coverage report states that 31% Americans in rural areas lack access to 25 Mbps/3 Mbps LTE speeds and 27% lack access to terrestrial internet [2]. Even in areas nominally covered by cellular service, the economies of tower deployments create frequent occlusion zones, especially in mountainous areas, due to shadowing at longer distances [9]. At the same time it is crucial to provide full coverage, because network connectivity is increasingly important for safety-critical applications, including self-driving vehicles [10].

2.2 Promise of Infrastructure-less Networks

Many mobile applications may be able to perform their functions with temporarily limited or no access to back-haul networks. Accordingly, there have been several efforts to create device-to-device (D2D) links between mobile devices.

D2D in cellular Doppler et al. put forward one of the first D2D proposals for cellular networks [11]. The cellular tower manages direct connections between user equipment (UE), which achieve lower latency and greater spectral efficiency than by forwarding their traffic through the evolved NodeBs (eNBs), or base stations. The evolution of D2D in cellular networks is LTE Direct, defined in 3GPP Release 12, which enables discovery and connection establishment among cellular devices without eNB involvement. LTE Direct range, however, is limited to 500 meters due to low antenna height, which is insufficient for robust connectivity, or multi-hop forwarding, in many rural areas.

D2D in WiFi WiFi networks can establish D2D communications through WiFi Direct [12]. The approach borrows from the existing 802.11 protocols and allows devices to negotiate which of them will act as an access point (AP). Lei et al. have evaluated the range in WiFi Direct networks and found it limited to 656 inches [13]. Pyattaev et al. have also found that WiFi Direct connects suffer from interference on the unlicensed band as well as sharp increases in latency as the amount of traffic offloaded cellular traffic increases [9].

D2D in ISM In spite of its initial intent for device communications, the ISM band has increasingly been used for general telecommunications. Solutions such as Sigfox [14], Z-Wave [15], 802.11ah (WiFi HaLow) [7], and 802.15.4 low-rate wireless personal area networks (LR-WAN) [16] support the sporadic exchange of short messages between devices do not meet the QoS requirements of mobile application traffic. DASH7 supports star topologies with data rates of 13 kbps/16 channels, 50/8, and 166/4 [5]. Experiments show practical range of 900 m [17], which give DASH7 limited potential to patch coverage in rural scenarios. GoTenna adopts FSK and a proprietary Aspen Grove dissemination

protocol to relay text messages and other low-rate data over multiple hops albeit with no guarantees on delay.

Semtech introduced LoRa chirp spread spectrum (CSS) chip in 2009. The main advantage of LoRa is its range – radios based on Semtech chips support data rates between 0.3 and 11 Kbps and robust links at distances up to 9 km in urban and over 30 km in rural scenarios [18, 19]. The LoRa Alliance publishes a carrier sensing multiple access (CSMA) LoRaWAN protocol, which allows devices to communicate via gateways [20]. However, LoRaWAN error rates of 50% on low data rate channels make it unsuitable for application streams with QoS requirements [21]. Symphony Link uses a time division multiple access (TDMA) protocol across multiple frequencies to schedule LoRa transmissions between its nodes and a gateway, but with the low rate of 37 B packets every 2 seconds [21].

Recent research proposes new approaches to LoRA-based messaging. Cardenas et al. propose a messaging system on top of LoRaWAN for emergency communications [22]. Hochst et al. propose to address rural connectivity gaps with a custom System-on-a-Chip(Soc) LoRa transceiver [23]. Mai et al. propose multi-hop, schedule communication over LoRa for low latency IoT applications [24]. Lundell et al. on the other hand, propose a mesh networking protocol based on Ad-hoc On-Demand Distance Vector (AODV) and Hybrid Wireless Mesh Protocol (HWMP) [25]. Leonardi et al. underline the need for bounded end-to-end delay in IoT applications and introduce RT-LoRa to scheduling for real-time LoRa traffic [26]. However, none of the proposed solutions provide enough link bandwidth for voice flows.

In summary, there is a need for a third-leg of mobile communications that fills the coverage gaps left by cellular and WiFi approaches, while providing communication channels able to carry the traffic of modern mobile applications.

3 Beartooth Radio

The Beartooth radio, shown in Figure 1, is a pocket consumer device that connects to smartphones through Bluetooth and establishes a multihop network with other Beartooth radios through LoRa. The radio is based on the Semtech SX1276 chipset coupled with an 11 cm dipole antenna.

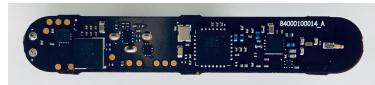
The SX1276 chipset modulates a chirp spread-spectrum (CSS) radio signal in the 900 MHz band amplified to 30 dbm at the antenna. LoRa encodes information with chirps, or transmissions of rising frequencies within the width of a channel (125 kHz or 250 kHz), where the starting frequency of chirp indicates a symbol [27]. The slope of a chirp is a function of channel width and the spreading factor, which defines the duration of each chirp



(a) Beartooth consumer device.



(b) Beartooth radio board front.



(c) Beartooth radio board back.

Fig. 1: Beartooth radio.

and its resiliency to radio interference. The SX1276 provides seven spreading factors, SF6 to SF12, while SF6 provides the highest data rate, 37.5 Kbps, SF12 provides the greatest robustness and therefore range with 260 bps [8]. The CSS encoding gives LoRa resilience to multipath effects, fading, and Doppler frequency shifts [28]. LoRa also protects bits in transmission with a configurable error correction rates using Hamming codes and with a cyclic redundancy check (CRC). Finally, the Beartooth radio achieves collision resistance by frequency hopping between channels on successive symbols. A pair of communicating nodes selects one of 50 orthogonal hopping sequences [28]. The current, proprietary implementation of a point-to-point Beartooth protocol makes this the first LoRa system to support real-time voice communications (<https://youtu.be/ECZRpeSu-EM>).

4 Beartooth Relay Protocol (BRP)

4.1 Protocol Requirements

In designing the BRP we had to consider customer requirements, constraints of the LoRa chip, and FCC regulations. Beartooth customers want to build networks that cover hundreds of square miles and support voice and data streams. The SX1276 LoRa chip, provides 50 10.9 Kbps channels at SF7, which must carry data as well as control packets. As such, the protocol must be extremely light-weight and precludes the adoption of existing link-layer protocols. The FCC limits transmit power to 30 dbm and each transmission take no more than 400 ms on air without duty-cycle restrictions [29].

4.2 Protocol Operation

BRP operates in cycles of communication divided into stages, shown in Figure 2. During the Negotiation stage nodes either establish a connection, with Link Establishment pattern, or request the relay to schedule transmissions, with the Link Scheduling pattern. Once a relay schedules node transmissions, the nodes send data to the relay, following the Data Transmission pattern, which then forwards them to other nodes. While the control frames in Link Establishment may collide, Link Scheduling and Data Transmission messages follow a schedule set by the relay to guarantee collision-free medium access to each user. In an event of control frame collision in Link Establishment, relay will not acknowledge connection attempt and nodes will try to establish connection in the next cycle.

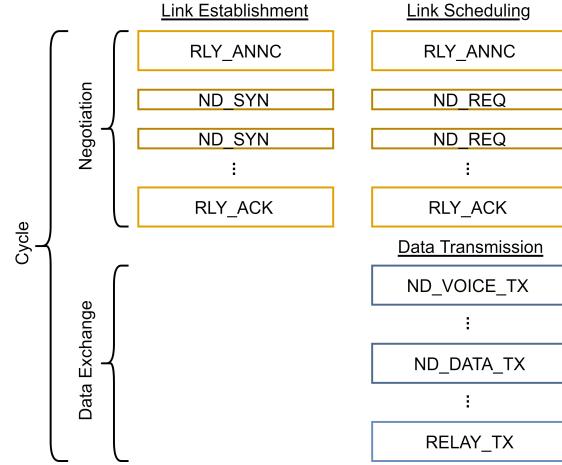


Fig. 2: Stages of the Beartooth protocol.

Negotiation The Negotiation stage establishes links between nodes and the relay and schedules transmissions. We currently initialize Beartooth devices as either relays, or nodes, though in future relays will be able to connect to other relays to establish multihop paths in the network.

Link Establishment Referring to Figure 3, to start a cycle a relay broadcasts the Relay Announce (**RLY_ANNC**) frame (Step 1), which includes the relay hardware ID, configuration ID and a timeslot table (**TS_TBL**) with available timeslots for nodes to establish connections. The configuration ID specifies required network parameters (Table 1 in Section 5). Nodes use the reception of **RLY_ANNC** to synchronize with a relay by establishing the start time of a Cycle. In the first iteration of the protocol implementation, we assume there is only one active relay in a network. Nodes will stick to a relay and ignore **RLY_ANNC** from other relays. If a node does not receive **RLY_ANNC** in some time, then it accepts announcements from other relays.

To connect with a relay, a node chooses a random available timeslot from **RLY_ANNC_TS_TBL** (2) in which to send the Node Synchronize (**ND_SYN**) frame containing the node ID (3). The relay collects **ND_SYN**s and adds the IDs of connected nodes into its **CTRL_TBL** (4), which will be used to build the **TS_TBL** in the next **RLY_ANNC**. The relay then reflects the IDs of connected nodes in the Relay Acknowledgement (**RLY_ACK**) frame (5). A node receiving a **RLY_ACK** finds its ID, adds the ID of the relay to its **CTRL_TBL** (6) and considers itself connected on previously acquired timeslot. If two **ND_SYN**s collide, nodes back off and repeat the Link Establishment process. It is important to note that as **RLY_ANNC** advertises only available control timeslots, nodes trying to connect to a relay will only consider available timeslots thus, frames can collide only with other, unconnected nodes.

To ensure that nodes do not need to repeat the connection process, entries in the **CTRL_TBL** on both nodes and the relay include a time to live (TTL) of 10 cycles. When a node stops receiving **RLY_ANNC**, it decrements the TTL of the connection. Similarly the relay decrements the TTL of a connection, if it does not receive a **ND_SYN** or a **ND_REQ** (described next) within a cycle. Reception of these packets resets the TTL to 10.

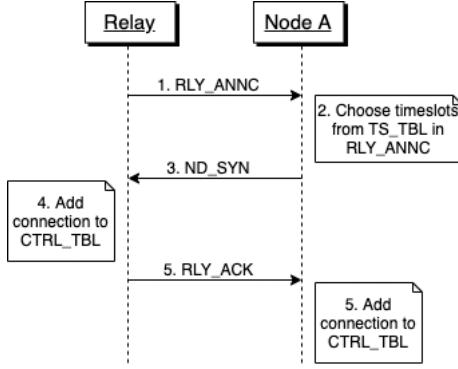


Fig. 3: Link Establishment pattern.
To connect with a relay, a node chooses a random available timeslot from **RLY_ANNC_TS_TBL** (2) in which to send the Node Synchronize (**ND_SYN**) frame containing the node ID (3). The relay collects **ND_SYN**s and adds the IDs of connected nodes into its **CTRL_TBL** (4), which will be used to build the **TS_TBL** in the next **RLY_ANNC**. The relay then reflects the IDs of connected nodes in the Relay Acknowledgement (**RLY_ACK**) frame (5). A node receiving a **RLY_ACK** finds its ID, adds the ID of the relay to its **CTRL_TBL** (6) and considers itself connected on previously acquired timeslot. If two **ND_SYN**s collide, nodes back off and repeat the Link Establishment process. It is important to note that as **RLY_ANNC** advertises only available control timeslots, nodes trying to connect to a relay will only consider available timeslots thus, frames can collide only with other, unconnected nodes.

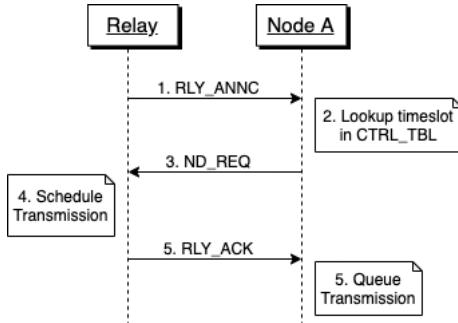


Fig. 4: Link Scheduling pattern.

Link Scheduling Referring to Figure 4, once a node connects with a relay it may start making requests to schedule its data transmissions. Upon receiving RLY_ANNC (1), a node looks up its timeslot in CTRL_TBL (2), and sends a Node Request (ND_REQ) frame on that timeslot containing a destination address (3). In practice, a node may make multiple requests in the same ND_REQ.

A relay collects all NDREQs and schedules transmissions in the available data slots (4). We implement a simple sticky scheduler, which gives priority to continuing flows from the previous cycle up to a limit. We schedule new streams greedily with priority given to voice streams. If there is no voice stream requested by the node, relay may schedule two data streams instead. The stickiness allows nodes to effectively reserve bandwidth for continued data stream, while the limit and randomness provide fairness.

After scheduling, the relay creates a traffic map `TRFC_MAP` that assigns nodes with voice and binary data timeslots and sends it out in a `RLY_ACK` (5). For example, at `TRFC_MAP` set to [23 45 45 45 67 67] may mean that node 23 will use the first timeslot for its binary data transmission, node 45 will use the next three slots for binary data transmissions, and node 67 will use the last two slots for a voice transmission on voice stream 3. Upon receiving `RLY_ACK` a node proceeds to queue up its transmissions for the Data Exchange stage (6).

Data Exchange Referring to Figure 5, after a node, here Node A, receives RLY_ACK (1) it looks up its transmission timeslot(s) in the TRFC_MAP (2). Depending on the type of transmission it requested in ND_REQ it forms a Node Voice Transmission (ND_VOICE_TX) frame, or Node Binary Data Transmission (ND_DATA_TX) frames and sends them in the assigned timeslot (3). ND_VOICE_TX is addressed implicitly by its timeslot, which allows us to reduce header overhead. ND_DATA_TX group as their destination.

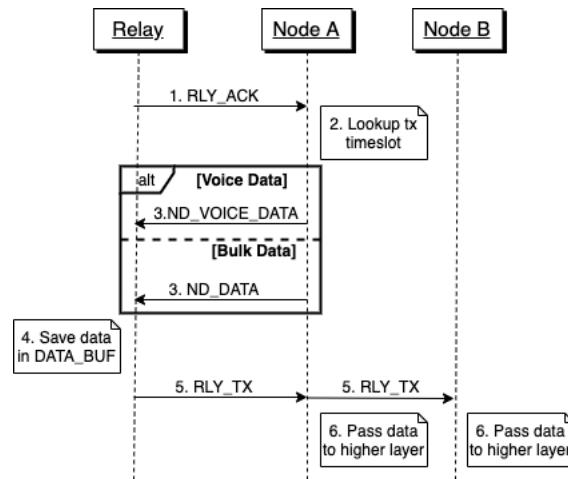


Fig. 5: Data Exchange pattern.

The relay collects all `ND_VOICE_TX` and `ND_DATA_TX` frames (4) and broadcast them in the `RLY_TX` frame (5). Again `ND_VOICE_TX` are addressed implicitly by their received order. Nodes receiving the `RLY_TX` pass onto the higher layer voice frames if their users subscribe to a particular voice channel, or data packets if `RLY_TX` contains `ND_DATA_TX` addressed to them (6).

Implicit Addressing ND_VOICE_TX frames do not include addressing information to avoid overhead. When relay receives them in that particular timeslots, BRP queries TRFC_MAP to match timeslots with respective `src_addr` and `dst_addr`.

4.3 Protocol Implementation

We want to investigate the degree to which it is possible to run a link-layer protocol on the smartphone. We implement BRP in C++ to be able to run it in hardware, or within an Android app by wrapping it in Kotlin calls. In our evaluation the Beartooth devices executes physical-layer functions and connects via Bluetooth to the app to process link-layer frames. As we show later, the Bluetooth interface introduces delays, which force a relaxation of timing with each protocol cycle.

5 Evaluation

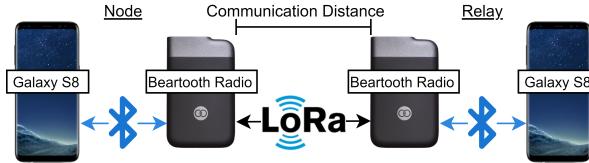


Fig. 6: Experimental setup.

The goal of the evaluation is to demonstrate the feasibility and performance of the software implemented link-layer protocol. To do so we consider a two-hop scenario illustrated in Figure 6 with one Node connecting to a Relay at some communication distance. In our experiments we send the data from a node through a relay back to itself, rather than from one node to another. Since nodes receive data later in the cycle it makes no difference if the receiving node is the sender, or another node. On the other hand, receiving data on the same node allows us to measure end-to-end latency without the need to synchronize clocks. To be clear, this is for convenience of measurement – we were able to run all experiments with multiple nodes communicating through a relay as well. The Beartooth radios connect through Bluetooth to smartphones and connections between nodes use LoRa links. We list LoRa configuration parameters in Table 1.

Cycle Duration The major challenge to a software implementation of a link-layer protocol is the delay between the physical layer and the software packet processing. In our implementation the largest and least predictable delay comes from the Bluetooth link between the Beartooth radio and the smartphone. We divide the Data Exchange stage into states of the protocol, during which certain events take place, such as the transmission and reception of particular frame. If nodes

Parameter	Value
Center Frequency	915 MHz
Spreading factor	7
Transmit Power	30 dBm
Bandwidth	250 KHz
Coding Rate	4/5
CRC	ON
Voice Encoding Rate	1.3 Kbps
Channel Capacity	10.9 Kbps
Num. Voice Groups	2
Num. Data Groups	2

Table 1: BRP parameters.

do not follow schedules strictly, the receivers may find themselves in the wrong protocol state and some miss protocol packets. To accommodate unpredictable delays we increase protocol state and cycle duration by multiplying all timing by a scaling factor. Our goal in this experiment was to measure the minimum scaling factor and cycle duration in which our protocol can still work correctly. To do so we started the experiment with the scaling factor of 20 and decreased it, until packet collisions and node state mismatch began to cause protocol errors.

Figure 7 shows a CDF of the cycle duration we were able to achieve under the scaling factor of 4.75. The x-axis shows cycle duration in seconds. We observe that the average duration of the cycle, measured on the node from the reception of one RLY_ANNC to another is 2.38s. The result shows that the software implementation of a link-layer protocol is almost 5 times slower than protocol requirements. This result shows that while software link-layer implementation provides flexibility, the added delay of Bluetooth links makes it impractical in production.

Latency To measure end-to-end latency we bounced back small packets from the node to the relay and back. This approach allows us to measure the time difference between transmission and reception on the same node, without the need for synchronizing clocks. Figure 8 shows the CDF of latency measurements. We measure the latency from the point of receiving input application-layer data for transmission to its reception in a RLY_TX. We observe that latency ranged from 0.7s to 4.78s with the mean of 2.71s. The variation in latency comes from the variation of receiving application-layer data in relation to the time in the protocol cycle. Data received just prior to the transmission of ND_DATA_TX achieves the lower latency of less than a full cycle, while data received just after may need to wait for the next cycle to start. Based on these measurements latency is proportional to cycle duration, and so speeding up cycle duration would proportionally reduce latency.

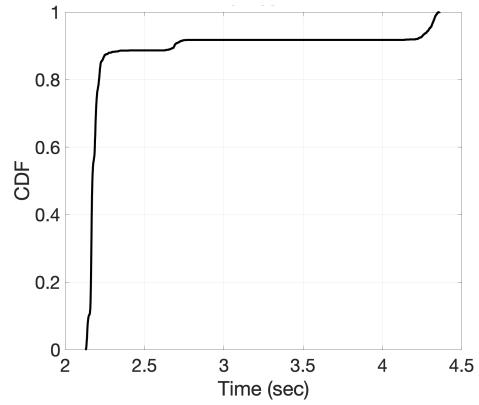


Fig. 7: Cycle duration.

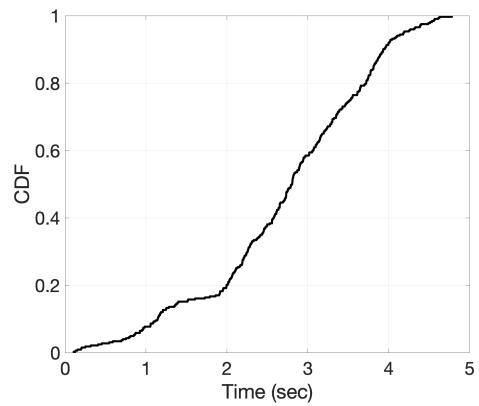


Fig. 8: Two-hop latency.

Throughput To measure application-layer throughput, we configure the network to use three voice streams, which equates to six data streams. We drive the traffic by sending six `ND_DATA_TX` frames in each cycle. Our results show the average sustained two-hop throughput of 0.782 Kbps. This throughput is of course lowered by the scaling factor. By moving protocol implementation to hardware, eliminating the Bluetooth link, and lowering scaling factor to 1, we can expect throughput of 3.71 Kbps. `ND_VOICE_TX` frames have same time on air as two `ND_DATA_TX`. Thus, we can expect the throughput of a voice channel to reach 1.3 Kbps. As it is, even with the scaling factor of 4.75 and throughput of 0.782 Kbps it is possible to transmit voice traffic encoded with Codec2 at 700 bps [30]. Thus Beartooth radios are the first LoRa system capable of sustained voice transmissions over multiple hops. We also extrapolate that by reducing the scaling factor to 1, we would be expect to sustain a throughput of 3.71 Kbps on a 10.9 Kbps link with the spectral efficiency of 0.341. The loss in the spectral efficiency of the protocol comes primarily from scheduling requests in the Negotiation stage. When multiplied by the 50 orthogonal channels, the 3.71 Kbps per channel throughput would provide up to 185.5 Kbps within a deployment area.

Range We conducted the range experiment with a node sending packets through a relay back to itself. We place the relay at the height of 250 m above ground level to create a line of sight link to a vehicle travelling along a roadway, as shown in Figure 9. The x and y-axis show longitude and latitude. During the experiment we were able to maintain a connection at a distance of 9.5 mi, or 15.2 km with the median latency of 2.26 s corroborating previous results [18, 19]. We note that since the communication is relayed, the coverage area extends to twice the measured distance at 19 mi, or 30.4 km.

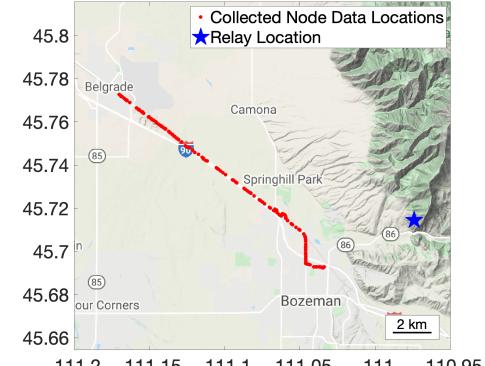


Fig. 9: Transmission range.

6 Limitations and Future Work

While running BRP on the smartphone provides flexibility in development, the approach carries several limitations.

Cycle Duration The majority of inflation in cycle time duration comes from the latency of the Bluetooth link between the Beartooth radio and the smartphone. To eliminate this delay the next generation of Beartooth radio will run BRP in hardware, reducing cycle duration scaling factor to 1. We will also reduce signalling within the protocol by making the Negotiation stage less frequent and reservations longer-lived by spanning multiple Data Exchange stages.

Multihop Paths The current implementation of BRP supports only two-hop paths. However, we designed BRP with the intent of extending it to multihop

paths, by forwarding data between relays. We believe that scheduled transmissions within BRP will be helpful in ensuring low latency and sufficient throughput for voice streams, but functionality around routing and bandwidth reservation will need novel, light-weight solutions to work reliably on LoRa’s low-bandwidth links.

Mobile Application Traffic Finally, we would like to experiment with real mobile application traffic beyond voice streams. The flexibility of BRP implementation means that the protocol may be reconfigured to match channel characteristics to message sizes as well as bandwidth and latency requirements of individual applications. We would like to evaluate whether a link-layer protocol can dynamically adapt to application layer requirements in a resource constrained network. We would also like to explore the possibility of modifying current mobile app functionality to take advantage of local area network connectivity, when a link to the cloud is not available.

7 Conclusion

Infrastructure-based networks based on cellular and WiFi coverage struggle to provide full coverage. In this paper we position LoRa-based Beartooth networks as a third leg of communications capable of supporting mobile application traffic beyond cellular and WiFi networks. We present an experimental relaying protocol for Beartooth radios and evaluate the performance of its software-based implementation. While ultimately the protocol will be deployed on Beartooth radios in hardware, even when running on a smartphone it provides sufficient throughput for voice flows, making Beartooth the first LoRa system to do so. This study will inform future iterations of the Beartooth Relay Protocol to support offline mobile application traffic.

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