On the Feasibility of Digital VHF Communications in Crisis Scenarios

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***Abstract*—Communication is key, especially during a crisis. In case of larger incidents, existing infrastructure often faces outages, making it difficult – if not impossible – to communicate. While first responders have communication solutions for these cases, civilians remain disconnected. To avoid such stressful situations, we study Rattlegram, a novel communication solution that uses acoustic coupling of smartphones with VHF/UHF handheld radios to transmit digital information. We compare it to existing protocols for the VHF/UHF band and evaluate its performance in simulations and field tests. We demonstrate its applicability, showing that even a cheap handheld radio can be used to establish communication up to a distance of over 18 km in rural and close to 1 km in urban environments. The results highlight that Rattlegram is a viable technology that can be the base for affordable, infrastructure-less emergency communication for the masses.**

***Index Terms*—Crisis Communication, Emergency Communication, Acoustic Communication, VHF, SDR.**

I. INTRODUCTION

Communication is an integral part of our daily lives. With the introduction of smartphones, we have become accustomed to being online and reachable anytime and anywhere. In everyday life, one often forgets about the fact that both Wireless LAN (WLAN) and cellular connectivity rely on infrastructure. With cyberattacks and natural disasters becoming ever more prevalent, disruption of wireless infrastructure due to power outages or its physical destruction are no longer an abstract threat. Large floods such as in the Ahr valley in Germany in 2021 [1], in South Pakistan along the Indus and Kabul rivers in 2022 [2], and Emilia-Romagna in Italy in the recent year [3] can damage or even completely destroy critical infrastructure like communication networks or electrical grids.

While first responders, like the police and firefighters, already have established communication solutions that can operate independently of civilian networks, the public lacks the tools to organize themselves. In this paper, we study *Rattlegram*, a novel, Open Source acoustic communication technology that is designed to operate over Frequency Modulation (FM) radio, coupling smartphones with Very-High Frequency (VHF) radios. An overview of the system is depicted in Figure 1. The acoustic transmission between smartphone and radio uses Rattlegram, a state-of-the-art Orthogonal Frequency-Division Multiplexing (OFDM)-based physical layer, which is FM-modulated for radio transmission. The handheld radios are primarily designed for the amateur radio 2 m and 70 cm band at 144–146 MHz and 430–440 MHz, respectively.[1] Compared to LoRa or other Low Power Wide Area Network (LPWAN) technologies, using the VHF band provides better propagation characteristics and the devices support a much higher transmit power, compared to low-power nodes (typically a factor of ≈ 40).

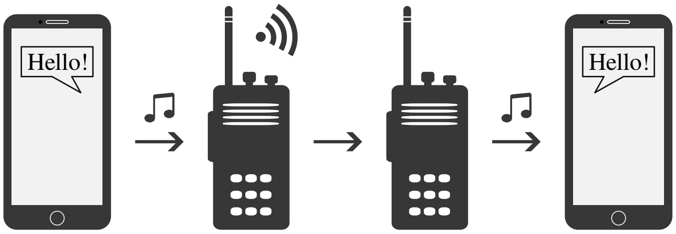

Figure 1. Schematic overview of the communication system.

In this paper, we study the performance of Rattlegram in simulations and field tests, and compare it to AX.25 and FX.25 with AFSK 1200 modulation, the current standard for digital communication in the VHF band. We, furthermore, extend Rattlegram to experiment with different modulations. The experiments show that, in contrast to existing technologies, Rattlegram allows acoustic, over-the-air coupling of the smartphone and the radio, while offering similar or better performance with regard to throughput and robustness against noise, hardware impairments, and channel effects. In our field test, we are able to establish communication over 18 km in a rural environment with low-cost consumer radios, demonstrating the applicability of system.

Our main contributions can be summarized as follows:

- We extend Rattlegram, a state-of-the-art acoustic physical layer designed for use with VHF radios.
- We compare Rattlegram to AX.25 and FX.25 through simulations, showing that Rattlegram is able to deal with acoustic multipath, which allows over-the-air coupling of the smartphone with the radio.
- We conduct field tests in different environments to demonstrate the practical feasibility and applicability of the technology.

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[1] While the 70 cm band is technically in the Ultra-High Frequency (UHF) band, we refer to both bands as VHF for more concise formulations.

II. BACKGROUND AND RELATED WORK

Fast and efficient coordination of available resources is important to react to crisis situations. First responders are, therefore, equipped with communication solutions like TETRA that can operate independently of infrastructure. Yet, such devices are often costly, hard to configure, and operate on dedicated frequencies, which renders them unsuitable for use by the public. More recently, satellite communication with ordinary smartphones became reality. While this technology is outstanding for issuing emergency messages for isolated incidents. They are not well suited for major emergencies that affect a larger area, like earthquakes or floods, which cause a much higher communication demand.

An interesting technology for such use-cases is LoRa, a wireless technology that uses Chirp Spectrum Spread (CSS) modulation and operates at 433 MHz, 868 MHz, or 915 MHz. Due to its transmission range and low power consumption, LoRa is a popular protocol for Internet of Things (IoT) applications and mesh networking. It can, however, also be used as a wireless protocol for emergency networks [4]. In an experimental setup with a 3 dBi antenna, Höchst et al. [4] achieve a transmission range of up to 2.89 km. While this can be a practical solution, we explore VHF communications that support lower frequency bands and use radios with much higher output power.

This frequency band is also considered by the *Serval Project* [11], which aims to establish a communication infrastructure for disaster scenarios by using a mesh network. The main application of this network is to provide people in the affected regions with peer-to-peer SMS-like communication and a Twitter-like social media application. While the base mesh uses Bluetooth as its communication technology, the Serval Mesh extender uses Wi-Fi and VHF packet radio to extend the meshes range [12]. Currently, one of the use cases and deployment targets for these mesh extenders are fractured island states such as Vanuatu. It is planned to allow these extenders to use High Frequency (HF) and VHF communication, depending on the distance between nodes. The current *RFD900+* UHF radios [13], which operate in the 921MHz frequency band and have a transmit power of 1W, reach a transmission range between 100m and several kilometers, based on the landscape and vegetation in tests.

A. AX.25

For VHF, the most common digital communication protocol in the amateur radio community is AX.25 [5]. While there are other digital modes (e.g., M17, DMR, D-Star, POCSAG), they are less popular and require specialized hardware or direct access to the discriminator of the FM modulator, which is not possible with most portable radios. AX.25 is a link-layer protocol that is used for applications like packet radio (an Internet protocol for amateur radio) or Automatic Packet Reporting System (APRS). APRS enables automatic reporting of the GPS position but also short text messages and weather data. Exploiting these features, Hongyim and Watanachaturaporn [6] designed an Emergency Message Beacon System (EMBS) that uses APRS. Their experimental setup uses a transceiver with a transmission power of 24.77 dBm that operates at 144 MHz. The transmission range achievable with this setup was 2.1 km for a Line-of-Sight (LOS) scenario.

While AX.25 does not specify a physical layer, it is most commonly used with AFSK 1200, which is similar to the Bell 202 modem [7], using 1200 Hz and 2200 Hz audio tones to modulate data with a rate of 1200 bit/s. While AX.25 uses a 16-bit CRC for error detection, the protocol does not define any scheme for error correction. This can be problematic, especially for larger frames, as a single bit flip leads to frame loss. For that reason, FX.25 was proposed, which adds Forward Error Correction (FEC) in a backwards compatible manner, wrapping the AX.25 with a preamble and postamble to add redundancy bits [8]. This way, legacy receivers can still decode the inner AX.25 frame, while FX.25 receivers benefit from the redundancy.

The system setup for AX.25 is similar to Figure 1, with AFSK 1200 being used for the audio link to the radio. It is, however, designed for connecting to the radio via cable. Rattlegram, which we will study in this paper, is a more advanced variant for the acoustic link, which was designed to overcome this limitation.

B. Acoustic Data Transmission

In recent years, acoustic data transmission has become a niche technology for low-bandwidth short-range wireless communication. *Nearby* is a platform developed by Google that provides nearby device discovery, pairing, and connection establishment using Bluetooth, Wi-Fi, and audio [9]. The latter uses 16-Frequency Shift Keying (FSK) in the 16.5 kHz to 18.5 kHz band to modulate its data, reaching a rate of up to 94.5 bit/s. Furthermore, a 127 bit Direct-Sequence Spread Spectrum (DSSS) code is used for noise resilience [10]. Multiple Google products already use this technology, including Chromecast's guest mode, Google Play Games, and Audio QR in Google Pay. While the audio communication of *Nearby* also uses a state-of-the-art acoustic physical layer, it targets another application domain with much lower bandwidth requirements than Rattlegram.

III. RATTLEGRAM

Rattlegram[2] is an Open Source Android and iOS application that allows the transmission of up to 170 Byte messages via acoustic signals, using the smartphone's microphone and speakers. When launched, the app provides a log of transmitted and received messages and automatically accesses the microphone to listen for message signals. Furthermore, the user can compose and transmit messages, as can be seen in Figure 2.

Rattlegram employs an OFDM-based physical layer with 160 ms symbols that are extended by a 20 ms guard interval. Each OFDM symbol uses 256 subcarriers with a total bandwidth

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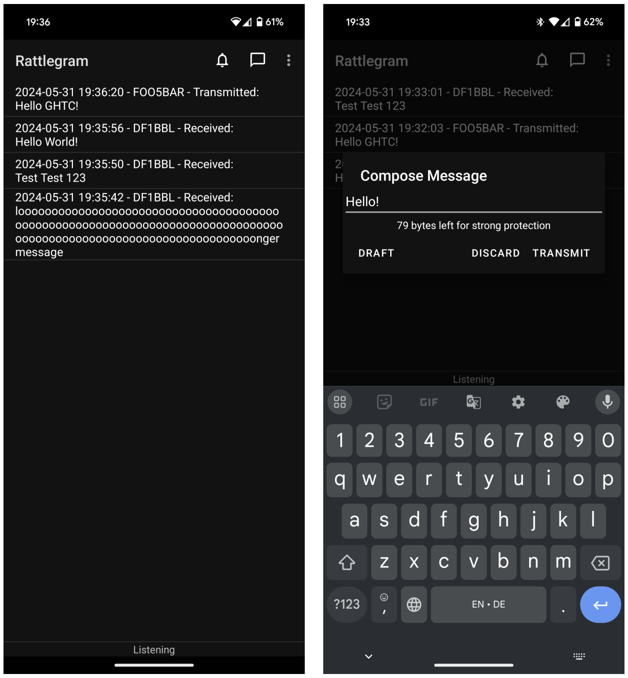
[2] https://github.com/aicodix/rattlegram



2024-05-31 19:36:20 - FOO5BAR - Transmitted:
Hello GHTC!

2024-05-31 19:35:56 - DF1BBL - Received:
Hello World!

2024-05-31 19:35:50 - DF1BBL - Received:
Test Test 123

2024-05-31 19:35:42 - DF1BBL - Received:
looooooooooooooooooooooooooooooooooooooo
ooooooooooooooooooooooooooooooooooooooooo
oooooooooooooooooooooooooooooooooooonger
message

2024-05-31 19:33:01 - DF1BBL - Received:
Test Test 123

2024-05-31 19:32:03 - FOO5BAR - Transmitted:
Hello GHTC!

Compose Message

Hello!

79 bytes left for strong protection

Figure 2. User interface of the Rattlegram app.

of 1600 Hz. The whole frame consists of six OFDM-symbols: one synchronization symbol, one preamble symbol, and four payload symbols. Since each symbol has a length of 180 ms, the whole frame has a length of 1080 ms. Synchronization and channel estimation is done, using the Schmidl-Cox algorithm [14]. The second symbol of the frame is the preamble, which contains metadata, including a call sign. This symbol uses Binary Phase Shift Keying (BPSK) to encode 256 bits, which are split into 72 data bits and 184 parity bits from a Bose–Chaudhuri–Hocquenghem (BCH) code.

The remaining payload symbols use Quadrature Phase Shift Keying (QPSK) modulation to map the 2048 encoded bits. Depending on the payload size, different Polar codes are used: For messages smaller than 86 Byte a 712/2048 code; for messages between 86 Byte and 128 Byte a 1056/2048 code; and for messages between 129 Byte and 170 Byte a 1391/2048 code. This implies that, in contrast to most other wireless technologies, the number of encoded bits and, therefore, the frame size remains constant, i.e., frames with smaller payload use more redundancy.

A. Rattlegram CLI

While the Rattlegram app provides the functionality to send and receive acoustic signals via the smartphone, this functionality is not well suited for a simulation study. Therefore, we created *rattlegram-cli*, a command line tool that uses the Rattlegram's C++ library. The rattlegram-cli tool provides the same basic functionalities regarding signal encoding and decoding but reads and writes to *WAV* files instead of audio hardware. This allows for a more flexible handling of the signals for our studies.

Table I
DATA RATES FOR THE CONSIDERED TECHNOLOGIES, DEPENDING ON THE FRAME SIZE.

	85 Byte	128 Byte	170 Byte
BPSK	378 bit/s	569 bit/s	756 bit/s
QPSK	630 bit/s	948 bit/s	1259 bit/s
8-PSK	756 bit/s	1138 bit/s	1511 bit/s
AX.25	917 bit/s	996 bit/s	1039 bit/s
FX.25	586 bit/s	571 bit/s	758 bit/s

We, furthermore, added the option to use BPSK and 8-PSK to modulate the payload symbols. In the default case (QPSK), the 2048 payload bits are encoded across four OFDM symbols. Since BPSK and 8-PSK encode 1 bit and 3 bit per subcarrier, each configuration requires a different number of OFDM payload symbols (eight for BPSK, four for QPSK, three for 8-PSK).

B. Data Rate

The throughput of the Rattlegram protocol depends on the symbol mapping, which defines the duration of the frame. Since the duration of an OFDM symbol including guard interval is 180 ms and synchronization and preamble symbols have to be considered, the data rate of Rattlegram R_{Rattle} is

$$R_{Rattle} = \frac{\#data\ bits}{(\#payload\ symbols + 2) \cdot 180ms} \qquad (1)$$

In comparison, an AX.25 frame requires a synchronization sequence, a start-of-frame and end-of-frame indicator, a 16-bit CRC, as well as additional frame headers (e.g., control info and address field). In addition, AX.25 uses bit stuffing to avoid long strings of zeros and ones, which could cause problems to the synchronization algorithm. This makes it non-trivial to specify a closed-form throughput formula, which is further complicated by FX.25 adding redundancy, depending on the payload length. We, therefore, use *direwolf*,[3] a popular Open Source AX.25 and FX.25 implementation, to generate frames and measure their duration to calculate the throughput.

The resulting rates are summarized in Table I. For small packet sizes, the throughput of AX.25 is about 50 % higher than Rattlegram's default QPSK configuration. Since AX.25 uses AFSK 1200 with 1200 bit/s, the effective data rate converges to 1200 bit/s for large frames, which can also be achieved with Rattlegram. However, the overhead for the FEC of FX.25 is significant and results in way lower data rates than Rattlegram.

IV. SIMULATION

In our simulations, we consider the acoustic channel and the RF channel separately. We use direwolf to generate AX.25 and FX.25 frames, and rattlegram-cli for Rattlegram frames. Both applications output 8 kHz WAV files with 16 bit samples, to

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[3] https://github.com/wb2osz/direwolf

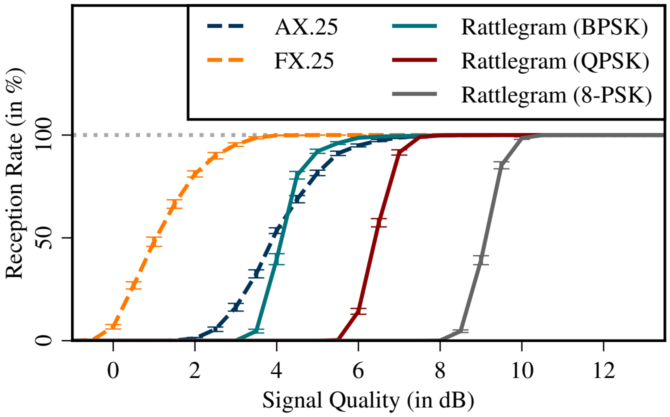

Figure 3. Frame reception rate for 128 Byte frames over an AWGN channel.

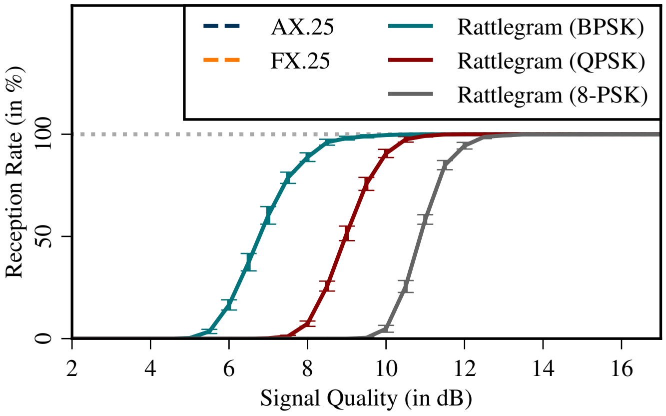

Figure 4. Frame reception rate for 128 Byte frames over a tapped-delay line channel model.

which we apply noise and channel effects, and try to decode the resulting signal. The Rattlegram frames use a center frequency of 1500 Hz and consider our three symbol mappings (BPSK, QPSK, and 8-PSK). AX.25 and FX.25 frames uses AFSK 1200.

A. Acoustic AWGN

In our first experiment, we consider the audio channel with Additive White Gaussian Noise (AWGN). For a fair comparison of the technologies, normalization of the signals is important. While AX.25 and FX.25 have a constant envelope and are, therefore, trivial to normalize, the OFDM-based physical layer of Rattlegram is more challenging, given OFDM's higher Peak to Average Power Ratio (PAPR). We scale the frames such that the maximum amplitude of the Rattlegram frame corresponds to the amplitude of the AFSK signal. Note that this implies that the frames have a different average power due to their technological differences.[4] When applying noise, comparable frames will, therefore, have different Signal to Noise Ratios (SNRs). For that reason, we plot the frame reception rate not over the SNR but the *Signal Quality*, which indicates a given noise level. Hence, only relative values are of interest.

The results for 128 Byte messages are shown in Figure 3. The error bars in this and the following plots indicate the confidence intervals of the mean for a confidence level of 95 %. As expected, each curve approximates a steep sigmoid shape with a range of 2-4 dB between 0-100 % frame reception rate. In these experiments, FX.25 shows the best performance but only with a relatively small margin of approximately 3 dB to the Rattlegram BPSK mode. The three Rattlegram modes are spaced by about 3 dB, i.e., the 8-PSK mode requires a 3 dB higher SNR than QPSK, for example. Since the audio channel is usually easy to control and a high SNR is easy to achieve by moving to a quieter environment or holding the devices closer, 8-PSK might well be a practical option.

B. Acoustic Multipath

Multipath propagation and the resulting frequency selective fading and inter-symbol inference are among the biggest challenges in wireless communications. With acoustic channels the effect can be more pronounced, since sound waves propagate much slower than electromagnetic waves. For example, a path delay of 1 ms is common for audio, resulting from a difference in path lengths of only 30 cm. For an RF transmissions, the same delay would correspond to a path difference of 300 km, which is less common. In our simulations, we, therefore, focus on audio multipath effects, which we model with a finite impulse response filter. The channel taps are based on the room impulse response from Di Carlo et al. [15], which showed that significant reverberation of a sound signal did not last longer than 70 ms.

The results are shown in Figure 4. We can see that the AX.25 and FX.25 packet reception completely fails, while Rattlegram performs only slightly worse than over an AWGN channel. The harsh difference between Rattlegram and AX.25/FX.25 are due to the symbol lengths of the modulation schemes. While Rattlegram's OFDM symbols have a length of 160 ms with a 20 ms guard interval, AX.25/FX.25 have a symbol length of 0.83 ms and are, therefore, more susceptible to Inter-Symbol Interference (ISI) introduced by the channel.

To verify this effect, we placed two Google Pixel 4a smartphones at distances between 10 cm and 30 cm in different environments (on a carpet floor, on a windowsill, and on a table). In all configurations Rattlegram worked reliably, while AX.25 and FX.25 failed.

C. RF AWGN

Apart from the acoustic channel, we also consider the RF transmission through a 12.5 kHz FM channel with a maximum frequency deviation of 2.5 kHz. Modulating an audio signal with a bandwidth of 3.75 kHz results in a used bandwidth of 12.5 kHz according to Carson's bandwidth rule for FM modulation. This configuration is usually referred to as *narrowband FM* and supported by amateur radio equipment.

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[4] We believe that this is a fair comparison, since sound cards and speakers do not have a fixed output power but a given dynamic range.

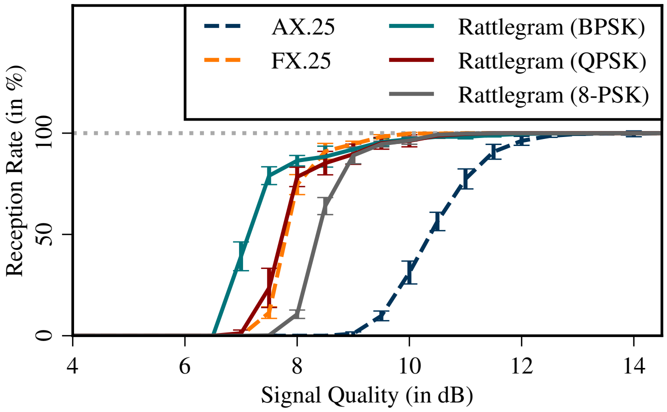

Figure 5. Frame reception rate for FM-modulated 128 Byte frames over an AWGN channel.

In these experiments, we want to focus on the performance of the RF transmission and, therefore, apply the noise after FM modulation.

The results are shown in Figure 5. For the FM transmission, we can observe that the error curves for the different symbol mappings are even closer to each other than for the acoustic transmission. While Rattlegram is slightly better in this case, the technologies are still very close, suggesting that the range of the radio transmissions should be approximately equal.

We conducted further simulations with Carrier Frequency Offset (CFO) and Sampling Frequency Offset (SFO). However, for the relevant parameter ranges, we observe no impact on the performance or gained any other relevant insights. Overall, our conclusion is that the advantages of Rattlegram (i.e., the possibility of over-the-air coupling without cable) do *not* have to be traded off for other disadvantages.

V. FIELD TESTS

To demonstrate the applicability of the technology for crisis communication, we conduct field tests in a rural and an urban environment. Since we already established the fact that AX.25 and FX.25 are not well suited for audio channels, the field tests focus on the RF transmission. To this end, we connect the radios via cable and send a pre-generated audio file that contains AX.25, FX.25, and Rattlegram frames with the same configuration as in the simulations (i.e., 128 Byte messages and narrowband FM). Connecting the radio via cable also excludes effects from the acoustic environment, avoiding noise from traffic, pedestrians, or nature, which could impact the results.

We use three different radios to get a cross-section of different models and price ranges: a *Baofeng GT-5R* (≈ 30 €), an *Alinco DJ-500* (≈ 100 €), and an *Icom IC-T10* (≈ 250 €).[5]

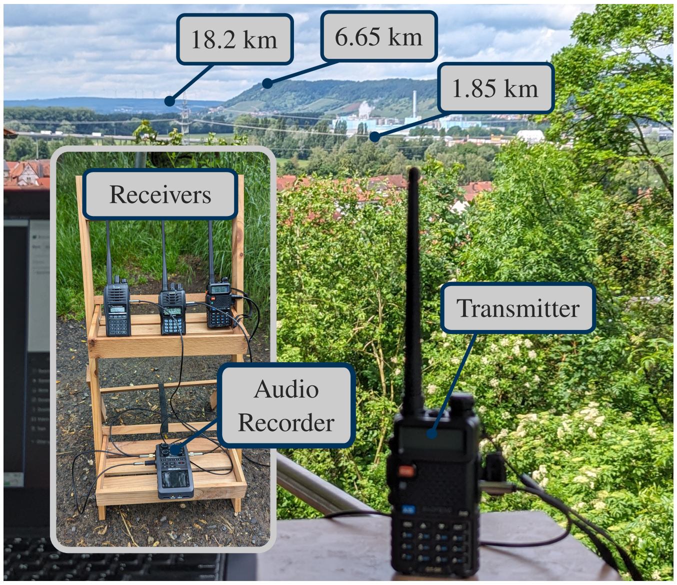

Figure 6. Overview of our field test setup and the locations of the measurement spots.

In both field tests, we use the Baofeng radio as a stationary transmitter, since it can be used for automatic transmission without additional specialized equipment. Using the *VOX* functionality, the radio switches to transmit mode automatically as soon as it detects a signal on its line-in port. To avoid transients at the beginning of the frame or skipping the first part of the frame due to delays in triggering the transmission, we precede each frame with a 0.5s noise signal, which is long enough to trigger VOX reliably. The audio level of both the generated audio file and the line out of the laptop leave some headroom to avoid potential non-linearities or clipping. The transmit power of the Baofeng is set to *High*, which corresponds to 5 W, according to the datasheet.

Individual frames are spaced by four seconds to avoid occupying the channel and have some break in-between frames, since the handheld radios are not designed for continuous transmissions. Every three minutes, we, furthermore, interleave an audio message with our amateur radio call sign, a short explanation of the experiment, and a link to a website with further information to comply with regulatory requirements. In addition, we monitor the channel for interference and potential messages from other operators.

On the receive side, we use all three models to investigate the impact of the hardware on the achievable performance. We record the received signal in 48 kHz WAV files with 16 bit samples and, furthermore, disable the squelch (i.e., the noise gate) to avoid cutting off weak signals during reception.

A. Rural Environment

Our experiment in a rural environment focuses mainly on the coverage, which might be the main interest in an area with low population density. We, therefore, use the 2 m band between 144 MHz and 146 MHz, which provides better coverage. As

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[5] There were earlier Baofeng models that had issues with out-of-band emissions. Such radios, especially when adopted by the masses, could cause more harm than good in case of an emergency, as they could interfere, for example, with communication between first responders. However, current generations are FCC-certified and do no longer have these issues. In the context of this work, the main point is that there are working radios available on the market in this price range.

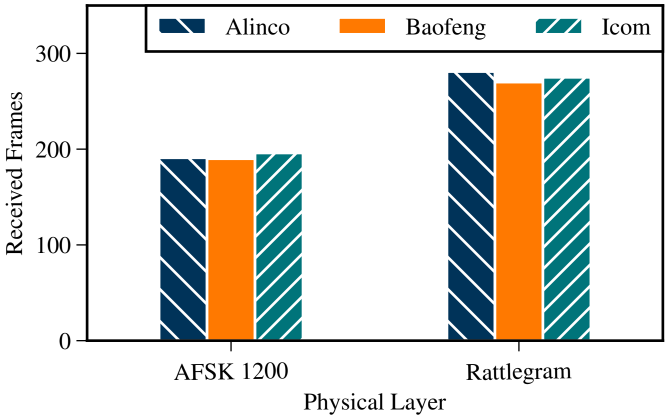

Figure 7. Number of received frames per radio model and technology.

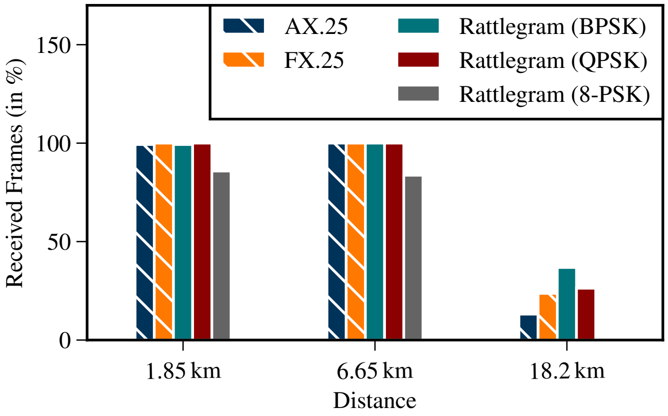

Figure 8. Reception rate at different distances for each technology.

shown in Figure 6, we place the transmitter at an exposed location and measure at distances of 1.85 km, 6.65 km, and 18.2 km. The line of sight is mostly unobstructed, with some trees in between the two closer locations. At each location, we place the radios on a stand and record the received signal with a Zoom H6 multi-track audio recorder, as shown in the inset in Figure 6. The signal is then decoded in post-processing.

Figure 7 shows the total number of frames that were received by each device for AFSK 1200 (i.e., AX.25 and FX.25) and the three Rattlegram modes (i.e., BPSK, QPSK, and 8-PSK). The fact that the numbers per mode are very similar across devices shows that there is no large, systematic performance difference and that the devices are able to decode both digital modes. Since the radios are primarily designed for voice communication, we wondered whether the noise-like, flat spectrum of the OFDM-based physical layer of Rattlegram might be attenuated or otherwise filtered by the radio. The results show that this does not seam to be the case. Furthermore, since all radios received the same signal, the decoding performance in this field test is mainly determined by the propagation environment and less by the quality of the radio.

Apart from the impact of the device, we evaluated the coverage by plotting the received frames for the three locations. The results are depicted in Figure 8. They show perfect reception within 6.65 km for all modes, except for Rattlegram with 8-PSK modulation, which seems to be more fragile. Since there is nearly no difference for the two closer locations, we assume that the losses are primarily caused by dynamics in the environment and less from a low SNR. The measurement at 18.2 km was at the optical horizon of the transmitter. Here, the signal quality was audibly worse and decoding performance was degraded to a point that no 8-PSK frames were received. While FX.25 and the Rattlegram BPSK and QPSK modes show similar performance in this field test, it is important to remember that this is only RF performance and FX.25 would not work without connecting to the radio via cable.

Overall, this field test showed that we are able to establish communication at a distance as far as 18.2 km even with cheap 30 € radios. At more exposed locations, other weather conditions, or unusual propagation effects (atmospheric ducts, Sporadic E), this might reach much further, way beyond the optical horizon. In the context of this work, the most important insight is that in rural areas with low population density, we are able to communicate over long distances.

B. *Urban Environment*

Apart from coverage in line-of-sight scenarios, we were interested how the technology performs in an urban environment with shadowing from buildings. In this experiment, we use the 70 cm amateur radio band, ranging from 430 MHz to 440 MHz, since we believe that in areas with high population density, one would prefer smaller cells with higher frequency reuse. The coverage of the 2 m band might even be a drawback here, since it also causes interference in a large area.

To understand the impact of buildings, we use mobile receivers in this experiment, attaching the radios to an open compartment of a backpack. To track our route during the field test, we use the *Komoot* Android app to record a GPS track. The transmitter is placed outside the window on the second floor, at a height of approximately 12 m above the ground. We chose this receiver position as it emulates a transmission setup that is available to many citizens in their houses. While a transmitter position on the roof of a multi-floor office building would provide better results, not every citizen might be able to access such a transmitter position. We placed the radio outside the window to avoid attenuation by the coated window panes, which can attenuate RF signals.

For the evaluation of our results, we use the audio recordings of each radio and the GPS track. In post-processing, each packet reception is mapped to the nearest recorded point on the route and saved as a packet reception rate of 100 %. Furthermore, we determine the coordinates of a potential signal reception every 20 s and if no packet was received we save this point with a packet reception of 0 %. In the next step, we generate values for coordinates that are not assigned to a (potential) packet reception by interpolating the values based on the timestamp in the interval between two (potential) packet receptions.

Exemplary results for the Icom IC-T10 are shown in Figure 9, where we plot the reception rate for Rattlegram QPSK frames.

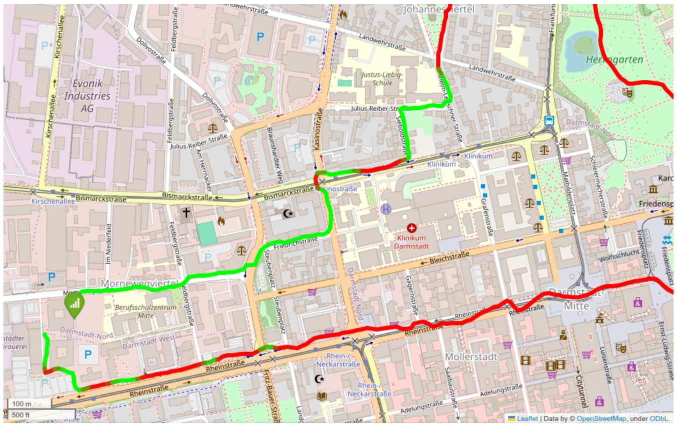

Figure 9. Reception rate on a track in an urban environment.

The position of the receiver is indicated by a green marker on the left on the figure. Green traces on the route indicate a packet reception of 100 %, while red traces indicate a packet reception of 0 %. What was surprising to us is that Rattlegram's default QPSK configuration performed best. We assume that this is the case, since BPSK frames are much longer and the channel is only estimated at the beginning of the frame. For that reason, the estimate might become outdated, if the frame is longer than the coherence time of the channel, i.e., the channel changes to such an extent that the channel estimate from the beginning of the packet is no longer accurate enough. 8-PSK, in turn, performs worse than QPSK due to the smaller inter-symbol distance and less margin to correct errors. In that regard, the results suggest that QPSK presents a good tradeoff between throughput and robustness.

Considering coverage, we can observe a maximum transmission distance of 974 m for a quasi-LOS path with no taller buildings obstructing the path. In general, the northern part of the route was less obstructed by tall buildings, while taller office buildings mostly blocked the southern part of the route. This leads to a much better reception on the northern part of the route, which can be observed for all configurations. The southern part of the route only shows signal reception close to the transmitter when the view is not obstructed by a large building, e.g., when moving across the neighboring parking lot.

VI. SUMMARY AND DISCUSSION

Overall, we believe that Rattlegram is a great invention and a viable physical layer that could provide the base for crisis communication systems. In contrast to AX.25 and FX.25, it allows coupling the smartphone with a handheld radio without using a cable. This advantage is achieved, while providing comparable throughput and performance to FX.25. The only downside is the more complex implementation, which is, however, not an issue, given the availability of Open Source implementation. We, furthermore, observe, that the QPSK symbol mapping configuration performs best out of the three tested symbol mapping configurations due to a good compromise between robustness and frame duration, which is relevant with regard to the coherence time of the channel. Hence, QPSK is a good choice for the standard modulation scheme.

With regard to its applications in crisis communication systems, we discussed and demonstrated the practical applicability of the physical layer. In rural environments, we saw a great coverage and also in urban scenarios, we achieved a maximum range of over 950 m. Furthermore, we observed that shadowing heavily degrades signal reception. Clusters of larger buildings can block the reception of the transmission completely, even for short transmission distances. Residential areas with two to three-story buildings were the best environment in our test, since the signal could propagate above the buildings without hindrance, allowing almost LOS transmission. We conclude that the current setup works well in residential areas of cities but reaches its limits in highly urbanized areas with tall, clustered buildings, such as city centers. With these characteristics, we believe that the physical layer of Rattlegram can provide a solid base for a crisis communication network stack and application.

Furthermore, we found that even the cheap Baofeng radio performs exceptionally well. Combining it with a smartphone app, it offers a cheap, infrastructure-independent communication solution with good coverage. This enables citizens to send text messages to exchange information and organize themselves in local communities in case of an outage of the communication infrastructure. Using a smartphone, one could also use GPS to broadcast someone's position or send audio or video snippets. The latter could, for example, be realized by splitting the data into chunks and distributing them with Disruption-Tolerant Networking (DTN) protocols.

While the *German Federal Office of Civil Protection and Disaster Assistance* recommends citizens to have a battery-powered radio or a wind-up radio in their *Guide for Emergency Preparedness and Correct Action in Emergency Situations* [16], these radios can only be used to receive FM broadcast radio and do not allow duplex communication. Since most VHF handheld radios also support FM broadcast reception, the recommendation could be changed to VHF handheld radios, which are still affordable but also provide a viable communication solution for citizens in a crisis situation.

Using the amateur radio frequency bands has the additional advantage to benefit from existing relay infrastructure to further increase coverage. Amateur radio operators have a long tradition to help in crisis events, and they still maintain a sizeable infrastructure. RepeaterMap,[6] for example, lists over 950 FM relays for the 2 m and 70 cm bands in Germany. While these relays might also fail in case of power outages, some of them are equipped with batteries and could stay operational for a certain time. Furthermore, they only need to be powered to continue operation. Getting a cellular network operational after a crisis is more complex and takes much longer. We believe that Rattlegram is, therefore, well suited for the immediate reaction to crisis events.

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[6] https://repeatermap.de/

VII. CONCLUSIONS

Communication is an integral part of our daily lives. It is so normal to us that we often take it for granted. Yet, natural disasters can lead to disruptions due to power outages or destruction of the infrastructure. While first responders may have their own radio communication solutions, civilians stay disconnected as their smartphones become useless. In this paper, we explore how Rattlegram, a novel and innovative OFDM-based physical layer for acoustic transmission via smartphones, could be used with handheld radios to enable infrastructure-less communication between citizens. We conducted extensive simulations and two field tests to evaluate its performance and demonstrate its practical feasibility.

We show that Rattlegram performs better than currently widespread solution from the packet radio domain, especially for the acoustic communication between smartphones and handheld radios. Furthermore, we demonstrated that this communication setup can establish a connection up to a distance of 18 km in rural areas and close to 1 km in an urban environment. This is possible even with cheap handheld radios that can be purchased for 30 €. We believe that Rattlegram can be the base for an affordable solution that allows citizens to establish communication in emergency situation to exchange information and coordinate themselves.

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REFERENCES

[1] J. Seidel, H. Lay, and M. Göddertz. "Ahrtal unter Wasser: Chronik einer Katastrophe." (2021), [Online]. Available: https://reportage.wdr.de/chronik-ahrtal-hochwasser-katastrophe.

[2] The Visual Journalism Team. "Pakistan floods: Map and satellite photos show extent of devastation." (2022), [Online]. Available: https://www.bbc.com/news/world-asia-62728678.

[3] D. Ghiglione and S. Bettiza. "Italy floods leave 13 dead and force 13,000 from their homes." (2023), [Online]. Available: https://www.bbc.com/news/world-europe-65632655.

[4] J. Höchst, L. Baumgärtner, F. Kuntke, A. Penning, A. Sterz, and B. Freisleben, "LoRa-based Device-to-Device Smartphone Communication for Crisis Scenarios," in *17th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2020)*, Blacksburg, VA, May 2020.

[5] Tucson Amateur Packet Radio Corporation, "AX.25 Link Access Protocol for Amateur Packet Radio," Standard Version 2.2, Jul. 1998.

[6] N. Hongyim and P. Watanachaturaporn, "A Design and Implementation of an Emergency Message Beacon System Using APRS Protocol," in *17th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Phuket, Thailand, Jun. 2020.

[7] Bell System Data Communications, "Data Sets 202C and 202D Interface Specification," Tech. Rep., May 1964.

[8] J. McGuire, I. Galysh, K. Doherty, and H. Heidt, "Forward Error Correction Extension to AX.25 Link Protocol for Amateur Packet Radio," in *TAPR Digital Communications Conference*, Tucson, AZ, Sep. 2006.

[9] *Google Nearby*. [Online]. Available: https://developers.google.com/nearby.

[10] P. Getreuer, C. Gnegy, R. F. Lyon, and R. A. Saurous, "Ultrasonic Communication Using Consumer Hardware," *IEEE Transactions on Multimedia*, vol. 20, no. 6, Jun. 2018.

[11] P. Gardner-Stephen, *The Serval Project: Practical Wireless Ad-Hoc Mobile Telecommunications*, 2011. [Online]. Available: http://developer.servalproject.org/files/CWN_Chapter_Serval.pdf.

[12] K. Hawtin and P. Gardner-Stephen, "Self-Configuring Heterogeneous HF/UHF/Wi-Fi Disaster Communications Networks," in *2017 IEEE Global Humanitarian Technology Conference (GHTC)*, San Jose, CA, Oct. 2017.

[13] RFDesign, *RFD900+ Modem*. [Online]. Available: https://rfdesign.com.au/products/rfd900-modem/.

[14] T. Schmidl and D. Cox, "Robust Frequency and Timing Synchronization for OFDM," *IEEE Transactions on Communications*, vol. 45, no. 12, Dec. 1997.

[15] D. Di Carlo, P. Tandeitnik, C. Foy, N. Bertin, A. Deleforge, and S. Gannot, "dEchorate: A Calibrated Room Impulse Response Dataset for Echo-Aware Signal Processing," *EURASIP Journal on Audio, Speech, and Music Processing*, vol. 2021, no. 39, Nov. 2021.

[16] K. Brouwers, *Guide for Emergency Preparedness and Correct Action in Emergency Situations*. Federal Office of Civil Protection and Disaster Assistance (BBK), Dec. 2018.