BACHELOR PAPER

Term paper submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Engineering at the University of Applied Sciences Technikum Wien - Degree Program Information and Communication Systems and Services

Performance of Delay- and Disruption Tolerant Networks over an emulated Combat-Net Radio (CNR) Channel

By: Thomas Halwax

Student Number: 1410258050

Supervisor: Priv. Doz. Dipl.-Ing. Dr. Karl Göschka

Vienna, May 14, 2017

Declaration

“As author and creator of this work to hand, I confirm with my signature knowledge of the relevant copyright regulations governed by higher education acts (for example see §§21, 42f and 57 UrhG (Austrian copyright law) as amended as well as §14 of the Statute on Studies Act Provisions / Examination Regulations of the UAS Technikum Wien).

In particular I declare that I have made use of third-party content correctly, regardless what form it may have, and I am aware of any consequences I may face on the part of the degree program director if there should be evidence of missing autonomy and independence or evidence of any intent to fraudulently achieve a pass mark for this work (see §14 para. 1 Statute on Studies Act Provisions / Examination Regulations of the UAS Technikum Wien).

I further declare that up to this date I have not published the work to hand nor have I presented it to another examination board in the same or similar form. I affirm that the version submitted matches the version in the upload tool.“

Vienna, May 14, 2017 Signature

Abstract

Tactical radios are the workhorses for mobile ground troops to transmit voice and data. The contribution of this paper is to implement the transmission of bundle messages created by a Delay- and Disruption-Tolerant Network (DTN) daemon over an emulated Very High Frequency (VHF) radio channel and to measure the achievable transmission duration and data-rate for increasing distances. The channel is provided by the Extendable Mobile Ad-hoc Network Emulator (EMANE). All common properties of real radio devices are mapped onto the appropriate configuration parameters of the emulator. For distances between 0 and 26 km the transmission durations for files of relevant sizes from 256 to 8192 Bytes are measured. The computed data-rate decreases beyond a distance of about 10 km in a sublinear way up to a cut-off of about 27 km. Compared to values from literature, the emulation results prove reasonable.

Keywords: VHF tactical radio, CNR, DTN, IBR-DTN, EMANE, emulation, performance

Kurzfassung

Very High Frequency (VHF) Funkgeräte für den taktischen Einsatz bilden trotz der Verfügbarkeit mobiler Breitbandgeräte das Rückgrat für die Kommunikation von Bodentruppen. Die vorliegende Arbeit evaluiert die erreichbare Datenrate bei der Übertragung von Delay- and Disruption-Tolerant Network (DTN) Bundles über einen emulierten schmalbandigen Kommunikationskanal. Alle wesentlichen Eigenschaften der Geräte und des Wellenausbreitungsmodells werden auf die Steuerparameter des Extendable Mobile Ad-hoc Network Emulator (EMANE) abgebildet. Zur Messung der Performance werden Dateien mit einer Größe zwischen 256 und 8192 Bytes übertragen und die Messung der Übertragungszeit für wachsende Distanzen zwischen Sender und Empfänger wiederholt. Die berechneten Datenraten verringern sich ab einer Entfernung von 10 km sublinear, wobei die maximal nutzbare Entfernung bei etwa 27 km liegt. Die Datenraten der Emulation haben sich, im Vergleich mit Werten aus der Literatur die in einem Experiment unter realen Bedingungen gewonnen wurden, als schlüssig herausgestellt.

Contents

1 Introduction

Military ground forces are used to operating in hostile environments. They do not only put their lives in danger, they also have to use their communication equipment under these circumstances. Very High Frequency (VHF) tactical radio devices are sometimes the only way to transmit the Common Operational Picture (COP) to the headquarter or to coalition warriors. One of the most common protocols for sharing a semantically correct COP is the community driven Multilateral Interoperability Programme (MIP) Data Exchange Mechanism (DEM). The DEM relies on the Transmission Control Protocol (TCP) protocol that is either not supported by tactical radios or does not perform well in environments characterized by long delays and frequent disruptions. Designed for interplanetary communication, Delay- and Disruption-Tolerant Networks (DTNs) are a reliable way to deal with these problems.

Halwax introduced a proxy for the DEM over DTNs that has been tested upon a reliable and fast TCP network [1]. This proxy is fully transparent for existing DEM instances and connects them without any modification. No preceding configuration is needed and even the User Datagram Protocol (UDP)-based discovery mechanism is supported.

DTNs may use different ways for transporting data, even over a serial line provided by tactical radio devices. The DTN daemon implementation (IBR-DTN) used for the proxy was done by Morgenroth [2] and the source code is available on GitHub. Its modular architecture allows the software to get extended with new transport mechanisms. IBR-DTN provides a datagram layer out-of-the-box that is recommended as a starting point for custom convergence layers . To connect the tactical radio devices to the DTN daemon, one has to develop a new convergence layer for serial communication. The objective for this paper is the investigation of the postulated hypotheses:

Hypothesis 1 (H1): *The IBR-DTN datagram convergence layer is a valid starting point for the development of a custom serial convergence layer since it enables reliable communication over a VHF tactical radio channel.*

In order to prove H1 and to move the runtime environment for the existing proxy towards a more realistic scenario, this work replaces the error-free network with an emulated VHF radio channel. The properties of real tactical radio devices are mapped onto the input parameters of the Extendable Mobile Ad-hoc Network Emulator (EMANE). In order to verify the feasibility and performance of data transmission between two nodes over a Combat-Net Radio (CNR) channel, a location based scenario gets used. While one node remains stationary, the other one moves to predetermined locations. The stationary node sends data of varying size via the DTN daemon to the mobile node and the overall transmission duration is measured resulting in a computed net data-rate.

Hypothesis 2 (H2): *The EMANE input parameters chosen for the VHF tactical radios are valid and the behavior of the emulator is comparable to observations of real deavices.*

In an attempt to vaildate H2 this work compares the results of the performance measurements with the results published by Golan et al.. They used IP based tactical radio devices in a rural environment and measured the net (user) data-rates for UDP traffic.

2 VHF tactical radio devices

Mature VHF tactical radio devices are the workhorses for mobile troops. They can be used for voice (Push To Talk (PTT)) and data communication, are robust, easy to handle and easy to maintain. Equipped with an appropriate battery they can be operated for up to 24 hours.

2.1 Frequency range, channels and bandwidth

VHF refers to radio waves in the frequency range between 30 MHz and 300 Mhz, with a corresponding wavelength between 10 m and 1 m. In most countries the upper frequency for tactical radios is limited to 108 MHz because this is the lowest frequency used for aviation systems. Depending on local frequency regulations there might exist additional restrictions or frequency gaps in the VHF band the use of which is not allowed.

Tactical radios use descrete narrowband channels with a channel spacing of 25 kHz, so a maximum number of 3120 channels can be used in one of the following modes affecting the Physical (PHY) layer.

2.1.1 Analog FM compatibility mode

In order to ensure backward compatibility with outdated tactical radio devices, a simple analog Frequency Modulation (FM) mode can be used. This mode can only be employed at fixed frequencies and is comparable to broadcasting radio. It does not provide any kind of security and can be tapped by easy-to-build equipment.

2.1.2 Digital modes

For an improved spectral efficiency, error detection, error correction and of course encryption standardized waveforms like Singe Channel Ground and Airborne Radio System (SINCGARS) are used for digital voice and data communication in one out of the following modes:

fixed frequency mode The device uses a single channel only. If noise or interferences are overlapping the signal, the Signal to Interference plus Noise Ratio (SINR) at the receiver might get too low for the signal to be detected reliably. The only way to overcome this issue is to change the affected channel or the frequency, respectively. From a tactical point of view, the sender and its location can easily be detected by using electronic reconnaissance equipment.

frequency hopping spread spectrum mode The device rapidly switches between the carrier channels (several times per second) by using a pseudo-random sequence. Noise or narrow-band interference on discrete channels are only applied for a short interval, and a fraction of the available channels is used for redundancy. Since the pseudo-random sequence is derived from a secret cryptographic key known only to the sender and the receiver this technique provides an improved resistance against jamming attacks.

2.2 Operational modes at the Medium Access Control (MAC) layer

2.2.1 Combat-Net Radio (CNR)

When CNR mode is selected, devices will use Carrier Sense Multiple Access (CSMA) to access the medium. Only one device is allowed to transmit voice/data at a time and each device meters the SINR level to check whether the network is busy. If so, other devices sharing the same channel must remain silent and switch to the receive mode (half-duplex). The PTT behavior is a widely known example for this mode.

2.2.2 Packet-Net Radio (PNR)

The PNR mode avoids half-duplex operations by using a Time Division Multiple Access (TDMA) mode. All devices share the same channel but are only allowed to send within their associated time slice. From a users point of view, one can access the medium simultaneously since the time slices are on the magnitude of milliseconds.

Only IP (packet) based communication is allowed in PNR mode. Whenever a users employs PTT, the device switches the operational mode back to CNR.

2.3 Data communication

2.3.1 CNR

CNR requires the application to deal with a serial line communication using a RS-232 interface. The tactical radio device acts like a modem and provides transmission rates ranging from 9600 bit/s up to 115000 bit/s in the asynchronous mode.

2.3.2 PNR

Tactical radio devices provide an ordinary 10/100 BaseT ethernet interface for the PNR mode. The transmission rates are similar to the ones in the CNR mode. A notable limitation of PNR mode is its very common restriction to allow IP/UDP packets only.

2.4 HF amplifiers and antennas

The operation range of tactical radio devices is determined by the amplifiers High Frequency (HF) output power. Most handheld or manpack devices deliver a maximum of 5 W HF power. Vehicle mounted or stationary devices use additional amplifiers to provide at most 50 W for long range operations.

Antennas play a major role when it comes to SINR. Using an optimized antenna at the sender and receiver can bring a power gain up to 10 dBi[1]. In the military domain, omnidirectional rod antennas with a typical gain of 3 dBi are used.

[1] dBi reads *decibels-isotropic*. The denoted antenna gain is meant to be in comparison to a hypothetical lossless isotropic antenna.

3 Extendable Mobile Ad-hoc Network Emulator (EMANE)

EMANE is a network emulator framework designed and implemented by the United States Naval Research Laboratory (NRL). The framework provides a set of tools, services and an Application Programing Interface (API) for the modelling of wireless networks and their behavior. The API allows changing parameters at runtime. Network interfaces are the boundary between the emulator and applications. This facilitates the deployment of a System under Test (SUT) because no effort is needed to customize the SUTs for the test. In contrast to a simulator, the emulator behaves like a real system and may be used as a replacement during research.

The emulator provides physical models for the calculation of signal propagation and interference in consideration of transmission power, antennas and the geographical location of participating nodes.

A variety of scenarios can be built with EMANE, starting with only two nodes emulated on a single host machine up to a distributed emulation with a great number of nodes running on multiple hosts.

EMANE is an open source project and available on GitHub. Currently, EMANE supports cross platform deployments for all major operation systems (Unix, Linux, OS X, MS Windows).

3.1 Architecture

EMANE has a pluggable layered architecture that allows for an easy extension with custom PHY and MAC models. Figure 1 shows the high-level architecture.

The core abstraction for a participating node is the Network Emulation Module (NEM). It acts like a pipeline and encapsulates the specific MAC and PHY layers required for wireless communication. One or more optional shim layers can be used to either monitor or modify the communication between layers.

The NEMs are connected to the Over-The-Air (OTA) channel on the downstream side and to the emulation/application boundary interfaces on the upstream side.

Whenever a packet enters the NEM at the emulation/application boundary, each layer adds metadata while the packet travels downstream (towards the OTA channel). At least at the PHY layer, the metadata is evaluated and restrictions are applied to the packet by adding delays or even by dropping the packet. The same is true whenever a packet arrives via the OTA and is traveling upstream (towards the emulator/application boundary).

All parameters are defined by using XML files. While some are static, a remarkable number of parameters can be modified at run-time, either by applying events (see section 3.4) or by using the Python binding for the API.

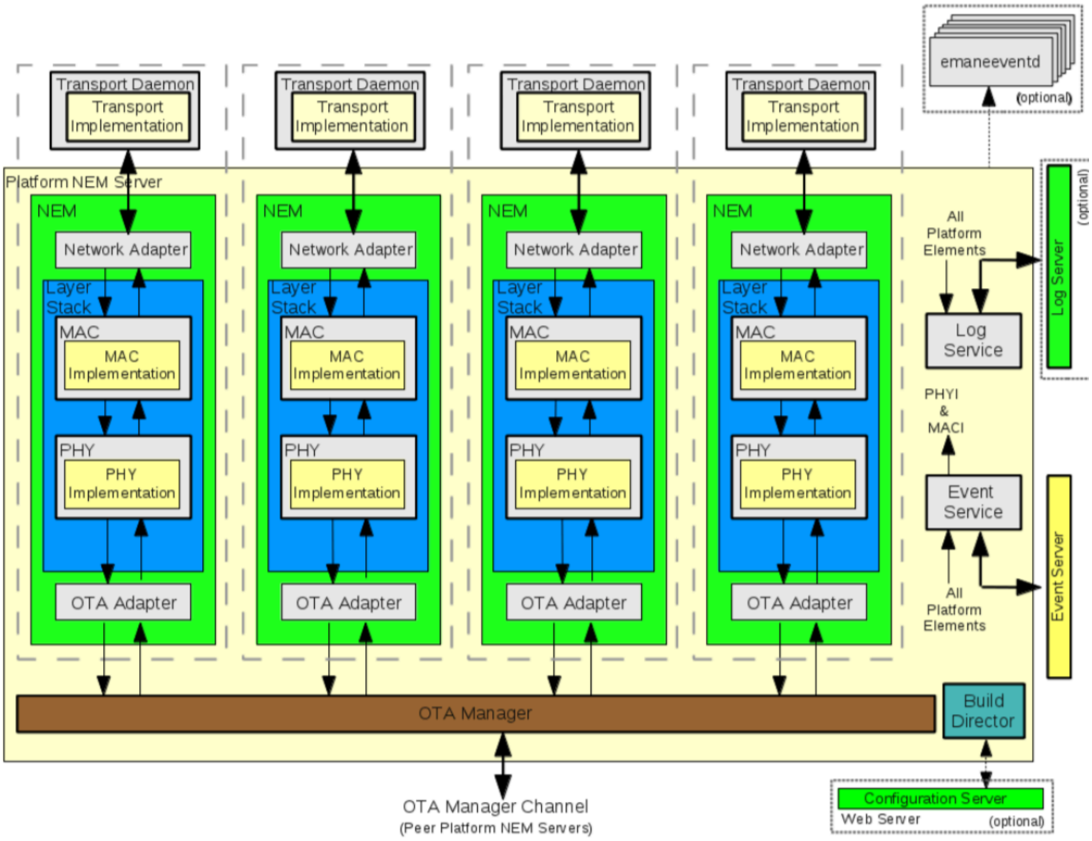

Figure 1: High-level architecture of EMANE including all optional components. Source: EMANE User Manual [4]

3.2 Physical (PHY) layer

The primary objective of the PHY layer is to calculate pathloss and the input power at the receiver side based on multiple parameters like transmission power, antenna gain, bandwidth and noise. Out-of-the-box, there is only one universal PHY layer model.

3.3 Medium Access Control (MAC) layer

Besides a TDMA and a Wireless LAN (WLAN) layer (IEEE 802.11abg) the generic RF Pipe MAC layer is used for waveforms that do not comply with the first two models. It is able to add delays and jitter and to limit the maximum data-rate for each node. Additionally, it allows the definition of a Probability of Reception (POR) as a function of the SINR at the receiver.

3.4 Events

Events are messages triggered from the outside of the emulator that affect the behavior of components. EMANE supports four types of events:

pathloss These events are consumed by the PHY layer to calculate receive power for a packet.

location Just like pathloss events, location events are consumed by the PHY layer. But instead of providing a value for pathloss, a geographic location (latitude, longitude and altitude above ground) is used. The resulting pathloss is calculated according to the selected propagation model.

comm-effect In order to apply dynamic values for delays, jitter, etc. these events are consumed by the comm-effect shim layer.

antenna-profile The PHY layer consumes these events that modify the location of the antenna in space (azimuth, pitch, roll, yaw).

4 IBR-DTN

Delay- and Disruption-Tolerant Networks (DTNs) are a way to allow an "offline-first" communication paradigma. Even in our ever-connected mobile world there are circumstances where no online communication is possible. Since mobile applications are required to deal with this issue, DTNs provide a store-carry-forward mechanism where a predetermined end-to-end communication path is not required. The origin of DTNs is the interplanetary communication and by June 2016 the National Aeronautics and Space Administration (NASA) has putted their DTN communication system on the International Space Station into productive operation [5].

IBR-DTN is an implementation of and an extension to the DTN Request for Comments (RFC) 5050 [6] and 6257 [7] accomplished by Morgenroth [2]. Their work presents a modern, lightweight and portable software that was created as an improvement to the existing implementations (DTN2 [8] and ION [9]). Pöttner et al. have compared the performance of the existing implementations [10]. They measured a raw TCP throughput of 940 Mbit/s and found values of 843 Mbit/s for IBR-DTN, 720 Mbit/s for DTN2 and 449 Mbit/s for ION. This ranking, the openness for extension and the source code availability on GitHub were the reasons for choosing IBR-DTN for this work.

4.1 Convergence layers

DTNs use convergence layers as an abstraction for the concrete transport of bundles between DTN nodes and for neighbor discovery. Considering the OSI network protocol stack the convergence layers are located on top of the transport layers (see figure 2).

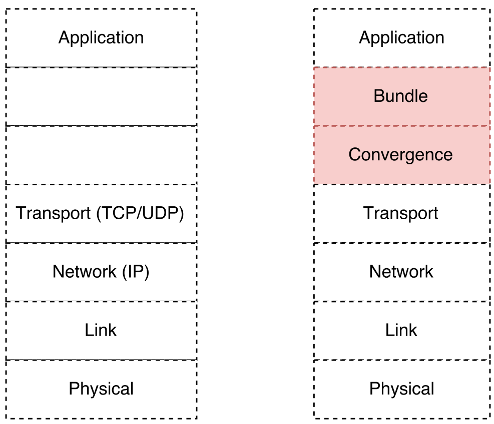

Figure 2: Comparison of protocol layers between the IP stack and the DTN protocol stack (Source: DTNs: A Tutorial [11])

IBR-DTN provides connection-oriented and connection-less convergence layers. In the present work, the *UDPDatagramConvergenceLayer* and the associated *DatagramConnection* are used. Both provide several parameters to adjust their behavior:

- flow control and error correction
- maximum segment/fragment size
- number of retries

For flow control and error correction, the authors used Acknowledgement (ACK) and Negative Acknowledgment (NACK) signals. ACK is required to signal the successful transmission of a bundle. In contrast to this behavior, NACK will either reject a bundle (permanent rejection) or trigger a retransmission of a lost or corrupt bundle (temporary rejection).

The appropriate settings for the parameters will be examined in the sections 5.1 and 5.2.

5 Performance evaluation

This work evaluates the performance of the IBR-DTN implementation over an emulated VHF radio channel. The tactical radio device is assumed to operate in the CNR mode (see sections 2.2.1 and 2.3.1). Performance metering is done using a simple file transfer. Since the result is intended to be a basement for the implementation of a custom serial convergence layer for IBR-DTN, the file sizes must be related to the typical payload size of the problem domain. The proxy introduced in [1] is designed for military data communication using the DEM. The *Fraunhofer Institute for Communication, Information Processing and Ergonomics* maintains a set of 21 default test messages which are part of the MIP Test Reference System (MTRS) [12]. The sizes of the messages used for the System-Level Test (SLT) *Suite 1* range from 213 Bytes up to 6829 Bytes. Derived from these sizes our tests will use payloads from 256 Bytes up to 8192 Bytes.

The hardware used for these tests is an Apple MacBook Pro with an Intel Core i5 processor running at 2.4 GHz. The system is equipped with 16 GB of RAM and a 512 GB SSD. All examined software frameworks and tests are executed on CentOS 7 Linux running within a VMWare Fusion virtual machine. 2 GB of RAM are assigned to the VM and it can access all processor cores.

5.1 Source code changes for IBR-DTN

5.1.1 Adaption of the ACK timeout

In order to enable error detection and retransmission of lost bundles, the *DatagramService* requires an ACK packet to indicate the successful transmission of a bundle. The time for waiting for an ACK packet is limited and has a default value of 50 ms. This default is suitable for well-connected networks but does not match the properties of an unreliable and relatively slow VHF channel. Since the value is not controllable via a run-time configuration, the source code was modified for this test and the default was set to 1000 ms. The ACK timeout itself is adapted by using an Exponential Weighted Moving Average (EWMA) algorithm. The input for the algorithm is the measured and weighted Round-Trip Time (RTT) between sending a bundle segment and the reception of the corresponding ACK signal.

$$timeout_{new} = (timeout_{old} \times weight_{average}) + ((1 - weight_{average}) \times RTT_{measured} \times weight_{rtt-event})$$

Similar to the default value for the ACK timeout, changes caused by large RTTs are applied insufficiently for this use-case. The values for $weight_{rtt-event}$ for a successful transmission (signal arrives within the timeout period) were increased from 2 to 3, and for an unsuccessful transmission (no ACK within the timeout period) from 2 to 6. All modifications made do only affect the *DatagramConnection* class.

5.1.2 Fragmentation

IBR-DTN is capable of splitting bundles into fragments. The maximum payload for each fragment can be configured using the `limit_payload` parameter. VHF tactical radios use CSMA (half-duplex network access) and all participants have to remain silent as long as the network is busy. In order to keep the time interval for sending DTN bundles and the corresponding ACK signal short and allow a responsive network, the payload is limited to 768 Bytes.

The IBR-DTN daemon on the receiver side reassembles the fragmented bundles and makes them available via the API. Due to a bug in the *FragmentManager* class, the bundles were not delivered to clients connected via the API. The fix for this bug was accomplished by this author and was merged into the GitHub repository by the creator of IBR-DTN.

5.2 Daemon configuration for IBR-DTN

IBR-DTN comes with a file containing predefined configuration settings. For our test run most of these values remain unchanged. Only these listed below were customized:

local_uri Changed to reflect the DTN hostname for both instances (*dtn://radio-1* and *dtn://radio-2*).

limit_payload Changed to *768* Bytes to allow fragmentation and keep the VHF half-duplex channel responsive.

discovery_interval Changed to *20* seconds instead of 5.

net_interfaces List of aliases for the network interfaces used by the convergence layer (*lan1*).

net_lan1_type The name of the convergence layer to use for this interface alias (*dgram:udp*).

net_lan1_interface *emane0* is the name of the interface provided by the operation system.

routing Instead of epidemic routing the value is set to *default* to allow only routing to connected neighbors.

routing_prefer_direct Changed to *yes* to forward singleton bundles directly if the destination is a neighbor.

5.3 EMANE setup

The maintainers of EMANE provide a very useful tutorial available on GitHub [13]. For the present work Tutorial 2 has been modified. A noteworthy advantage of the chosen setup is its virtualized runtime environment. Relying on Linux Containers (LXC) allows an easy deployment and avoids the time-consuming setup of hardware. Scaling from two nodes to almost any number is only constrained by the computing resources available.

EMANE and the IBR-DTN daemon are started within the same LXC node. Since IBR-DTN exposes its API on all available interfaces, `dtnsend` and `dtnrecv` are running outside the countainers. Also the location events processed by the EMANE event-daemon are triggered at the LXC host to get applied to both LXC containers. Figure 3 shows the setup of the Linux host and the two nodes *node-1* and *node-2* running within a *LXC*.

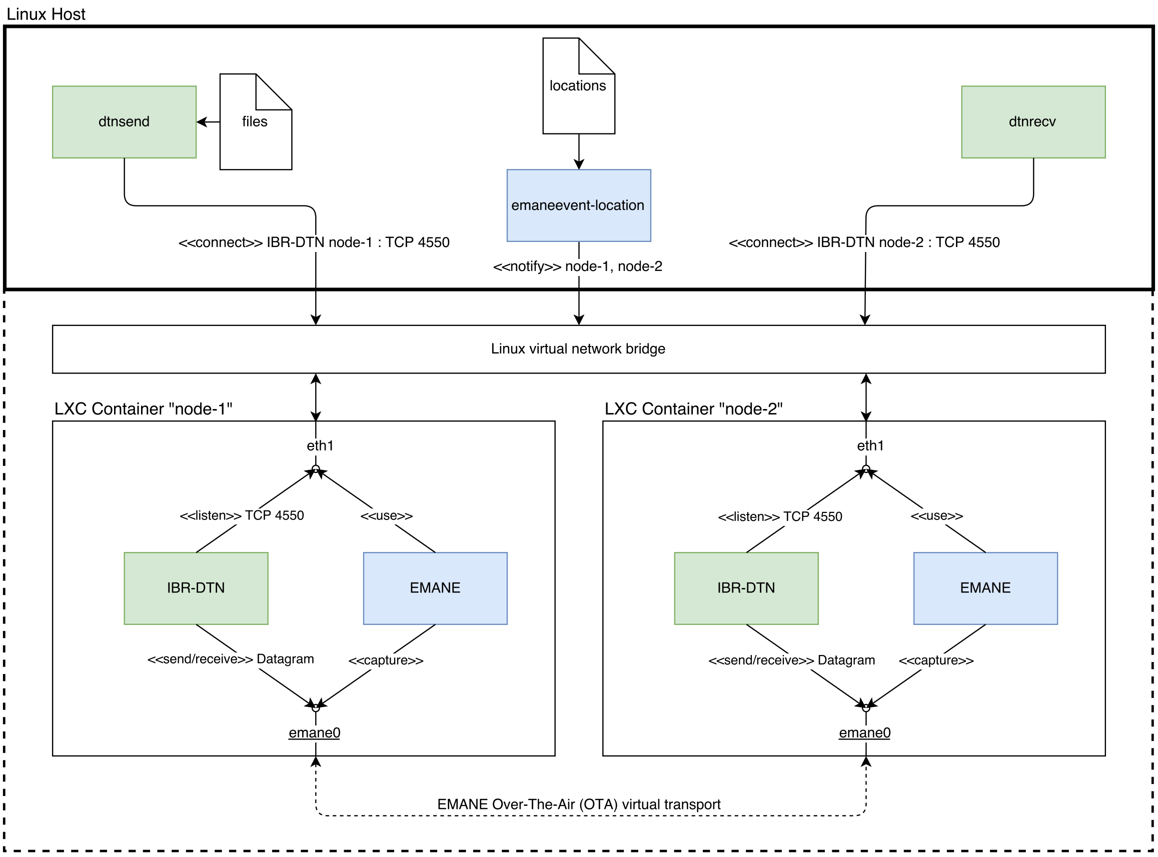

Figure 3: EMANE setup using LXC based on the tutorial provided by Adjacent Link LLC.

5.4 Data flow between IBR-DTN and EMANE

The key to understanding the data flow between IBR-DTN (or any other network enabled application) and EMANE is the usage of virtual ethernet network interfaces (see the interfaces named *emane0* inside the LXC containers in Figure 3). These interfaces are derived from a

TUN/TAP device that allows user space programs to register a network device with the (Linux) kernel. All ethernet frames (for *TAP* devices) or IP packets (for *TUN* devices) received by or sent to the interface are processed by the user space program. EMANE creates a *TUN* interface if the *virtual transport* option is selected for the emulation/application boundary.

Whenever the IBR-DTN daemon hosted by *node-1* sends datagrams to the *emane0* interface, they get processed by the corresponding EMANE daemon. The daemon controls a single NEM and applies all parameters required to emulate the behavior of the wireless device. The resulting packet containing the original payload and the applied metadata is forwared to all other EMANE instances using a IP multicast group registered on the LXC container's *eth1* device.

These datagrams are received by the EMANE instance hosted by *node-2* and get processed by applying the required operations like calculating the SINR, the POR, and values for delay and jitter. Depending on the results of these operations the original datagram may get sent to the *emane0* interface or may even get dropped.

5.5 EMANE plattform configuration for VHF

The configuration of EMANE is done using XML files. Since both nodes used in our experiment are equipped with the same tactical radio device type, the configuration of the PHY and MAC layer is shared among them.

Whenever possible the default parameters of EMANE are used. The subsections below include only customized parameters.

5.5.1 PHY layer

frequencyofinterest The receiver will "listen" for incoming signals at this frequency. Set to 38.5M (hz).

frequency The frequency the emulator uses to send. Also set to 38.5M (hz).

fixedantennagain The assumed rod antenna has a gain of 3.0 dB.

fixedantennagainenable Set to *on* to allow the calculation of the additional gain at the transmitter and the receiver.

bandwidth Since the VHF tactical radios use a narrow-band channel, the value for this parameter is set to 25000. See section 2.1 for details.

noisemode Is set to *outofband* to allow noise processing for all packets.

propagationmodel Instead of the *freespace* propagation model that does not take reflections and multipath propagation into account, this paper prefers the *two-ray-flat-earth* propagation model for path-loss prediction. The property is set to *2ray*.

txpower The output power of the HF amplifier is assumed to be 50 W which is equivalent to 46.99 dBm. To calculate the power in dBm[1] the following formula is used:

$$P_{(dBm)} = 10 \times log_{10}(1000 \times P_{(W)}/1W)$$

5.5.2 MAC layer

For this paper, the *RF-Pipe* model has been chosen out of the three available MAC models since the CNR mode does neither comply with the TDMA nor with the WLAN layer (IEEE 802.11abg). In contrast to the real devices, the *RF-Pipe* model does not support half-duplex operations. Neither do the other models available.

datarate The tactical radio devices provide a serial RS-232 interface with a maximum data-rate of *57600* bit/s.

delay Each packet gets delayed by *0.7* seconds upfront its transmission OTA.

jitter Jitter makes the delay value fluctuate by ± 0.10 seconds to add an even more realistic touch.

pcrcurveuri The Packet Completion Rate (PCR) can be defined as a function of the SINR via a file containing key-values pairs. In the absence of validated data for the PCR the default key-value pairs are used (see figure 4).

5.5.3 NEM

No changes to the default parameters of the NEM were made. There exists, of course, a separate NEM per node and thus a configuration file because each node runs its own instance of the EMANE daemon which has to be identified by a unique id.

5.6 Scenario

Mobile (ground) troops typically operate within a distance of max. 60 km to their headquater. The VHF tactical radio devices described in chapter 2 are unable to span these distances without a relay. Powered by a 50 W HF amplifier up to 40 km are possible for voice communication under perfect conditions. Of course, external influences as weather conditions, geographic location and plant coverage may reduce or even increase the coverage significantly. This paper does not consider any external influences and assumes Line of Sight (LOS) conditions. The latter is a simplification that will almost never be met in an experimental real-life scenario.

For our experiment only two nodes are involved. One remains at a fixed location and the other one moves to five selectively chosen locations. Once the location has been reached, the

[1] dBm is the ratio in decibels (dB) of the measured power with reference to one milliwatt (mW)

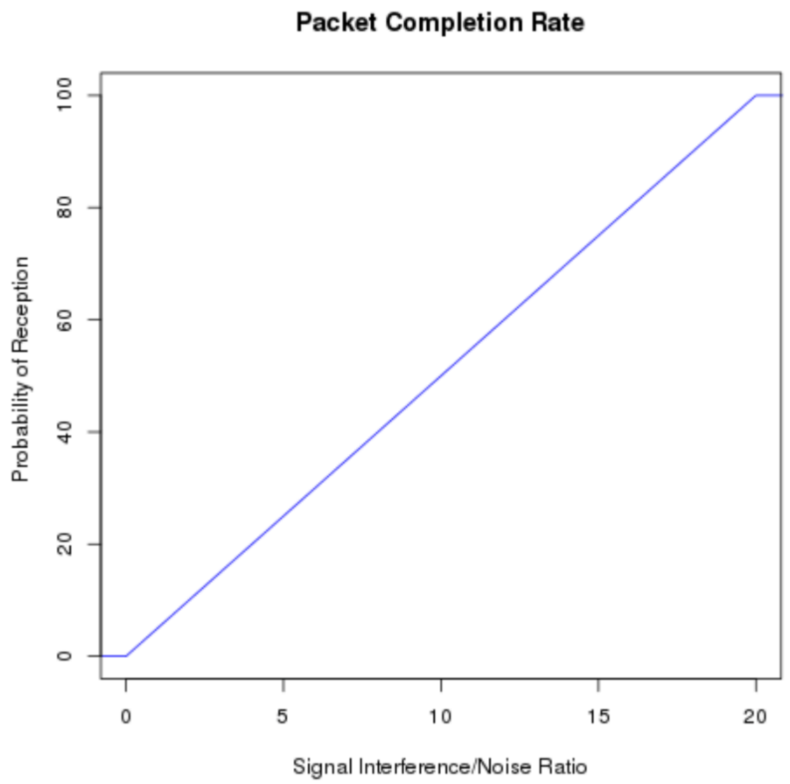

Figure 4: Default Packet Completion Rate for the *RF-Pipe* model.

parties use tools from the IBR-DTN framework to transmit files of varying size (from 256 to 8192 Bytes). Each file gets transmitted 100 times and the duration of the transmissions is measured. Table 1 shows the location of both nodes. Since we use the two-ray-flat-earth propagation model, the altitude of the nodes is meant to be the height of the antenna above ground level and has a constant value of 3 m.

Location Id	node	Latitude (DD)	Longitude (DD)	LOS distance (km)
0	node-1	48.319324	16.113900	
0	node-2	48.319324	16.113900	0
1	node-2	48.293524	16.120244	2.9
2	node-2	48.255917	16.015676	10.3
3	node-2	48.198102	15.901499	20.7
4	node-2	48.240606	15.794965	25.14
5	node-2	48.198685	15.761420	29.4

Table 1: The geographical location of both nodes used during the experiment. While node-1 stays at its location, node-2 moves from location-0 to location-5. The unit for latitude and longitude geographic coordinates is *decimal degrees* (DD).

In order to provide any kind of EMANE events to all nodes participating, the command must be issued on the host and not on the LXC node. An EMANE location event is needed to move node-2 to a (virtual) location within the emulator:

```
host$ emaneevent—location —i emanenode0 2 latitude=48.198102 longitude=15.901499
    altitude=3.0
```

Using the EMANE shell on the LXC nodes one can verify the current location of the nodes. The NEM id in the listing below corresponds to the id of the nodes listed in Table 1:

```
node$ emanesh localhost get table 1 phy LocationEventInfoTable

nem 1   phy LocationEventInfoTable
|NEM|Latitude |Longitude|Altitude|Pitch|Roll|Yaw|Azimuth|Elevation|Magnitude|
|1  |48.319324|16.1139  |3.0     |0.0  |0.0 |0.0|0.0    |0.0      |0.0      |
|2  |48.198102|15.901499|3.0     |0.0  |0.0 |0.0|0.0    |0.0      |0.0      |
```

5.7 Measurement

Besides the DTN daemon itself, the IBR-DTN framework provides some useful tools out-of-the-box. Instead of writing own code just for testing purposes, this work uses the unmodified `dtnsend` and `dtnrecv` binaries. Both tools allow users to send and receive files using the (Linux) command line and were also used by Pöttner et al. for their performance tests [10].

In order to measure the net transmission duration for a given file, two bash scripts are used that employ a *named pipe* for Inter-Process Communication (IPC). The receiver uses the blocking `dtnrecv` with a timeout of 60 s and waits for the reception of a bundle. As soon as a bundle gets delivered to the receiver it sends the current system timestamp to the sender via the *named pipe* to signal its readiness. The sender reads from the (blocking) *named pipe* and writes its own system timestamp from the previous pass and the one received via the *named pipe* to a log file. Then it sends the current payload file to the DTN daemon using `dtnsend` and waits for the next signal.

The receiver loops 100 times though the steps described above, sends a *QUIT* signal to the sender and exits. Figure 5 shows the structure of the measurement settings.

5.8 Analysis

In order to obtain conclusive results from the experiment, a statistical analysis of all collected transmission duration measurements was carried out. The probability density of the transmission time values does not follow a normal distribution but is right-skewed. Figure 6 shows the histogram calculated for packets with a size of 512 Bytes at a LOS distance of 0 km. The width of the classes for this chart is 50 ms.

Utilizing the *R* computation language [14], all measured values are described using quartiles. The *median* Q_2 cuts the data in half, which means 50% of the values are lower and 50% are

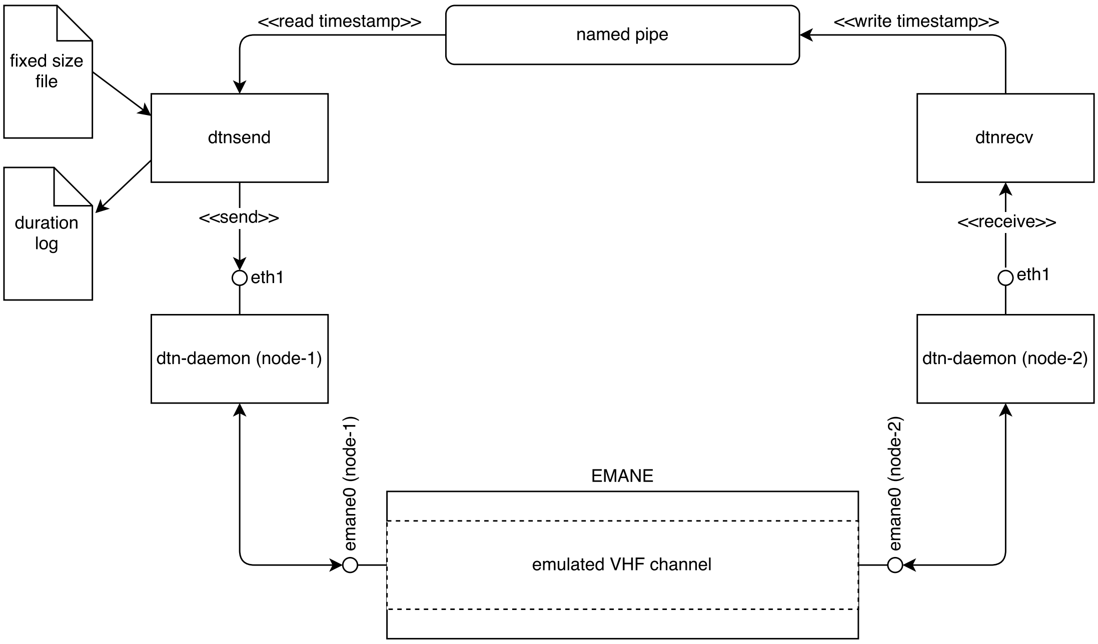

Figure 5: Tools and IPC used to measure the net duration of the file transfer via DTN over EMANE.

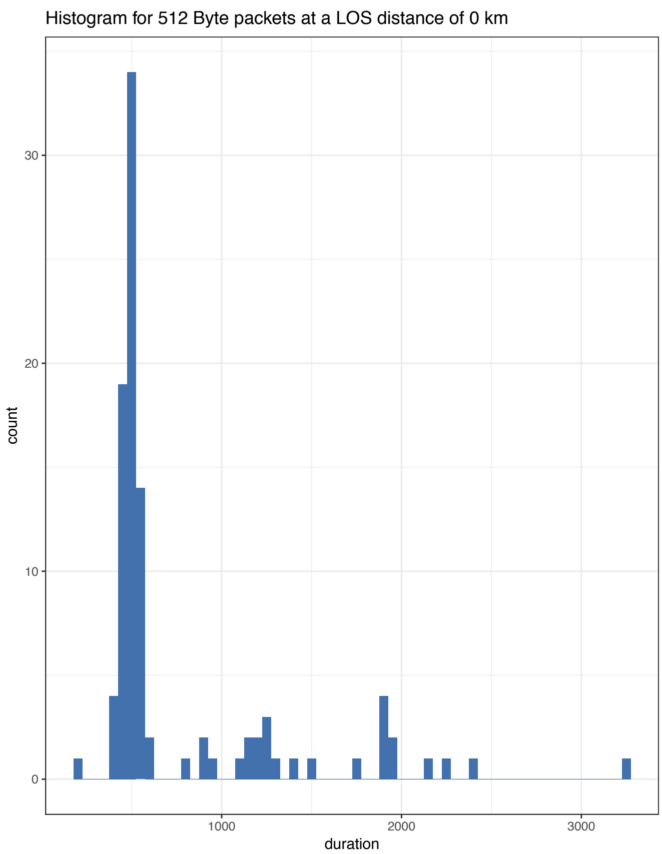

Figure 6: Histogram for 512 Byte packets for a LOS distance of 0 km

higher than the *median*, respectively.

The first quartile Q_1 separates the lowest 25% from the highest 75% and the third quartile Q_3 splits off the highest 25% from the lowest 75%. 50% of all values are located within the Inter-Quartile Range (IQR) $Q_3 - Q_1$.

The figures 7 to 11 show *box-plots* as a representation of the quartiles. Instead of displaying the minimum and maximum values, whiskers are used to denote values that are still within $\pm 1.5 \times IQR$. All values beyond these ranges are called *outliers* and are drawn as translucent circles. The charts are scaled to a maximum value of 35000 ms at the y-axis even though some data series contain occasional values beyond this upper fence.

5.9 Results

A comparison of the values for the transmission duration at a fixed packet size over the LOS distance reveals that the *median* value for the time required to transmit the packet is almost stable for distances between 0 km and 10.3 km. Doubling the distance to 20.7 km does not double *median* value but increases it by 57.8%. When rising the distance to 25.14 km the same observation can be made again.

Inspection of the *mean* values shows a slightly different picture since they are monotonously increasing. This is due to the fact that *mean* values are not robust but are heavily influenced by extreme values. The value of Q_3 rises with growing distances indicating that the scattering of the transmission duration rises, too. An exception to this observation is the LOS distance of 2.9 km where the values of Q_2 and Q_3 shrink compared to their predecessor for an unknown reason.

Table 2 shows the values discussed. Additionally, the data rates for both the *median* and for the *mean* transmission duration are listed.

LOS (km)	Q_1 (ms)	Q_2 (ms)	Q_2 DR (B/s)	*mean* (ms)	mean DR (B/s)	Q_3 (ms)
0	478.2	513.5	997.08	768.0	666.67	841.0
2.9	482.2	506.5	1010.86	855.5	598.48	578.2
10.3	478.8	525.0	975.24	888.6	576.19	1185.0
20.7	792.0	828.5	617.97	1133.0	451.90	1223.0
25.14	797.2	829.0	617.60	1227.0	417.28	1547.0

Table 2: Q_1, Q_2 (*median*), Q_3 values and *mean* values with the corresponding data-rates, calculated for a packet size of 512 Byte for growing distances.

At the maximum distance of 29.4 km the transmission duration of the communication channel is already out of scope. Some of the DTN bundles could not be delivered within 60 seconds and are considered as lost. Since the transmission of bundles is still reliable at a distance of 25.14 km one may assume the maximum suitable range to be around 27 km.

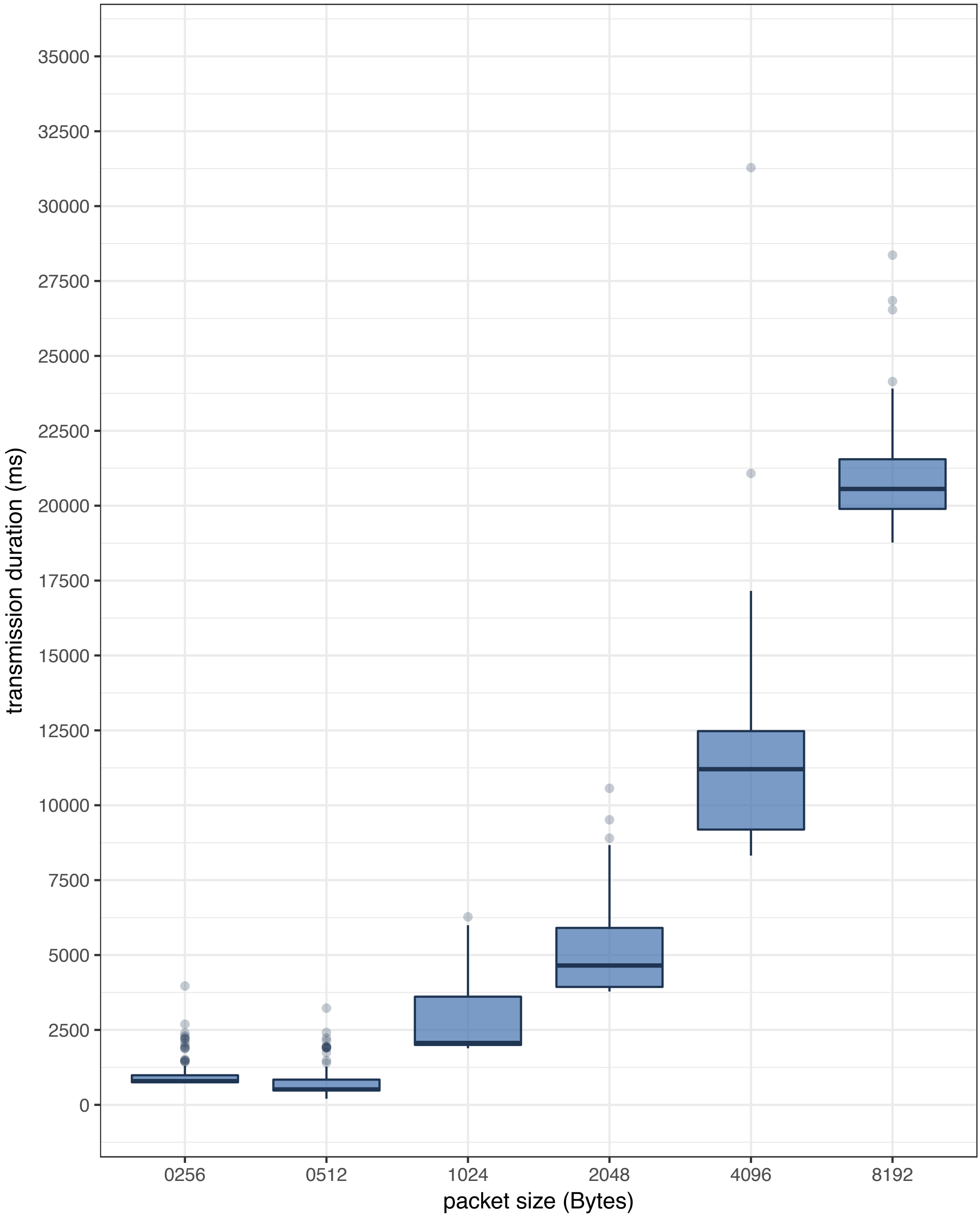

Figure 7: Box plots with whiskers for a LOS distance of 0 km. Transmission duration (ms) as a function of the packet size (Bytes).

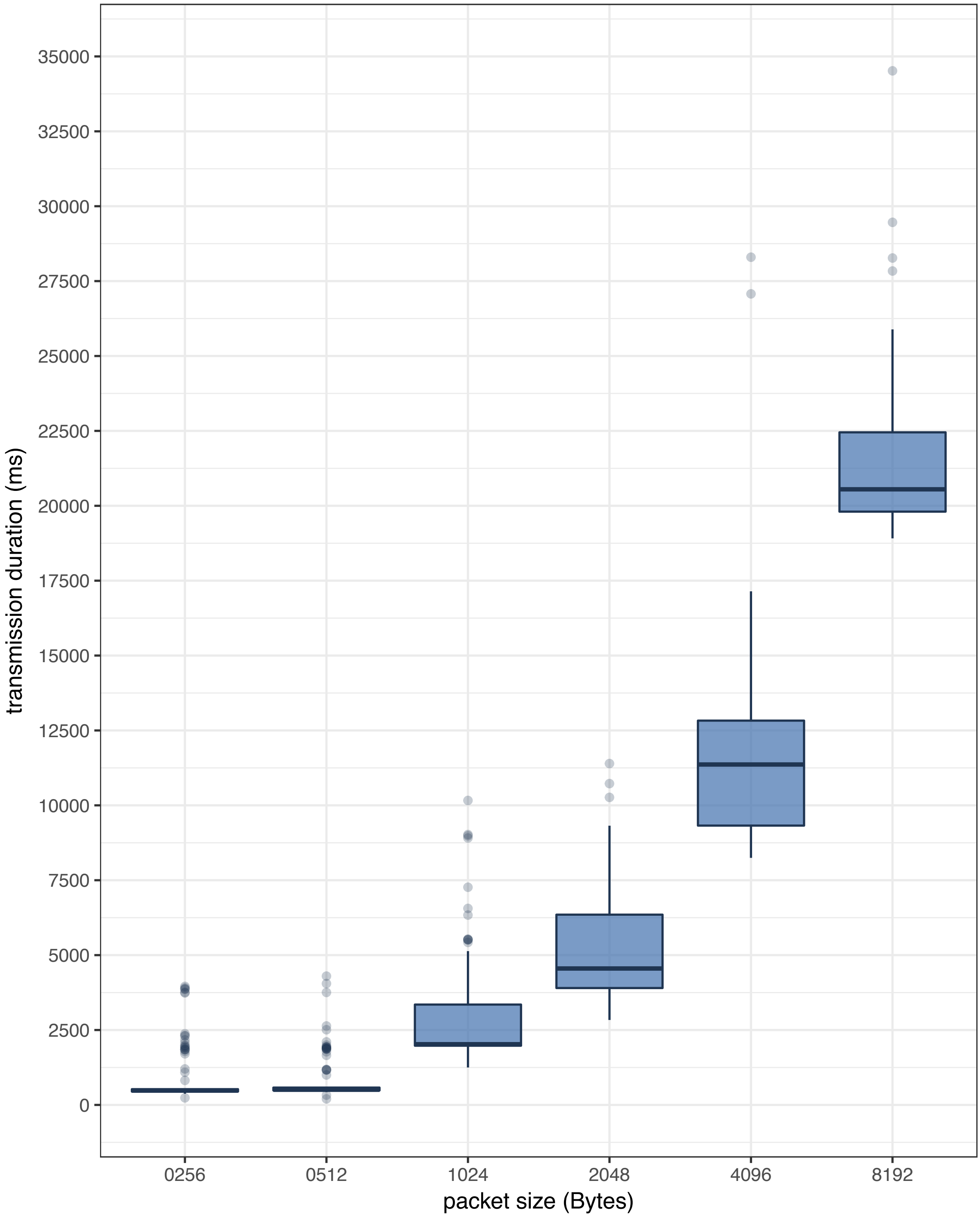

Figure 8: Box plots with whiskers for a LOS distance of 2.9 km. Transmission duration (ms) as a function of the packet size (Bytes).

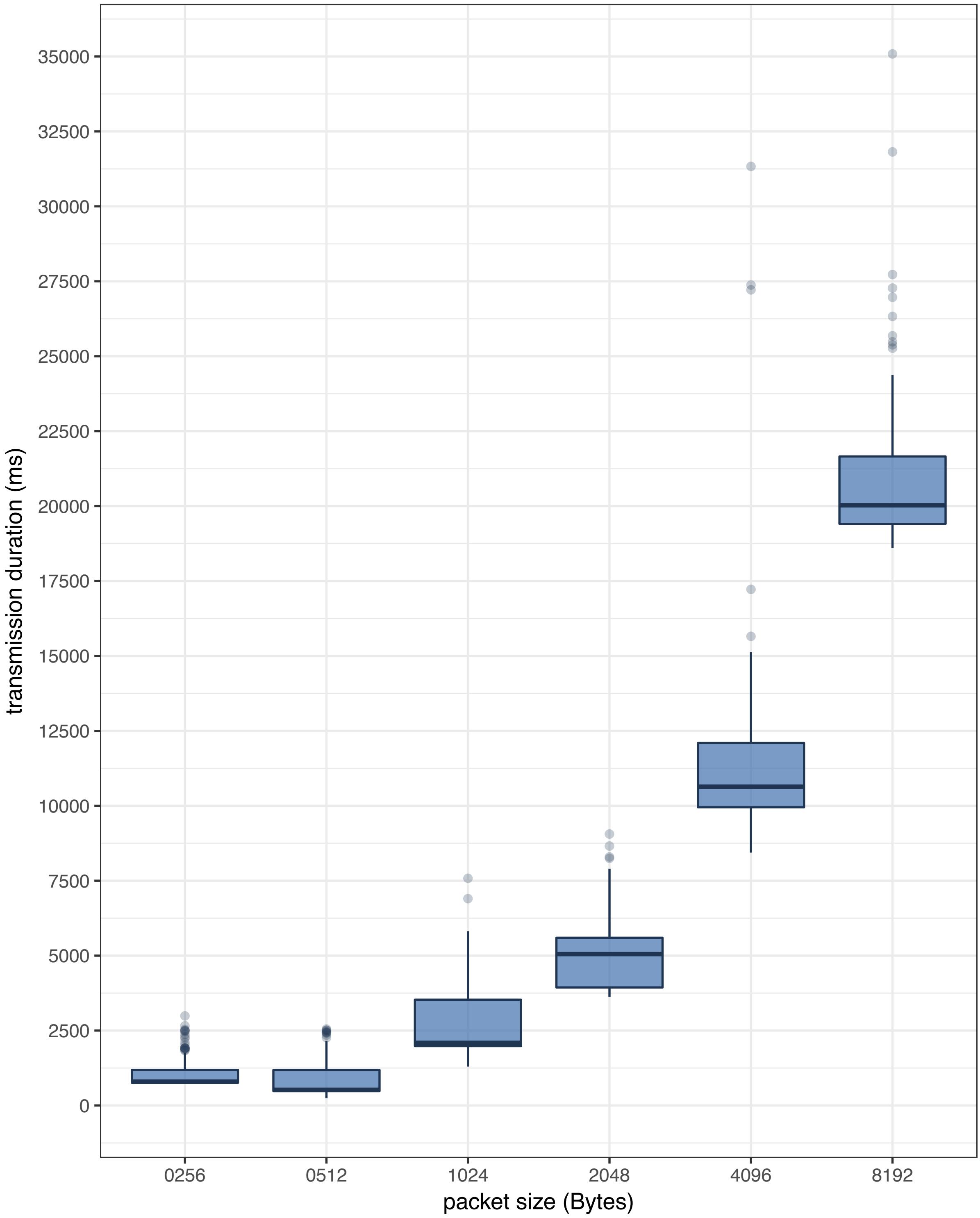

Figure 9: Box plots with whiskers for a LOS distance of 10.3 km. Transmission duration (ms) as a function of the packet size (Bytes).

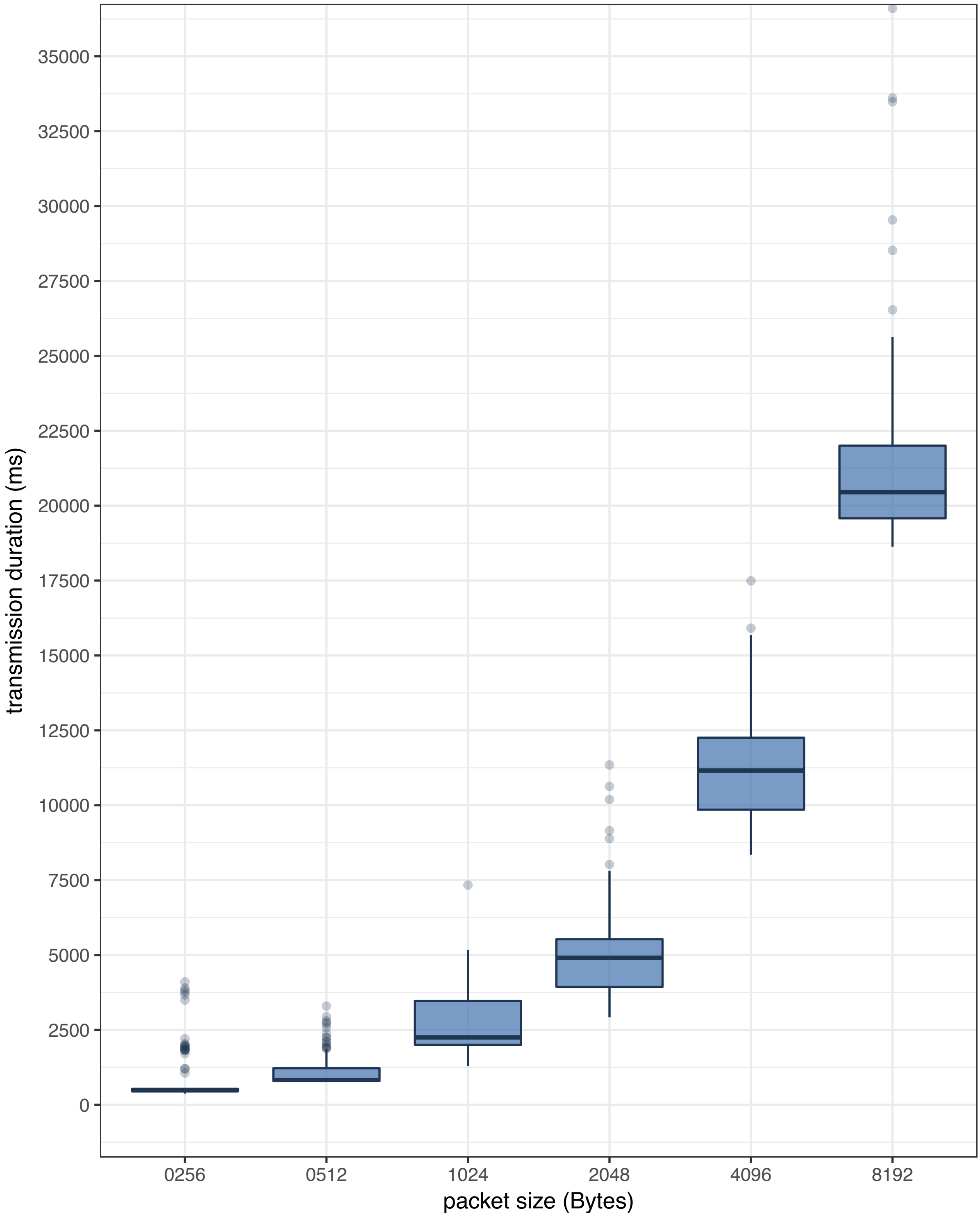

Figure 10: Box plots with whiskers for a LOS distance of 20.7 km. Transmission duration (ms) as a function of the packet size (Bytes).

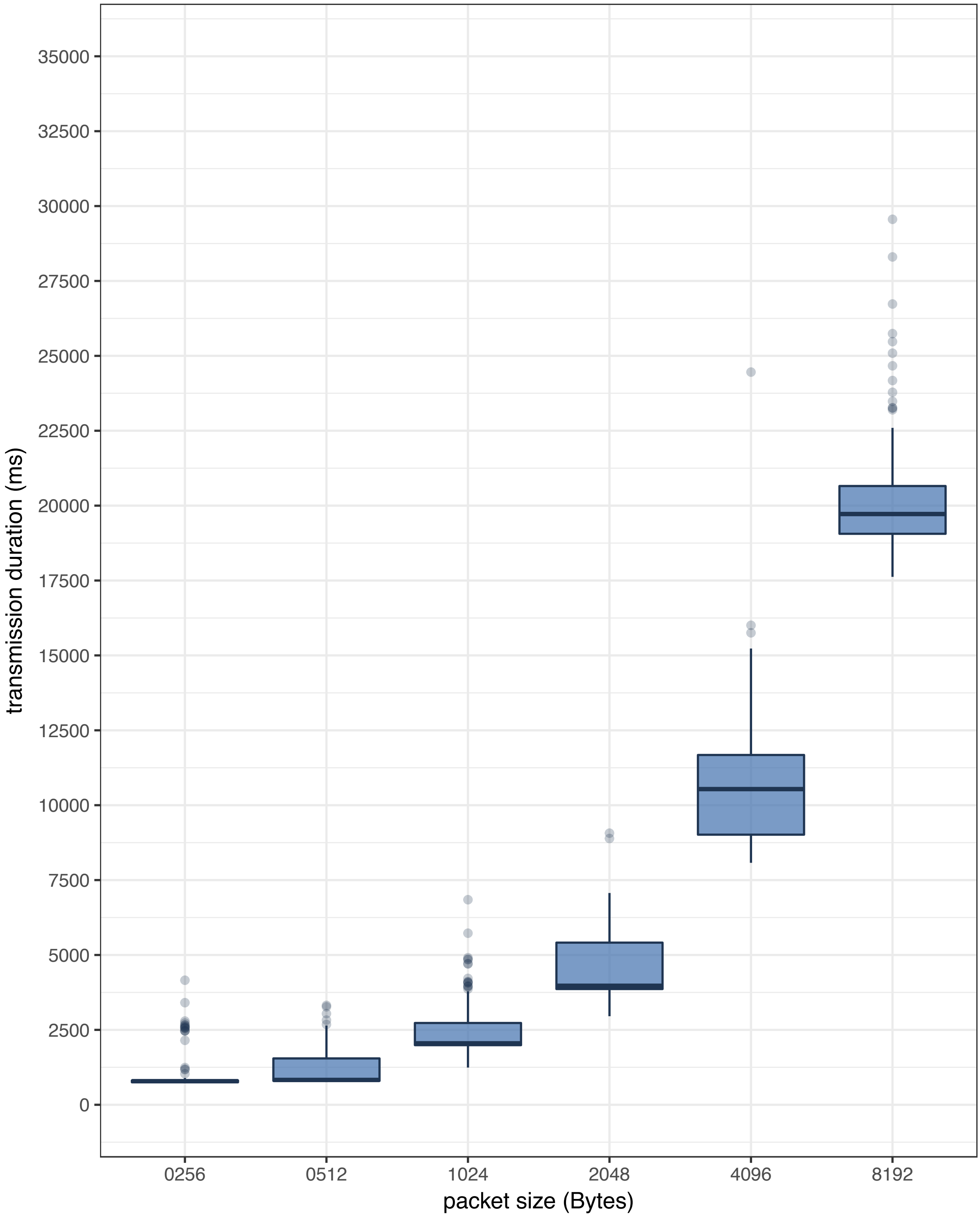

Figure 11: Box plots with whiskers for a LOS distance of 25.14 km. Transmission duration (ms) as a function of the packet size (Bytes).

5.9.1 Validation of Hypothesis H1

By reliably transmitting packets of varying size over the emulated CNR channel, IBR-DTN has been observed to be a valid fundament for the prospective development of a custom serial convergence layer. The bug found during the experiment has been fixed and the modified parameters for the ACK timeouts yielded a stable data transmission up to a maximum LOS distance.

5.9.2 Validation of Hypothesis H2

Golan et al. [3] have used RRC 9310AP tactical radios to measure the IP/UDP performance in a real life rural environment. Their radio settings are similar to the one in this work: a 50 W HF amplifier with an 3 dBi antenna mounted 3 m above ground. By transmitting a 1 MB file over UDP they measured the bit-error rate (BER) as a function of the distance between sender and receiver. The BER reached a value of 1 at a maximum distance of 26 km, no further communication was possible beyond this point. They limited the UDP datagram size to 512 Bytes, which is a little less than the DTN payload size of 768 Bytes used in this paper. Even though the authors operated their radios in PNR mode, the results are comparable to the ones in the present work. The former observed data-rates are significantly higher for short distances (1125 Bytes/s vs 667 Bytes/s), whereas the data-rates for long distances go down to 250 Bytes/s while the lowest data-rate calculated in this paper remains at 417 Bytes/s (see table 2). As a consequence, the assumptions made for the emulator are considered valid, even though the EMANE parameters need further adjustments to approximate real-life behavior.

6 Summary

The present work makes use of the EMANE to create an almost realistic transmission channel for the DTN datagram convergence layer. The simplifying assumptions for the scenario (LOS conditions, etc.) are suitable for this initial exploration. Both hypotheses turned out to be correct and the author of this work is planning to implement a custom convergence layer for serial line communication in a future project.

6.1 Related Work

Wang et al. have described the common characteristics of legacy tactical radio waveforms and discussed the implications for the implementation of a Mobile Ad-Hoc Network (MANET) over legacy tactical radio links. In contrast to common myths about the achievable data-rates they pointed out that doubling the physical bit-rate does not double the data-rate. This is due to dominating parameters like the Receive/Transmit (Rx/Tx) turnaround time and the ratio of the size of the waveform preamble in comparison to the payload size. Using a data-rate of 56 kbit/s the link throughput decreased from 45 kbit/s for a Rx/Tx turnaround time of zero down to 14 kbit/s for 100 ms. Applying the 56 kbit/s waveform to a simulated environment, a link data-rate of 10 kbit/s (1,250 Bytes/s) was achieved for a packet size of 500 Bytes. These results match closely with the ones described by Golan et al. [3]. The latter authors were able to transmit packets with a size of 512 Bytes at 1,250 Bytes/s in a real-life scenario .

Kotz et al. carried out a survey about simplifying assumptions for Radio Frequency (RF) propagation models made in the literature [16]. The authors focused on research papers in the field of MANETs and concluded, that a great number of publications rely on six "axioms" like "The world is flat", "All radios have equal range" or "Signal strength is a simple function of distance". A presented real-world scenario contradicts all axioms and the authors question the results of previously published simulation results. The present work also relies on a subset of these axioms. Although the *two-ray flat-earth* model used for the EMANE was considered inadequate for MANETs it "... has been reasonably accurate for predicting large-scale signal strength over distances of several kilometers ..." (see [16], p. 4). In addition to this, the absence of a realistic three-dimensional terrain model and of asymmetric link capabilities are drawbacks of the emulation. The present work has nonetheless shown the chosen parameters for EMANE to be correct in principle since the results do closely match the ones of a real-life experiment.

Le Naour et al. developed a realistic and reproducible channel model for a narrowband tactical radio operating in frequency hopping mode [17]. They selected a exremely challenging environment in the Swiss Alps for their experiment. By using a TDMA channel access operating at a data-rate of 2,400 bit/s a maximum distance of 16 km was achievable. Due to poor SINR values caused by multipath propagation no reliable communication was possible beyond this point. This experiment shows once again that the results of an emulation have to be treated with caution because standard propagation and terrain models are not suitable for reflecting real-life conditions.

Acronyms

ACK Acknowledgement

API Application Programing Interface

BER bit-error rate

COP Common Operational Picture

CNR Combat-Net Radio

CSMA Carrier Sense Multiple Access

DEM Data Exchange Mechanism

DTN Delay- and Disruption-Tolerant Network

EMANE Extendable Mobile Ad-hoc Network Emulator

EWMA Exponential Weighted Moving Average

FM Frequency Modulation

HF High Frequency

IPC Inter-Process Communication

IQR Inter-Quartile Range

LOS Line of Sight

LXC Linux Containers

MAC Medium Access Control

MANET Mobile Ad-Hoc Network

MIP Multilateral Interoperability Programme

MTRS MIP Test Reference System

NACK Negative Acknowledgment

NASA National Aeronautics and Space Administration

NEM	Network Emulation Module
NRL	Naval Research Laboratory
OTA	Over-The-Air
PCR	Packet Completion Rate
PHY	Physical
PNR	Packet-Net Radio
POR	Probability of Reception
PTT	Push To Talk
RF	Radio Frequency
RFC	Request for Comments
RTT	Round-Trip Time
Rx/Tx	Receive/Transmit
SINCGARS	Singe Channel Ground and Airborne Radio System
SINR	Signal to Interference plus Noise Ratio
SLT	System-Level Test
SUT	System under Test
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
WLAN	Wireless LAN
VHF	Very High Frequency

Bibliography

[1] T. Halwax, “A proxy for Military Data Communication over Delay- and Disruption-Tolerant Networks,” BSc Thesis, UAS Technikum Wien, Information and Communication Systems and Services, 2017, not published.

[2] J. Morgenroth, “IBR-DTN - Event-driven Software-Architecture for Delay- and Disruption-Tolerant Networking,” PhD Thesis, TU Braunschweig, Carl-Friedrich-Gauß-Fakultät, Institut für Betriebssysteme und Rechnerverbund, 2015. [Online]. Available: http://www.digibib.tu-bs.de/?docid=00061364

[3] E. Golan, A. Kraśniewski, J. Romanik, P. Skarżyński, and R. Urban, “Experimental performance evaluation of the narrowband VHF tactical IP radio in a real environment,” in *Military Communications and Information Systems Conference (MCC), 2013*. IEEE, 2013, pp. 1–5.

[4] S. M. Galgano, K. B. Patel, and E. Schreiber. (2013) EMANE User Manual v0.8.1. [Online]. Available: https://downloads.pf.itd.nrl.navy.mil/docs/emane/emane.pdf

[5] National Aeronautics and Space Administration. (2016) New Solar System Internet Technology Debuts on the International Space Station. [Online]. Available: https://www.nasa.gov/feature/new-solar-system-internet-technology-debuts-on-the-international-space-station

[6] K. Scott and S. Burleigh, “Bundle Protocol Specification,” Internet Requests for Comments, RFC Editor, RFC 5050, November 2007. [Online]. Available: https://tools.ietf.org/html/rfc5050

[7] S. Symington, S. Farrell, H. Weiss, and P. Lovell, “Bundle Security Protocol Specification,” Internet Requests for Comments, RFC Editor, RFC 6257, May 2011. [Online]. Available: https://tools.ietf.org/html/rfc6257

[8] M. Demmer, E. Brewer, K. Fall, S. Jain, M. Ho, and R. Patra, “Implementing Delay Tolerant Networking,” Technical Report IRB-TR-04-020, Intel Research, Tech. Rep., 2004.

[9] S. Burleigh, “Interplanetary Overlay Network: An Implementation of the DTN Bundle Protocol,” in *Consumer Communications and Networking Conference, 2007. CCNC 2007. 4th IEEE*, 2007, p. 222–226.

[10] W.-B. Pöttner, J. Morgenroth, S. Schildt, and L. Wolf, “Performance comparison of dtn bundle protocol implementations,” in *Proceedings of the 6th ACM workshop on Challenged networks*. ACM, 2011, pp. 61–64.

[11] F. Warthman *et al.*, "Delay- and Disruption-Tolerant Networks (DTNs)," *A Tutorial. V3.2, Interplanetary Special Interest Group*, 2015. [Online]. Available: http://ipnsig.org/wp-content/uploads/2015/09/DTN_Tutorial_v3.2.pdf

[12] M. Gerz, N. Bau, A. Vogt, and R. Vogt, "Automated Conformance Testing of C2IS," DTIC Document, Tech. Rep., 2009.

[13] Adjacent Link LLC. EMANE introduction by demonstration. [Online]. Available: https://github.com/adjacentlink/emane-tutorial

[14] The R Foundation. The R Project for Statistical Computing. [Online]. Available: https://www.r-project.org

[15] H. Wang, B. Crilly, W. Zhao, C. Autry, and S. Swank, "Implementing mobile ad hoc networking (MANET) over legacy tactical radio links," in *Military Communications Conference, 2007. MILCOM 2007. IEEE.* IEEE, 2007, pp. 1–7.

[16] D. Kotz, C. Newport, R. S. Gray, J. Liu, Y. Yuan, and C. Elliott, "Experimental evaluation of wireless simulation assumptions," in *Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems.* ACM, 2004, pp. 78–82.

[17] A. Le Naour, F. Pipon, B. Nahoum, D. Mérel, and B. Obrist, "Performance of the FASTNET Narrowband VHF Frequency Hopping Tactical Radio in Challenging Multipath Environments," in *Military Communications Conference (MILCOM), 2014 IEEE.* IEEE, 2014, pp. 649–656.