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Crisis-Communication Between Farms: Disruption-Tolerant Networking with Commodity LoRaWAN Hardware

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Abstract:

In rural areas, where restoring public network infrastructure can take time, an alternative communication channel can be particularly valuable. This study explores the potential of repurposing Long Range Wide Area Networks (LoRaWAN) gateways as multi-hop network nodes to create a digital emergency communication system. Farmers, who are increasingly adopting Low Power Wide Area Networks (LPWANs) and are geographically spread, are identified as key stakeholders for such a system. Using OpenStreetMap data on farm locations, we found that connecting farm communities through LoRa communication is theoretically possible in many areas. Simulations using delay-tolerant network routing protocols confirm the feasibility of this approach under various scenarios. A proof-of-concept implementation demonstrates that small messages can be transmitted successfully using real hardware, validating the concept of a decentralized communication infrastructure based on existing equipment. Additionally, we conducted experiments to measure energy consumption, bandwidth usage, and latency in actual hardware setups. This work contributes to various Sustainable Development Goals by supporting resilient communication infrastructure in underserved areas (SDG 9: Industry, Innovation and Infrastructure), strengthening rural communities that are often the last to recover after emergencies (SDG 10: Reduced Inequalities, SDG 11: Sustainable Cities and Communities), and ultimately helping safeguard food systems through improved agricultural coordination and communication (SDG 2: Zero Hunger).

Keywords: Communication, Disruption-Tolerant Networking, Bundle Protocol, Version 7, LoRaWAN Gateways, LoRa Mesh Communication.

[Department statements, if appropriate, will be added by the editors. Teaching cases and panel reports will have a statement, which is also added by the editors.]

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1 Introduction

In today’s society, communication technologies play a crucial role in connecting people over long distances. This is particularly important for sectors like agriculture, which relies on shared labor and equipment to harvest cropland within tight time windows. Although often overlooked, agriculture is widely recognized as a form of critical infrastructure due to its responsibility in sustaining basic human livelihoods through food production. Ensuring the resilience of communication systems in this sector is therefore essential, especially in rural areas, where electric and digital infrastructure tends to be more fragile and disaster recovery often lags behind urban centers (Kuntke, Linsner, et al., 2022). This vulnerability is even more pronounced in low- and middle-income regions, where infrastructure investment is limited, yet the impacts of disruption are more severe (Imran et al., 2024). In this context, scalable, low-cost solutions based on commodity hardware can offer a practical path toward resilient and inclusive communication systems — aligning with the goals of Information and Communication Technology for Development to support social and economic development through accessible technologies.

In the past decade, the terms Agriculture 4.0 and Smart Farming were used to high-light several developments towards automated data generation and exchange between different stakeholders in the entire food production chain, by incorporating current trends in Information Technology (IT), such as the Internet of Things (IoT) and Cloud Computing (Rose & Chilvers, 2018). Farmers increasingly face reporting obligations towards an array of other actors, including the buyers, food processors, end customers, and governmental agencies (Mushi et al., 2023). This has led to an increased need for communication between devices like autonomous vehicles, weather stations, sensors, and actuators. To meet this demand while ensuring energy efficiency, technologies like Low Power Wide Area Networks (LPWANs) have been developed. A prominent example of LPWAN technology is the Long Range Wide Area Network (LoRaWAN), which allows for autarkic IoT networks that can operate independently from external managed infrastructure, unlike cellular data networks known from mobile phone connections. As already described, not only machinery depends on communication, but farmers also require reliable line communication between each other. Exemplary use cases are the bundling of labor and machinery of neighboring actors during harvest, as well as exchanges on prices with buyers and intermediaries or weather forcasts (Krone & Dannenberg, 2019) or other forms of data collection (Aparo et al., 2024). These use cases are particularly important for efficient agriculture in small-structured agricultural regions — be it in industrialized economies such as Germany or rural economies such as Uganda (Harris & Achora, 2018).

Major internet outages are a realistic possibility (Aceto et al., 2018; Grandhi et al., 2020), with unpredictable duration and extent. However, LoRaWAN networks could still facilitate basic data exchange in self-organizing networks during such events. This has led to proposals for using LoRaWAN technology in crisis situations, particularly when the main communication infrastructure is unavailable. Research has shown that adapting LoRaWAN’s star-of-star topology to form multi-hop networks is possible (Centelles et al., 2021). In combination with the store-and-forward approach *Disruption-Tolerant Networking (DTN) t*he success rate of delivering messages in crisis situations with rather unpredictable networking resources is increased (Baumgärtner et al., 2020). Two limitations of existing solutions are (1) their inability to work seamlessly with standard LoRaWAN networks, resulting in devices dedicated solely to crisis communication, and (2) the need for custom firmware on developer devices, which can be a barrier for non-technical users. In contrast, improving the software behind commercial LoRaWAN gateways could provide a simple solution that enables communication between neighboring farms without the need for specialized hardware or technical expertise in the event of a crisis. Farms are of particular interest here, as they are geographically dispersed actors that are often important anchor points in rural areas and also have a need for technology to optimize food production, which now increasingly includes IoT sensor technology. Since this approach does not require any special hardware expertise, it can be implemented simply by installing our software addition — which may even be running in the background beforehand — making it more accessible and inclusive than existing solutions.

The main question of this work is therefore: *How can LoRaWAN-based IoT setups be utilized to allow DTN-based peer-to-peer communication?* As part of our work, we make the following contributions:

- A tool[1] for calculating geographic statistics for wireless network planning based on OpenStreetMap data
- A concept that allows to send/receive payloads in a LoRaWAN-conform manner via commodity LoRaWAN gateways, along with a prototypical implementation
- An evaluation of the concept through simulations of 40 farm neighborhoods in two scenarios, comparing the performance of two DTN routing mechanisms
- A software library `chirpstack_gwb_integration`[2] as a companion to Chirp-Stack LoRaWAN Network Server, working with commodity hardware allowing to send/receive arbitrary payloads in a LoRaWAN-conform manner
- A software `spatz`[3] that builds a DTN routing, utilizing `chirpstack_gwb_integration`
- Benchmarks of real-world setups including resource consumption measurements of exemplary hardware

The developed tools and evaluations were conducted with the application area of agriculture in mind, but can also be transferred to other areas — especially where IoT technology is already being used, like smart cities (Basford et al., 2020).

2 Background

This section provides a concise introduction to LoRa, LoRaWAN, Disruption-Tolerant Networking (DTN), and the Bundle Protocol, which form the technical foundation for this work. It also reviews relevant research on adapting LPWAN technologies to address specific challenges.

2.1 LoRaWAN and LoRa

LoRaWAN was standardized by the LoRa Alliance in 2015 (LoRa Alliance, 2015). As a widely adopted LPWAN technology, LoRaWAN uses a proprietary spread spectrum technique to adjust and modulate signals within the sub-GHz ISM band. The physical layer of LoRaWAN is known as LoRa (Long Range), which operates in the unlicensed ISM band (e.g., in Europe 433/868 MHz, in North America 915 MHz). In certain regions, duty cycle regulations may apply, such as 1% in Europe for 868 MHz. As shown by Vejlgaard et al. (2017), interference issues can arise when these bands are heavily used. It is expected, that the level of such interference issues will grow with the deployment of more wireless IoT solutions. However, this problem is more pronounced in urban areas, whereas our focus lies on rural settings, particularly agricultural areas.

LoRa uses Chirp Spread Spectrum (CSS) as its modulation technique. The coding rate, which affects the Forward Error Correction (FEC), is typically set to 4/5 for standard LoRa frames. To balance signal range, data rate, and energy consumption, LoRa offers six different spreading factors (SF7 to SF12). These factors determine the number of symbols in a transmission, with each symbol being a sinusoidal signal sequence or transmission pulse. Notably, LoRa can accommodate a maximum payload capacity of 250 bytes per transmission, as specified in the LoRa Alliance's technical guidelines (LoRa Alliance Technical Committee Regional Parameters Workgroup, 2021).

The LoRaWAN standard leverages LoRa as its transmission technology, with predefined settings for code rate, spreading factor (SF), and bandwidth. It also defines the architecture and specifies requirements for compliant devices. A LoRaWAN setup employs a star-of-stars topology, where multiple end devices transmit data encapsulated in LoRa frames to one or more gateways. Each gateway is connected via IP to a single network server. To accommodate regional differences, LoRaWAN allows for various transmission preferences that respect local free ISM bands. Moreover, it enables flexible data rate configurations by combining SF and bandwidth, as outlined in the LoRa Alliance's technical guidelines (LoRa Alliance Technical Committee Regional Parameters Workgroup, 2021). For instance, in Europe (SRD860, 863-870MHz), data rate 0 uses SF12 with a 125 kHz bandwidth for long-range transmission, while data rate 6 employs SF7 with a 250 kHz bandwidth for the fastest LoRa configuration. As with any wireless technology, LoRaWAN-based systems are vulnerable to security attacks. Although the protocol design considers several security aspects, there is still a known attack surface that should be taken into account

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[1] https://github.com/PEASEC/distance-statistics
[2] https://github.com/PEASEC/LoRaWAN-DTN/tree/main/chirpstack_gwb_integration
[3] https://github.com/PEASEC/LoRaWAN-DTN/tree/main/spatz

when developing and deploying IoT systems based on this technology, including message replay, traffic analysis and spoofing attacks (Kuntke, Romanenko, et al., 2022).

2.2 Disruption-Tolerant Networking

Disruption-Tolerant Networking (DTN), has gained significant attention for its ability to provide resilient and flexible data exchange in challenging network conditions. The DTN approach is typically based on the *store, carry, and forward* paradigm, where network participants act as data mules that physically carry and opportunistically exchange data with other nodes encountered. This architecture makes it unsuitable for real-time applications like video conferencing or others that require a stable end-to-end connection. However, it provides robustness and fault tolerance for applications that can tolerate delays in data dissemination, such as messaging, sensor data, or file sharing. One area of application is disaster communication, particularly after network infrastructure outages caused by natural disasters (Setianingsih et al., 2018; Zobel et al., 2022). The Bundle Protocol Version 7 (BP7) is the most recent standard from the Internet Engineering Task Force (IETF) for this DTN architecture (Burleigh et al., 2022). To optimize data dissemination, different routing algorithms like epidemic routing or Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) can be employed (Lindgren et al., 2012). These routing algorithms enable optimization for properties such as fast/reliable bundle delivery or minimizing duplicates in the network. Advanced routing decisions that consider metrics like geographic locations (Baumgärtner et al., 2020; Cheng et al., 2010; Sánchez-Carmona et al., 2016), duty-cycle restrictions when using LoRa (Msaad et al., 2021), or workload of involved nodes (Wang et al., 2021; Zhang et al., 2013) are also available.

3 Related Work: Adapting LPWAN

Previous research has explored multi-hop networks using Low Power Wide Area Networks (LPWANs), including LoRa. For instance, Abrardo and Pozzebon (2019) modified a LoRa network by changing its topology to route data through intermediate nodes to the gateway. This setup was employed in an underground environment where the maximum range was limited to 200m. Other studies have utilized multi-hop networks for specific use cases. Zguira, Rivano, and Meddeb (2018) used a 802.11p-based multi-hop network to transmit sensor data from shared bikes to base stations. Additionally, Abrardo et al. (2019) or Dias and Grilo (2018) focused on increasing the range of LoRa networks while minimizing energy consumption by reducing transmission power through shorter distances. To achieve this, these studies relied on multi-hop networks that enable nodes to forward data to each other before reaching the base station or gateway. This approach was also employed in range-critical situations by Ebi, Schaltegger, R¨ust, and Blumensaat (2019), who used a multi-hop based mesh network topology instead of star or linear topologies. Other contributions, such as Lee and Ke (2018) and Huh and Kim (2019), explored expanding the coverage of LoRa networks through multi-hop networking. In these scenarios, data from sensor nodes is forwarded to the base station via intermediate nodes, allowing for larger-scale sensor network deployments.

Other work is exploring the use of Low Power Wide Area Network (LPWAN) technologies to enhance network resilience, such as through the development of long-range wireless data channels for TCP/IP-based network hardware (Kuntke et al., 2021). Vigil-Hayes, Hossain, Elliott, Belding, and Zegura (2022) describe a system that combines high-bandwidth networks with LPWAN to extend internet coverage. The key idea behind this approach is to leverage the strengths of both technologies, allowing useful service calls to be partially completed using limited data rate transfers and then fully completed when high-bandwidth access is available. In their test setup, Vigil-Hayes et al. (2022) achieved a transmission range of 400m with line-of-sight in an urban region, although this may have been due to the use of small LoRa chips. Their work focuses on addressed communication between two end nodes or an end node and gateway, rather than communication between gateways. Some studies have modified and extended protocols on the data link layer (OSI-layer 2) to support LPWAN-based networking. However, these modifications alone are not sufficient to implement a complete communication system based on the physical layer. Such a system would require a replacement of the previously used protocol on the data link layer with a new one designed specifically for LPWAN.

A similar approach to bidirectional communication is the Serval Project (Gardner-Stephen, 2011), which focuses on crisis communication and basic mobile connectivity for low-income or isolated communities. The respective application, called Serval Mesh, leverages the WiFi capabilities of Android-driven smartphones to enable text messages, calls, and data transmissions. A key benefit of this approach is that it creates a cost-effective physical layer that operates independently of local providers. However, using WiFi technology in the Serval Project also introduces limitations, including compatibility issues and reduced range compared to LoRa (Gardner-Stephen & Palaniswamy, 2011). To address these range limitations, researchers have developed inexpensive and weatherproof extenders that use Ultra High Frequency (UHF) to enable long-distance connections (Gardner-Stephen et al., 2017).

Höchst et al. (2020, 2023) have created a system that connects smartphones via Bluetooth with micro-controller boards capable of transmitting LoRa signals. This enables users to send SMS-like messages as LoRa signals between devices. The system has been tested and found to support device-to-device communication over a range of up to 2.89 km.

Baumgärtner et al. (2020) have developed a similar application, but with distinct differences from our approach. Firstly, their system focuses on emergency crisis communication in environments without any existing ICT infrastructure. In contrast, our goal is to establish a communication network that can serve as a substitute for internet-based communication in both short-term and long-term scenarios where previous ICT has been damaged. Secondly, the hardware implementation differs significantly: while the system of Baumgärtner et al. (2020) includes low-cost relay nodes and pager de-vices, our project leverages existing commodity LoRaWAN gateways to facilitate communication. This approach means that our system is always available for farms using LoRaWAN IoT technologies, without requiring specific actions for crisis prevention.

Our objective is to create a concept that enables addressed communication between LoRaWAN gateways within a multi-hop network, even without internet access. By utilizing the benefits of LPWAN technologies' physical layer, we aim to establish a resilient message transmission system. This concept is designed to ensure reliable and uninterrupted communication, making it an essential component in developing a robust communication system. The details of this use case and exemplary scenario will be presented in the following section.

4 Use Case and Scenario: Emergency Communication for Agricultural Areas

Farmers in developed and developing countries are increasingly adopting smart farming technologies involving IoT solutions (Vahdanjoo et al., 2025), with LoRaWAN being a popular choice due to its low-cost sensors and sequential costs. To build resilience into communication infrastructure in this domain, we see an opportunity to leverage the growing adoption of LoRaWAN setups for a self-operated communication network. Such a network could be used for emergency communication over long distances when landline and cellular networks are broken. It could also help organize farmers' workforces in situations of prolonged internet connectivity outages or enable neighborhoods surrounding farms to communicate with other nearby communities. We have identified three types of possible messages that could be exchanged in crisis scenarios, differing in their time priority:

Time-critical communication There are numerous reasons for a need for time-critical communication, such as medical emergencies. In the farming context, there is often a need to coordinate multiple neighboring actors required to combine their workforce during harvest within ideal time windows. Such messages are short but should arrive in seconds rather than minutes.

Time-relaxed communication

In emergency situations, there is also a need for regular communication between individuals in local communities. This involves transmitting small to large-sized data, including messages, photos, audio files, and videos (Touri, 2024). While not time-sensitive, this data exchange should still be transmitted as quickly as possible.

Sensor-related communication For technology-driven farming, analyzing recent environmental data is crucial for optimizing resource use such as water, fertilizer, fuel, and electric energy. However, many small farms lack access to various sensor stations due to financial constraints. This presents an opportunity for these farms to share data without having to invest in multiple sensors. Sharing weather forecasts, aggregated data from neighboring regions, and high-quality meteorological information can significantly enhance a farm's efficiency. Such data is likely extensive but not as time-sensitive as the other communication.

The next section will explore the possibility of connecting farms via LoRaWAN technology with reliable coverage over several kilometers using Germany as an example.

5 Farm-to-Farm Distances

To assess the feasibility of connecting neighboring farms via wireless communication technologies, we determined distances between farms. Since farm address databases are not readily available (and may not exist), we used data from the OpenStreetMap project to estimate these distances and developed a custom tool for this purpose.

5.1 Querying and Processing OpenStreetMap Data

The aim is to determine whether the given distances that a wireless communication system has to bridge between individual farms can be achieved with LoRaWAN. For this purpose, we developed a tool in python[4]. The tool's tasks can be roughly divided into three areas:

1. retrieving: query and filter OpenStreetMap data
2. processing: calculate distance matrix
3. presenting: generate statistics and graphs

The OpenStreetMap project's inconsistent data quality posed an issue when trying to retrieve farm information, particularly when comparing rural and urban areas. Objects next to large cities are often very accurately mapped and tagged, so also farm buildings `(building=farm)` even with details such as company names. But in rural areas those are less likely to be identified, resulting in a low recall performance when trying to query farm buildings in rural area. To overcome this limitation, we employed the tags `landuse=farmyard` and `landuse=farmland`, which better represent current farm business areas by including farmhouse, sheds, stables, and other related structures. However, this approach requires additional filtering to exclude non-relevant elements and reduce false positives. We filtered the retrieved data based on child elements within the farmyards and omitted those without any mapped buildings. To account for neighboring farmyards that might be part of the same business (e.g., due to complex polygon splits or street divisions), we merged nearby areas (up to 300m distance) to group related farms together. In emergency situations, even if multiple farm businesses share a communication link, this approach can still provide effective coverage. Finally, we randomly selected a building in each remaining area as the representative farmhouse that might host IT equipment, like a LoRaWAN gateway.

The processing step was more straightforward. We took the filtered farmhouses and calculated their center points, which enabled us to create a distance matrix that accounted for the curvature of the Earth using the `geopy.distance` library. To facilitate this process, we implemented comfort functions to store intermediate results and allow the creation of a distance matrix to be completed in stages. This was necessary due to the potential time required to complete the task, depending on the number of nodes and available computational resources. With the distance matrix in hand, we evaluated two key properties: (1) the minimum distances between farms, and (2) the count of neighboring farms within a range of [1, 2, 3, 4, 5] kilometers. We chose these ranges based on typical real-world coverage of LoRaWAN hardware, informed by our experience with deployments and literature (El Chall et al., 2019).

We used a combination of libraries — `geopandas`, `folium`, and `matplotlib` — to present the statistical findings. By embedding these results within a Jupyter Notebook file, we enabled further exploration and analysis of the data, making it easier to gain deeper insights into the characteristics of the farm distribution.

5.2 Analysis of Retrieved Data

To demonstrate the tool's capabilities we ran it for two different states: (1) Uganda as one developing country in Africa, and (2) Germany as one developed country in Europe. In Uganda we detected with our tool 778 buildings that represent just 0.49% of the official registered farming households (156,497) from 2020 (The Republic of Uganda, 2020). This discrepancy is due to various reasons, for example the incomplete nature of OpenStreetMap data, which relies on voluntary contributions and does not aim for 100% accuracy. Another reason could be, that there are rare situations where a building on a farming

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[4] https://github.com/PEASEC/distance-statistics

area is even required in Uganda, for example livestock is very likely living outdoors in most cases and due to a higher proportion of manual labor, the requirement for a machine shed is also not given. When comparing our results from Germany with official statistics from the agricultural sector from 2021, we found that the number of buildings we detected (117,744) represents 45% of the registered agricultural businesses (259,200) (Statistisches Bundesamt (Destatis), 2021). Despite these deviations, our analysis suggests that the concept can still be effective in certain areas.

We employed DBSCAN (Density-Based Spatial Clustering of Applications with Noise) (Ester et al., 1996) to cluster the buildings. This method groups points such that each member of a group has at least one neighboring member in the same group within a specified maximum distance. The results of our clustering experiments are presented in Table 2 (Germany) and Table 1 (Uganda). We varied two key parameters for these clusterings: the maximum Euclidean distance (ϵ) between two points and the minimum number of points required to form a cluster ($minPts$). Specifically, we tested three values for $minPts$: 3, 5, and 7 and three values for ϵ. As we see in literature quite high numbers for LoRaWAN data transmission range in Uganda of up to 29 km (Schweitzer et al., 2020) we used for this clustering also quite higher numbers (1km, 3km, 15km) compared to Germany (1km, 2km, 3km) based on our own empircally tests for the transmission range.

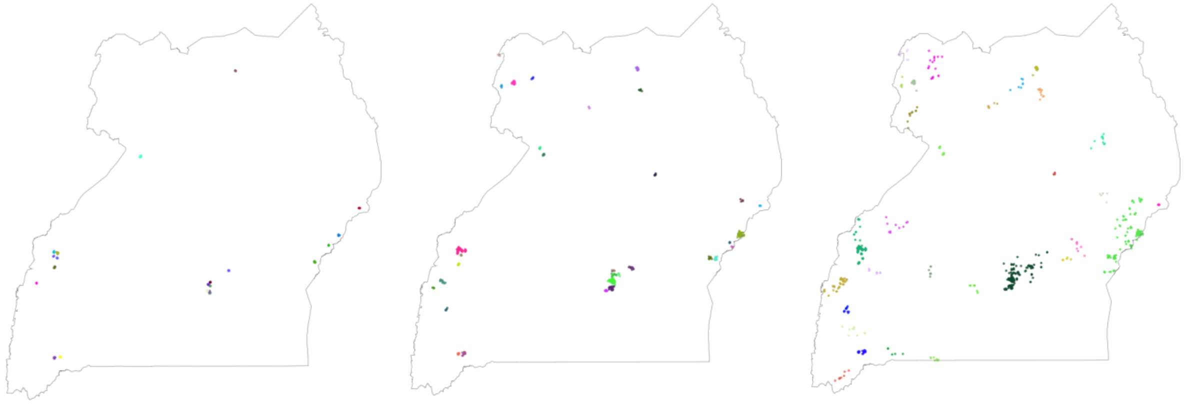
Table 1. Results of Different Clustering Parameters for Retrieved Farm Buildings in Uganda (N = 778)

ϵ	**1000m**			**3000m**			**15000m**		
min Pts	3	5	7	3	5	7	3	5	7
count	62	21	6	61	32	15	39	30	23
mean	5.10	6.76	8.67	8.44	12.75	21.00	18.18	22.40	26.74
std	2.92	2.43	1.75	11.09	12.73	14.94	31.92	35.29	34.50
median	4	5	8	5	6	15	8	10	12
max	16	12	12	57	57	57	153	153	149
noise	462	636	726	263	370	463	69	106	163

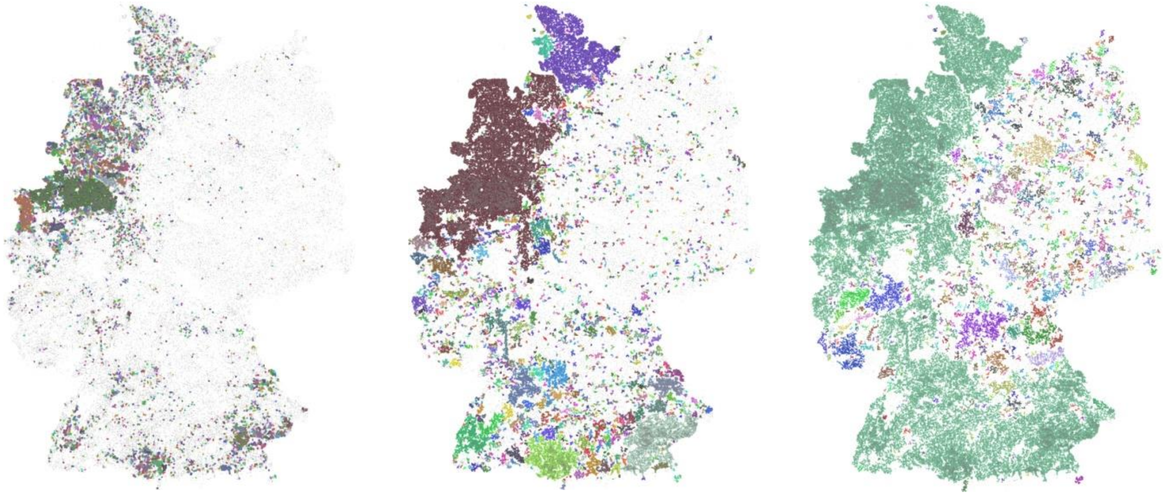
Table 2. Results of Different Clustering Parameters for Retrieved Farm Buildings in Germany (N = 117,744)

ϵ	**1000m**			**3000m**			**15000m**		
min Pts	3	5	7	3	5	7	3	5	7
count	7881	3462	1743	3345	1910	1401	1076	916	745
mean	10.68	16.35	19.69	32.73	52.12	63.83	107.71	122.79	143.87
std	163.76	188.38	68.78	836.33	1045.44	1059.23	2904.94	3058.33	2034.03
median	4	7	10	5	8	11	6	8	11
max	14,028	10,768	1863	46,643	44,396	38,674	95,328	92,615	50,657
noise	33,545	61,143	83,427	8252	18,199	28,318	1848	5265	10,563

The clustering results are visualized in Figure 1, where different configurations with colored clusters are plotted. As can be seen, the mean size of the clusters varies substantially across our data set, ranging from approximately 5 to 144 points. As expected, we observed that increasing the maximum Euclidean distance (ϵ) between two points reduces the number of noise points, effectively covering a larger portion of the data set with all clusters.



(a) ϵ = 1000 m (Uganda) (b) ϵ = 3000 m (Uganda) (c) ϵ = 15000 m (Uganda)



(d) ϵ = 1000 m (Germany) (e) ϵ = 2000 m (Germany) (f) ϵ = 3000 m (Germany)

Figure 1. Clustering results with maximum distance E and at least five elements per cluster (minPts = 5). Each element of a cluster is assigned a random color. All (including non-clustered) buildings are displayed as gray dots overlaid. Top row shows results for Uganda, while the bottom row shows Germany.

6 Simulation

Building on the insights gained in the previous section Farm-to-Farm Distances, we identified opportunities to establish networks that connect neighboring farms via LP-WAN technology, enabling small data exchanges such as messaging. In this simulation-based evaluation, we explore two DTN routing approaches using real-world data gathered from OpenStreetMap.

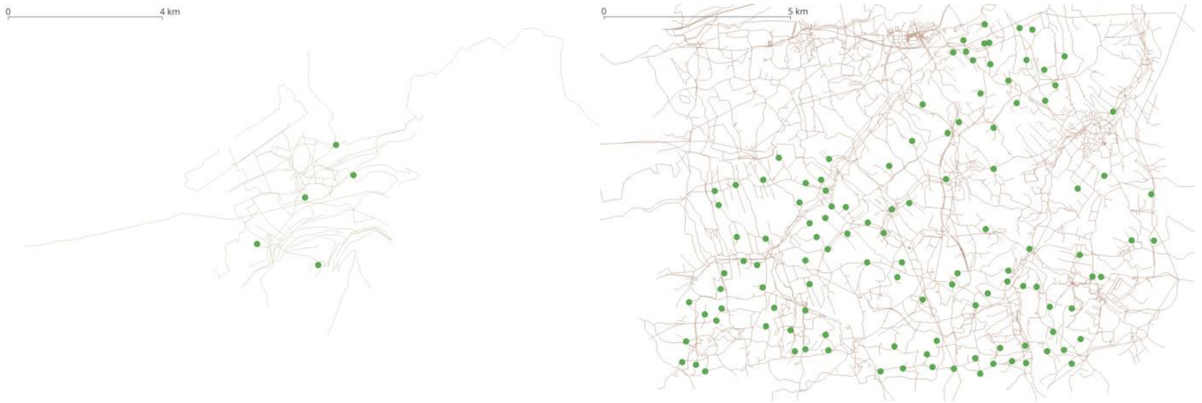
6.1 Setup

For this simulation-based evaluation, we utilize the ONE DTN simulation software (Keränen et al., 2009) to test two different network scenarios. The first scenario involves static nodes using only LoRaWAN as the transmission channel. The second scenario combines LoRaWAN with WiFi ad-hoc data exchange for mobile nodes. We base our simulation on real geographic data extracted from Open-StreetMap, which was previously used in Section Farm-to-Farm Distances. For this setup, we select a DBSCAN clustering result of Germany with moderate settings (ϵ = 2000m and *minP ts* = 5), which yields a cluster size of approximately 44,396 elements. To better approximate the size of local communities within our work's scope (connecting farms and people within a local community), we reduce large clusters by applying k-Means with $k = \lceil \frac{|c|}{100} \rceil$. This reduces each cluster with more than c elements with $|c| > 100$ to a community-sized cluster. Table 3 presents relevant statistics. We then select 40 randomly chosen clusters based on a 95% confidence interval (35.74, 39.10) to simulate our network scenarios.

Table 3. Statistics of the k-Means *post-processed* data set, used for picking simulation areas

count	mean	std	median	max
2660	37.42	37.42	11	224

The 40 selected clusters for simulation have an average size of approximately 38 elements (*std* = 37.29), indicating a relatively uniform distribution. Notably, the largest chosen cluster contains 116 elements, while three clusters are composed of just 5 elements each, representing the smallest groupings. For the mixed-mode scenario (combining LoRaWAN with WiFi ad-hoc data exchange for mobile nodes), we took into account the presence of pedestrians. To create a more realistic simulation environment, we exported additional path geometries from OpenStreetMap to enable our simulated pedestrians to move along streets and ways. Figure 2 illustrates two exemplary clusters with their corresponding paths, providing a visual representation of the movement and connectivity within these groups.



(a) Cluster 7, one of the smallest clusters with 5 elements

(b) Cluster 1, largest cluster with 116 elements

Figure 2. Static nodes (farms) overlaid on extracted OpenStreetMap paths, used for simulation of pedestrians

6.1.1 General Simulation Configuration

Both network scenarios (static LoRaWAN and mixed-mode LoRaWAN + WiFi) were simulated for each of the 40 clusters. The simulation duration was set to 12 hours, which is equivalent to 43,200 seconds. The update interval was configured at 0.05 seconds. In this setup, each cluster element was considered a static node, representing a farm in the simulation environment. To evaluate the performance of two widely used DTN routing protocols in our scenario, we ran all configurations with both PRoPHET and Epidemic routing algorithms.

6.1.2 Scenario Related Configuration

We configured the two network scenarios as follows:

Static Scenario

- A random static node (representing a farm) sends a message to a target within a distance that depends on the node size, specifically $\lfloor \frac{1800s}{|node|} \rfloor$
- Messages are sent by each node at a fixed interval, resulting in a message count per hour equal to the node size (both static and mobile).
- Message sizes are randomly generated within the range of 80 to 500 Bytes
- LoRaWAN communication has a maximum range of 2000m and a transmission speed of 7 kbps

Mobile Scenario

- Mobile nodes representing pedestrians are added.
- The number of mobile nodes is equal to the number of static nodes (one moving person per farm).
- A random node (either static or mobile) sends a message to a target within a distance that depends on the node size, specifically $\lfloor \frac{3600s}{|node|} \rfloor$.
- Message sizes are randomly generated within the range of 80 to 500 Bytes.
- Mobile nodes only have WiFi interfaces (smartphones) with a transmission speed of 54 MBit/s. They can exchange messages with other mobile nodes or static nodes within a range of 100m.

6.2 Results

The statistics of the messages sent are presented in Tables 4 and 5. The evaluation shows that, in both scenarios, the flooding-based Epidemic routing protocol achieves a higher message delivery probability, but at the cost of increased routed messages.

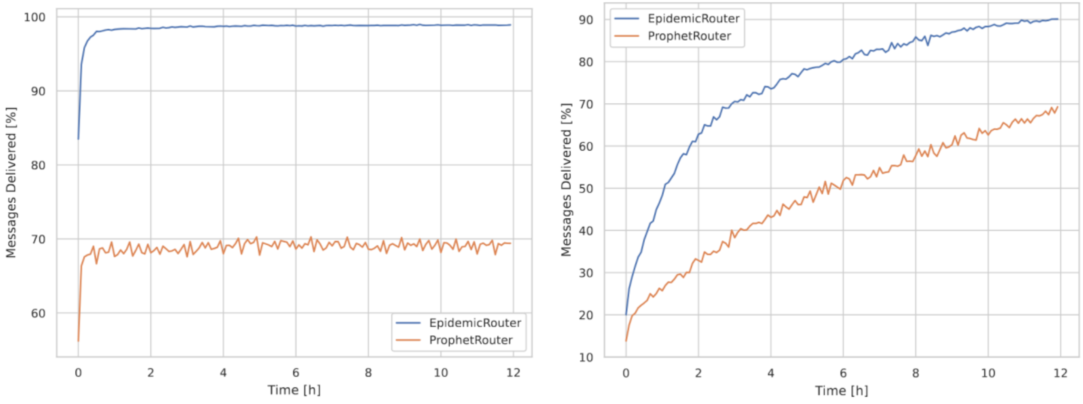
Table 4. Message statistics of *static* scenario. Mean over all 40 runs.

	created	**started**	**relayed**	**delivered**	**delivery_prob**	**latency_avg [s]**
Epidemic	927.75	66,411.25	66,410.63	917.03	0.99	0.29
PRoPHET	927.75	10,211.43	10,210.90	614.78	0.81	0.18

Table 5. Message statistics of *mobile* scenario. Mean over all 40 runs.

	created	**started**	**relayed**	**delivered**	**delivery_prob**	**latency_avg [s]**
Epidemic	927.75	123,095.88	123,095.40	835.18	0.88	3863.13
PRoPHET	927.75	54,895.90	54,895.55	631.78	0.72	7326.52

The message delivery rate over time is plotted in Figure 3. In the static scenario, Epidemic routing can deliver about 99% of created messages. Both PRoPHET and Epidemic routing exhibit almost constant delivery probabilities after a few minutes. However, from the second hour onwards, a gap develops between the two protocols. The results relate to all message types described in Section Use Case and Scenario: Emergency Communication for Agricultural Areas. Technically, however, it would be possible to use different routing algorithms for the different message types, provided that the type is directly visible in the frame, for example by means of a 2-bit type ID at a specified position. This would allow sensor-based communication that is less important for survival in the event of a crisis to be routed using PRoPHET, which would reduce the overall utilization of the radio channel and provide more resources for manually created messages (time-critical and time-relaxed), thus further increasing the probability of delivery. Interestingly, the static scenario with LoRaWAN-only communication achieves higher overall delivery performance compared to the mobile scenario. From a technical perspective, this is expected since mobile nodes must first come within WiFi reception range of another node before they can exchange messages. However, this has practical implications: For our primary use scenario of emergency communication, it may make sense to nudge users towards relying less on mobile ad hoc connections via WiFi and instead rely on static but connected LoRaWAN gateways for successful message delivery. This could lead to more efficient communication networks in scenarios where connectivity is critical.



(a) static (b) mobile

Figure 3. Message delivery rates of both scenarios. Mean over all 40 runs.

7 Concept

Following the results from our simulation (Section 6), we see an opportunity to create networks that connect neighboring farms using LPWAN setups for small data exchange, such as messaging. LoRaWAN technology offers a range of transmission distances, spanning several kilometers, depending on the settings, hardware, and geographic location. In this section, we outline our concept for connecting LoRaWAN setups of neighboured farms.

Our proposed system includes:

- A small server (hardware) in each farm building to run management software, as well as the required software for our system
- A local LoRaWAN network server (software) to collect and process data without limitations or running expenses

However, implementing LoRaWAN also comes with its own set of challenges, including:

- High airtime per frame (up to nearly three seconds)
- Duty cycle restrictions for many region/band combinations (e.g., 1% in the EU within the 868 MHz band)
- Low payload capacity
- Potential lack of network nodes (e.g., powered-down gateways)
- Wireless transmission failures due to various reasons (e.g., high noise in the used frequency band)

Despite these challenges, LoRaWAN offers a potential benefit: high transmission range (up to several kilometers) with the same hardware, which is already being used for IoT applications on farms.

7.1 Communication Via LoRaWAN Gateways

Our objective is to utilize neighboring LoRaWAN gateways to establish communication between them. To achieve this, we propose using a proxy that intercepts the communication between the LoRaWAN Network Server and a gateway, and then forwards our custom LoRa frames to another system with an identical processing pipeline. This approach allows us to add an emergency communication layer on top of the existing IoT setup without disrupting its regular operations. As shown in Figure 4, this concept adds a LoRaWAN Packet Forwarder AddOn that enables sending and receiving arbitrary LoRa(WAN) frames.

In our concept, the LoRaWAN network server software and our proxy software are hosted on a physical mini-server located next to the gateway. This setup ensures seamless integration with the existing IoT infrastructure.

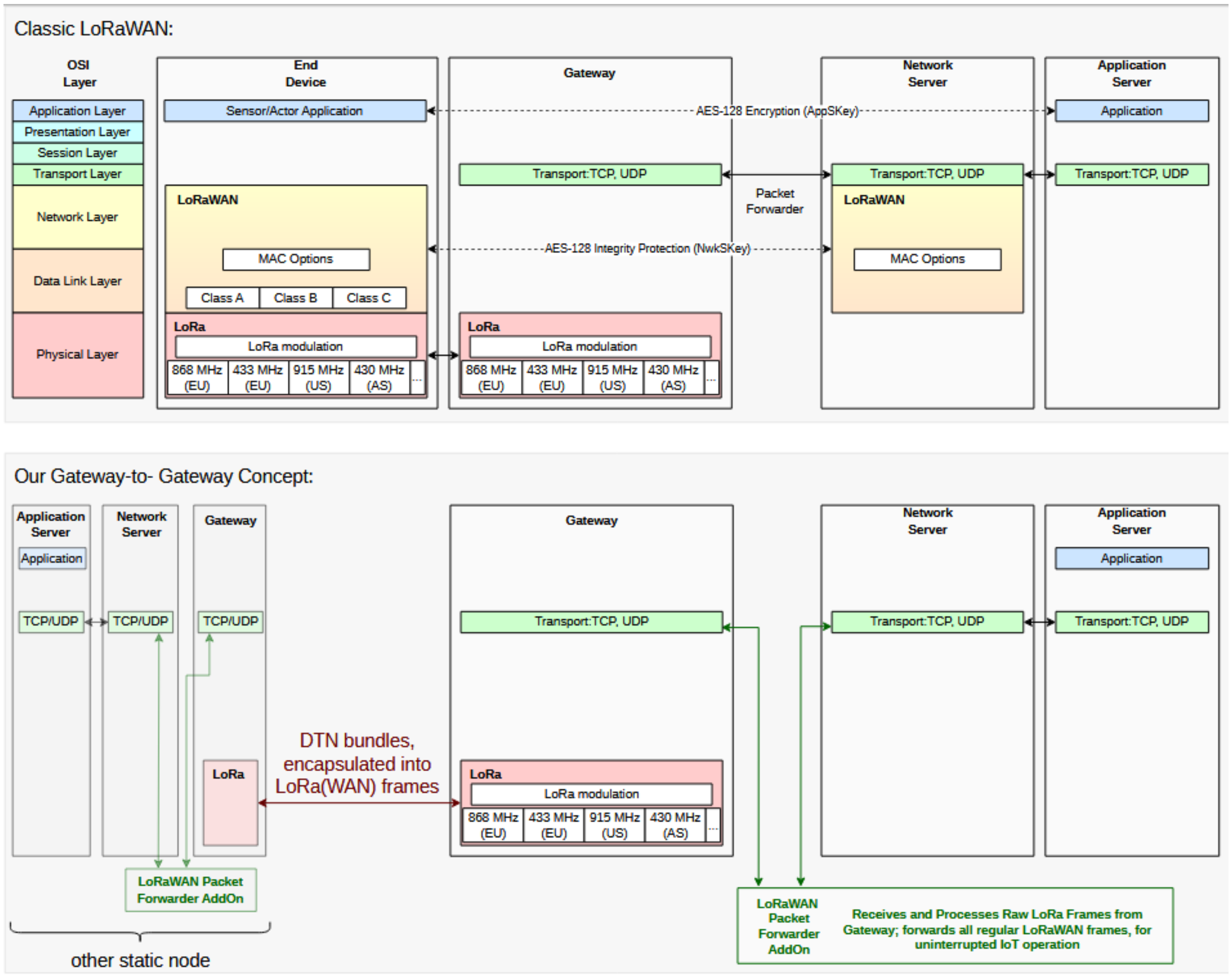


Figure 4. Concept of our AddOn: Regular LoRaWAN setup (top) is extended by a LoRaWAN Packet Forwarder AddOn, that allows to send and receive arbitrary LoRa(WAN) frames.

7.2 Custom LoRaWAN Frames and ISO/OSI Layers

Our custom frames operate within specific layers of the OSI model. On the *Physical Layer,* we are limited by LoRa transmission, as we utilize off-the-shelf LoRaWAN gateways. On the *Data Link Layer* and *Network Layer*, our implementation deviates from the standard LoRaWAN protocol (LoRa Alliance Technical Committee, 2020) by using custom frames (see Figure 5). For the upper layers (*Transport, Session, Presentation*), we employ BP7 (Burleigh et al., 2022) for message delivery, allowing applications to send and receive bundles.

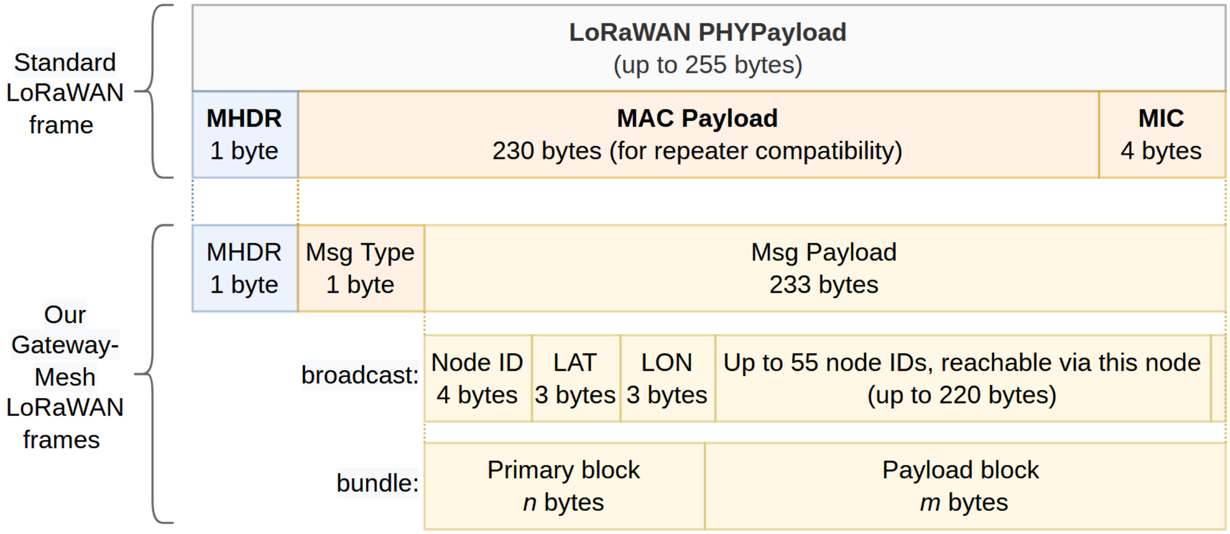


Figure 5. Structure of our LoRaWAN frames. The actual payload structure differs between the two message types.

Our custom frames differ from standard LoRaWAN frames only in the MACPayload and MIC fields. To ensure compatibility with future LoRaWAN repeaters (LoRa Alliance Technical Committee, 2020), we are restricted to using Data Rates 4, 5, and 6, which have a payload of 230 bytes (+ 4 bytes MIC). This is because 20 bytes are reserved for repeater-specific overhead. Our frames must adhere to these requirements.

The first byte identifies the payload content: either broadcast or bundle data. With only two types of messages, we have seven additional bits available for future use. Depending on the packet type (broadcast, bundle, or routing) the remaining 233 bytes are used as follows:

7.2.1 Broadcast Payload

The primary goal of broadcasting is to inform nearby systems about their own location and unique identifier (node ID). Similar to the LoRaWAN standard, we utilize 4-byte phone number-based IDs for each node, as well as 3 bytes for both longitude (LON) and latitude (LAT) values. This requires only a total of 10 bytes for basic broadcast messages. With the remaining payload capacity of 223 bytes, we can transmit up to 55 additional node IDs that are directly connected to this device. These could include smartphones currently registered with this device and likely reachable through it, such as nearby devices in close proximity.

7.2.2 Bundle Payload

Our bundle payload adheres to the Bundle Protocol version 7 (Burleigh et al., 2022), comprising two main blocks: primary and payload. If an application's data exceeds the Maximum Transmission Unit (MTU), it can be split across multiple bundles for transmission. The actual payload content depends on the specific application being used. For LoRaWAN transmissions, we allocate 1 byte for the application port number, serving as a reference point for upper-layer applications. These applications must consider using larger numbers for data that may be too heavy to transport via low-bandwidth channels, such as media files or software updates. In our test scenario, we used a simple messenger app with plain text content, which could be enhanced by compression using Brotli. It's essential to note that encryption is not applied up to this layer, so applications processing bundles must add encryption when necessary to ensure secure transmission. The bundle itself is encoded in Concise Binary Object Representation (CBOR) (Bormann & Hoffman, 2020) format, following the standard protocol.

7.2.3 Routing Between End-Devices

The integration of our gateway with proxy software enables us to send and receive frames, facilitating the creation of a resilient multi-hop communication network. To achieve this, we need a routing logic that can process bundles. When a bundle is received, there are two possible scenarios:

1. the current gateway is the intended destination, requiring internal forwarding to an application or end-device; or
2. the bundle must be forwarded externally, meaning it needs to be sent out by the gateway.

By leveraging the Bundle Protocol standard, we can enable applications to exchange data in new ways, such as through Bluetooth or WiFi on a smartphone. A key consideration is the address scheme used for routing bundles. We utilize phone numbers (E.123 notation) as Interplanetary Network (IPN) endpoint identifiers, assuming each user has one main mobile device and a unique phone number. Given our limited payload, we use 4-byte addresses that are calculated as CRC-32 checksums of the phone number.

8 Implementation

When inspecting ChirpStack, the de facto standard open-source LoRaWAN network server, we observed that all necessary communication between gateways and the server had been converted to Message Queuing Telemetry Transport (MQTT). This allowed us to leverage this existing framework to read LoRa frames received by a gateway and send messages via a LoRaWAN gateway. By sending commands to a gateway, we can specify our own payload, while respecting the limitations imposed by the data rate setup (SF and bandwidth). This approach eliminates the need to intercept the packet forwarder, as described in our concept. Instead, we implemented a specific MQTT client, which simplified the complexity of the implementation.

The modular design allowed us to separate two distinct functions:

1. An MQTT client that reads LoRaWAN frames and sends commands to a gateway.
2. A parser that converts LoRaWAN frames into DTN bundles with routing logic, connecting them to applications like our concept messenger app.

We implemented[5] these components as follows:

- The MQTT client was developed in Rust as a library called `chirpstack_gwb_integration`.
- The convergence layer application, `spatz`, was also implemented in Rust and uses the `DTN7-RS`[6] library as BP7 implementation.
- A simple browser-based messaging client was created using VueJS, which connects to a `spatz` instance via TCP/IP and allows users to send messages.

Figure 6 illustrates the components of our proof-of-concept implementation.

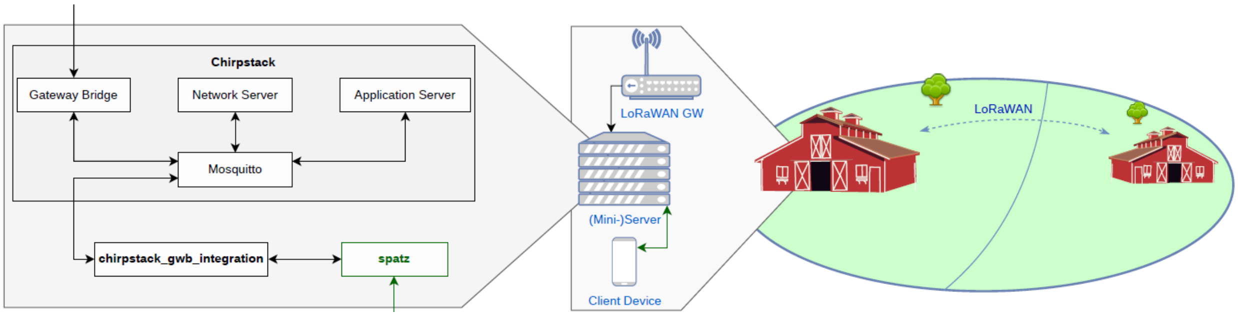


Figure 6. Proof-of-concept architecture: Regular LoRaWAN setup is extended by a LoRaWAN Packet Forwarder AddOn that allows to send and receive arbitrary LoRa(WAN) frames. The concept allows message exchange during network infrastructure outages

8.1 chirpstack_gwb_integration

The `chirpstack_gwb_integration`[7] library serves as a Rust interface for directly interacting with a gateway registered on a ChirpStack instance. Its primary goal is to enable independent LoRa frame

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[5] https://github.com/PEASEC/LoRaWAN-DTN
[6] https://github.com/dtn7/dtn7-rs
[7] https://github.com/PEASEC/LoRaWAN-DTN/tree/main/chirpstack_gwb_integration

transmission and reception without interfering with the standard IoT setup of a LoRaWAN instance. The library acts as a MQTT client, allows the creation of callbacks for incoming messages, and enables triggering of down-link commands as outgoing LoRaWAN frames with specific transmission parameters such as frequency, data rate, and payload.

8.2 spatz

The main application `spatz`[8] implements the Bundle Protocol convergence layer and routing logic. It enables external user interfaces to connect via WebSocket connections.

Key features of spatz include:

- Handling packet fragmentation when a retrieved bundle cannot be transmitted in a single LoRaWAN frame.
- Implementing epidemic routing, which has shown higher delivery probabilities in simulation results.
- A REST API for configuring settings, such as adding or deleting associated phone numbers (IPN endpoint identifiers).

9 Hardware Setup and Tests

For tests with real hardware, we used three nodes, where one node setup consists of a Linux mini-server (e.g. Raspberry Pi 4) and one LoRaWAN Gateway (e.g. Dragino LPS8):

a. A: Raspberry Pi 4, 4GB + Dragino LPS8,
b. B: Advantech UNO-2271G, 4GB, Celeron N6210 + Dragino DLOS8N, and
c. C: Advantech UNO-2271G, 4GB, Celeron N6210 + RAK 7268-N

Figure 7 depicts the used hardware. We use Debian 12 as Raspberry Pi operating system and Ubuntu 20.04-LTS on the Advantech UNO systems. Chirpstack v4 is installed according to the official *Quickstart Docker Compose* guide[9]. Our own software (`chirpstack_gwb_integration` and `spatz`) is packaged into Docker images and executed directly on the node hardware. We have two client options: (1) a browser-based messaging client that is served by its own Docker container on the node and allows it to be opened from a browser on a device (e.g. smartphone or laptop) on the same network; and (2) a modern looking Android application, that has a similar look'n'feel as a common messenger application (Orlov et al., 2023). With this setup, we were able to confirm the proper operation of our development with three nodes, and also perform basic performance and energy consumption measurements. The tests (usage) consist of a simple directed message exchange between two systems in a 10-second interval with 40 bytes messages, where one (passive) system directly answers to the (active) systems message, i.e., one system has received and sent a message in a 10 s time window.

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[8] https://github.com/PEASEC/LoRaWAN-DTN/tree/main/spatz

[9] https://www.chirpstack.io/project/guides/docker-compose/

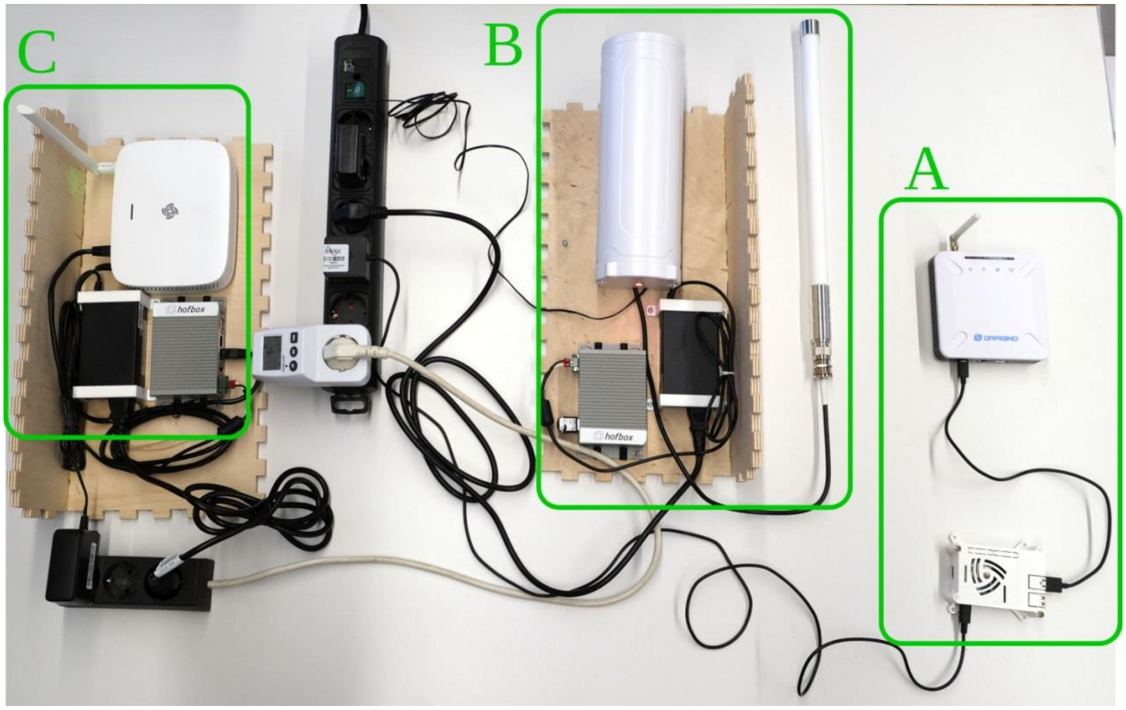

Figure 7. Three different node setups were used for evaluation.

9.1 Energy Consumption

In order to provide an understanding of the consumption of such a system when powered by emergency generators or backup batteries, we have measured the energy consumption. We measured for all three systems the complete power drain. For general power drain measurements, we used a classic ammeter (EKG-1). As System A allows to be powered completely via USB, we could additionally conduct a more detailed energy consumption measurement based on a USB logger (JOY-IT UM120).

The measurements (Table 6) based on the classic ammeter show no measurable difference in the power consumption when our system is active (usage) or idle. The regular variations in power consumption due to different background services on the Linux-based mini-servers and LoRaWAN gateways are far greater than the influence of our Spatz software and the active transmission from the LoRaWAN gateway. Figure 8 depicts an in-depth analysis of System A. Here we can see, that there is a slight impact in our usage scenario on the power drain. Sending and receiving messages in a 10 s interval increases the mean power consumption by 0.07 W.

Table 6. Energy consumption of our three test systems. System A and System B use WiFi connections, System C is connected via Ethernet

System:	**A**	**B**	**C**
Idle: Usage:	6.4 W – 6.9 W 6.4 W – 6.9 W	12.8 W – 13.1 W 12.8 W – 13.1 W	4.2 W – 5.0 W 4.2 W – 5.0 W

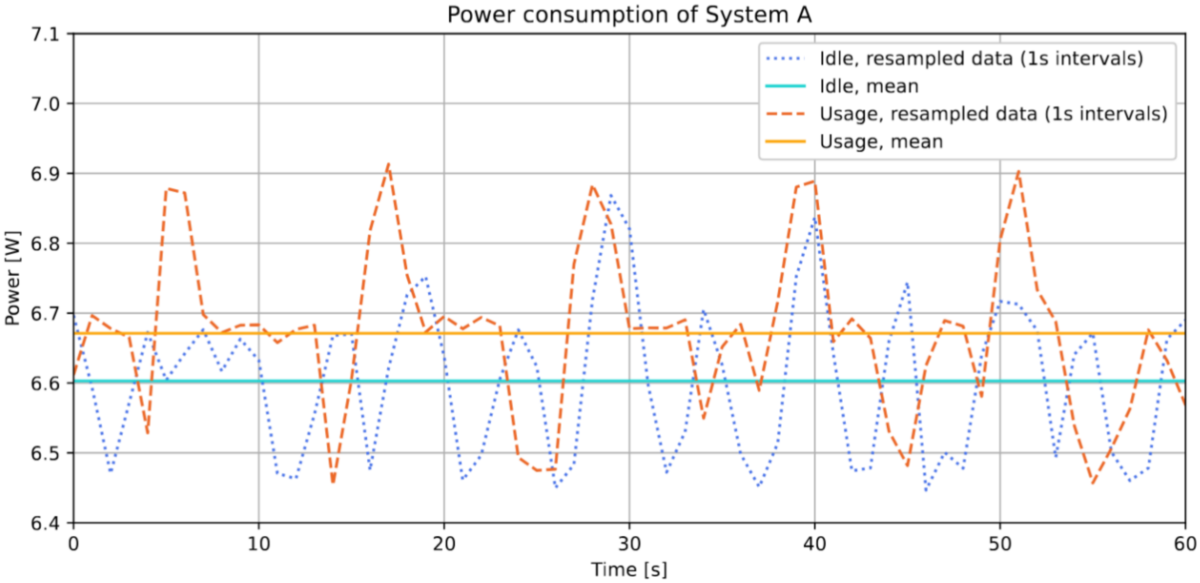

Figure 8. Power consumption of System A under two different situations. (1) Idle, i.e., no message transmissions, (2) Usage, i.e., triggered message transmissions in a 10s interval.

However, the choice of hardware used has a larger impact. Here we see that the system with the outdoor gateway (System B) takes considerably more energy compared to the other systems (System A and System C). Power optimizations are possible, but the data shows different out-of-the-box setups, not what optimizations can be achieved. In general, our systems have a similar power consumption to a WiFi router and should be easily powered by emergency generators or backup battery systems. The power consumption of our DTN software during active use is negligible; in terms of numbers, we measured an additional power consumption of 70 mW. Depending on the specific location, the energy consumption dimensions of the overall system could even be realized as completely self-sufficient systems, e.g., with solar panels or micro wind turbines in combination with an energy storage system.

9.2 Latency

Using a modified client that is connected to two systems simultaneously, we also determined the latency between the systems with our test parameters (message size 40 bytes, LoRaWAN Data Rate 0). Table 7 shows the resulting values. Accordingly, we can see that in our test setup, the latency is lowest when transmitting between systems B and C. This underlines the low speed and the resulting low bandwidth. Using higher data rates would reduce latency and increase bandwidth but at the expense of a lower range.

Table 7. Latency between tested systems

Systems:	**A ←→ B**	**B ←→ C**	**A ←→ C**
Latency (mean):	3.619 s	2.629 s	4.154 s

9.3 Hardware Costs

Table 8 lists exemplary hardware costs for different hardware. The cost of our evaluation setup hardware for one node starts at €250 (Raspberry Pi 4 + required accessories and a Dragino LPS8N-868). However, it should be kept in mind that these hardware requirements — at least a LoRaWAN gateway — are also necessary for regular LoRaWAN IoT setups, especially for farms that require long-range and cost-effective wireless transmission of sensor data.

Table 8. List of exemplary system component options with current prices (retrieved in November 2023)

Component	Type	Name	Price
		Raspberry Pi 4, 4GB RAM	~ €62
Mini-Server		Accessories (case, heat sink, power supply, 64 GB SDCard)	~ €28
Mini-Server		Intel NUC 8 Rugged Kit 4GB RAM, 64GB SSD	~ €250
LoRaWAN (indoor)	Gateway	Dragino LPS8N-868	~ €160
LoRaWAN (indoor)	Gateway	RAK 7268V2	~ €170
LoRaWAN (outdoor)	Gateway	Dragino DLOS8-868	~ €300

10 Conclusion

This research presents a novel approach for transforming commercial off-the-shelf LoRaWAN setups into DTN base stations, enabling long-range communication in rural areas by leveraging these LoRa-DTN base stations on farms. While previous studies have explored the use of multi-hop networks based on LPWAN technology to increase coverage (Abrardo & Pozzebon, 2019; Ebi et al., 2019), our work differs by focusing on the design and implementation of a communication system that provides support in crisis scenarios through DTN-based message transmission. Our approach uses commodity hardware, such as commercial LoRaWAN gateways, making it more feasible for deployment in emergency situations. Unlike existing works on IoT-communication extensions, which rely on specific devices or custom-built solutions, our design leverages the widespread availability of commodity hardware to provide a flexible and scalable communication system. By analyzing OpenStreetMap data, we can obtain approximations of farm locations, providing insight into the potential for implementing our approach across a whole country. Our simulation results demonstrated the feasibility of using LoRaWAN as the sole means of message transmission. A possible application scenario for this development is ensuring the exchange of short messages where no other reliable communication infrastructure is available — because of missing infrastructure or during times of communication infrastructure failure. The power consumption analysis showed that the complete system has a low total power consumption, with negligible overhead during active use (sending and receiving of messages). From a technical point of view, we see no reason not to use the proposed system if the necessary hardware is available, as there is no negative effect in terms of additional power drain when the system is not actively used — even in case it is used it has such a low energy consumption that should not be a problem for typical scenarios. Future work should aim to identify the feasibility of concrete application cases under realistic conditions, ultimately preparing this technology for real crisis scenarios, to evaluate how well the target group of farmers can handle the technology and understand its limitations and benefits. Also, the usability aspect could be addressed in future work with user interface improvements and a training concept to prepare the tool for public dissemination.

While the primary contribution of this paper lies in the design and evaluation of a technical solution, it also offers three substantive contributions to the field of Information and Communication Technology for Development. First, this work demonstrates the feasibility of leveraging existing LoRaWAN infrastructures in the agricultural sector to establish resilient communication systems for crisis scenarios. By supporting more reliable coordination and data exchange in food production systems, the approach contributes to the goals of SDG 2 (Zero Hunger) by promoting the stability and resilience of rural food systems. Utilizing commodity hardware, open protocols, and systems with minimal energy requirements, the proposed approach addresses disparities in communication resilience between urban and rural contexts - an issue particularly salient in low-resource settings. As such, it contributes to the advancement of SDGs 10 (Reduced Inequalities) and 11 (Sustainable Cities and Communities) by supporting inclusive access to digital infrastructure. Second, although empirically rooted in agriculture, the architectural and protocol-level principles underlying the work are applicable to a range of other development-relevant domains. Increasing reliance on IoT infrastructures in sectors such as water and sanitation (SDG 6: Clean Water and Sanitation), sustainable energy production (SDG 7: Affordable and Clean Energy), and industrial production (SDG 9: Industry, Innovation and Infrastructure) implies similar vulnerabilities to network disruptions. Building on the idea of ICT4D as dynamic socio-technical processes (Zheng et al., 2017), the presented model can thus serve as a transferable blueprint for enhancing communication resilience across these sectors. Third, the accessibility of the solution, both in terms of cost and technical complexity, supports broader digital inclusion objectives by enabling stakeholders with limited resources to establish and maintain critical communication infrastructure. In doing so, it contributes to local capacity building, enabling rural and remote communities to become active agents in shaping and securing their digital environments. Taken together, these contributions position the proposed system not only as a technical solution for emergency communication, but also as a scalable and infrastructure model within the ICT4D landscape.

Acknowledgments

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