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Heterogeneous IoT/LTE ProSe Virtual Infrastructure for Disaster Situations

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Abstract

Natural disasters of any kind can have catastrophic consequences for properties, infrastructure, and human lives. During large-scale calamities, two common problems are faced: (i) the partial or even complete destruction of communications infrastructure, and (ii) the difficulty of collecting accurate information on the disaster area and trapped victims. These two problems prevent a quick and accurate assessment of damage, leading to inefficient rescue operations and putting the lives of rescuers and victims in great danger. The LTE Proximity Services (ProSe) and the Internet of Things (IoT) are promising technologies that can offer an efficient solution to the aforementioned problems in the form of a rapidly established emergency network for post-disaster management. In this paper, we propose a solution for the establishment of an efficient emergency communications network for post-disaster situations based on the LTE Device-to-Device ProSe (D2D ProSe) technology and IoT devices. It facilitates fast and efficient service discovery that allows querying heterogeneous IoT devices such as health sensors, wireless cameras, smartwatches, or any other relevant devices or sensors. The goal is to allow rescuers to have access to information produced by various things available during the rescue operation. We take advantage of LTE ProSe to create a distributed D2D broadcast backbone that enables efficient and reliable message dissemination while reducing energy consumption and achieving high coverage. We then add a multipath forwarding mechanism, in which each service type of IoT device is ensured an optimal path for its traffic. Unlike previous works, we fully implemented our solution in the NS3 simulator and relied on realistic models (wireless channels, energy, and mobility) to evaluate its performance compared to previous solutions, which we also implemented on NS3. The obtained results show that our solution achieves significant improvement compared to those proposed in the literature. The entire code used in this project is freely available to the community through GitHub¹.

Keywords: Disaster Recovery, LTE ProSe, 5G, D2D communication

1. Introduction

In large-scale disasters, components of the communications infrastructure, such as cellular base stations (BSs) and wireless access points (AP) are susceptible to damage and, in some extreme cases, the entire communications system collapses and cannot operate for days [1, 2]. For example, during the 2011 tsunami on the eastern coast of Japan, approximately 13,000 base stations stopped operating properly, resulting in the loss of communication services in vast areas. Nearly 1.52 million lines were out of service for four days and the restoration of 90% to 95% of the system took 14 to 25 days, respectively [3].

¹https://github.com/iorisam/NS3_ED2D_IoT

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In general, during the first 24 to 48 hours in post-disaster scenarios, two major problems arise: (i) the absence of a communication system capable of connecting first responder teams, and (ii) the lack of relevant and up-to-date information on affected areas. These problems make it very difficult to assess the situation and carry out coordinated and informed response operations, which can slow rescue operations and may lead to the loss of lives.

Therefore, the establishment of a specific wireless emergency response network for disaster scenarios needs to occur in a way that is completely or partially independent of existing communications networks. The established network should be energy-efficient and integrate potentially operable and available IoT devices for more post-disaster awareness, efficient mission-critical tasks, and better-coordinated rescue operations [4, 5]. The established network should also be based on commercial telecommunications standards for better availability, cost-effectiveness, and worldwide compatibility.

Recently, the LTE proximity service (ProSe) has been attracting a lot of attention for building emergency communications networks [6, 7, 8, 9, 10]. LTE ProSe is a Device-to-Device (D2D) wireless technology standardized by the Third Generation Partnership Project (3GPP) for the construction of public safety networks and commercial applications [11]. It enables users to have D2D communications in close proximity without going through the core network. Thus, saving network and radio resources, and reducing communications latency while making it possible to have communications in out-of-coverage areas. LTE ProSe is considered one of the most promising wireless technologies for emergency communications, as it allows high scalability, manageability, privacy, security, and energy efficiency [12].

Although there have been extensive research efforts on addressing the challenges of constructing replacement networks for post-disaster situations using various communications technologies such as LTE ProSe, WiFi, and IEEE 802.15.4 (e.g. [13, 8, 14]), a lot of issues and shortcomings still need to be solved and overcome, including:

- Most LTE-based solutions (e.g., [15, 16, 17]) function in partial-coverage scenarios, i.e., they establish links between mobile User Equipments (UEs) scattered in an area with no cellular coverage and the closest access point (AP) that is part of an active cellular network. However, in some extreme cases, an emergency response network should also operate in completely out-of-coverage situations when the main communications system is completely out of order.
- Integrating IoT devices in public safety and emergency response operations is mostly considered in broadband networks (e.g. [18, 19]). The IoT devices allow for real-time data collection without human interaction. This is particularly important in situations where first responders are busy with critical tasks. For example, smart gear with sensors can indicate first responders' vital signs and temperature so they can be removed from dangerous situations.

Drones deployed in the affected area are another good example of IoT devices capable of helping during emergencies. They can provide a wide-angle video feed, up-to-date maps, and routes for rescuers to take during search/rescue operations, and detect alive victims buried beneath rubble using sensors such as heat, noise, and vibration. Therefore, the integration of operable IoT devices into an emergency response network should be considered, even with challenges in energy and connectivity.

- LTE ProSe-based emergency response networks mainly use a one-hop communication mechanism (e.g. [20]). To our knowledge, one of the available solutions that support multi-hop communication has been described in [21]. Although this solution allows multi-hop communication for higher area coverage, it has a few limitations. It only allows down-link communications and relies on the existence of a Group Authentication Server (GAS) for authorization, and the built network is only designed for file sharing between LTE ProSe-equipped UEs as no integration of other types of IoT devices was envisaged.

In this paper, we propose an LTE ProSe-based solution for building an emergency response network in a disaster situation. We provide details on a novel service-based forwarding scheme, where we select for each type of service provided by certain IoT devices a number of relay nodes responsible for delivering that specific service's traffic from requester to provider. We implemented and tested our solution using realistic

models of energy consumption, mobility, wireless channels, and most importantly the LTE ProSe model provided by the National Institute of Standards and Technology (NIST) [22] for the Network Simulator (NS3) [23]. We also had to re-implement some existing solutions using the same framework, as we are not aware of any realistic implementation of these solutions.

The main contributions of the proposed work are summarized below.

- Building an LTE ProSe-based emergency network that can be established in both partially covered and fully out-of-coverage disaster areas.
- Proposing an efficient multi-hop LTE ProSe broadcasting mechanism based on a relay selection algorithm for out-of-coverage situations.
- Enhancing the message forwarding scheme by prioritizing service traffic, that is, proposing a service-oriented dissemination scheme that enables multicasting messages based on the type of sender and receiver.
- Integrating both IoT and ProSe technologies into a post-disaster emergency response network, allowing fast and accurate situation assessment and more reliable communication links.
- Providing an open-source implementation of our solution (in addition to state-of-the-art solutions used for comparison) that is fully compatible with the NS3 [23]. Our implementation, available on [24], is based on the LTE ProSe code provided by the NIST [22].

The remainder of the paper is organized as follows. In Section 2, we present an overview of relevant solutions for post-disaster communications that are based on IoT technologies. In Section 3, we present the system model and formulate the problem statement. In Section 4, we present the details of how we built a communication backbone for an emergency network with support for IoT devices. Then we introduce our energy-aware service-oriented traffic dissemination scheme. In Section 5 and Section 6, we describe the comparative analysis between our proposal and state-of-the-art solutions and show the results obtained. In Section 7, we conclude with comments and future directions.

2. Related Work

Many strategies have been proposed for building post-disaster and emergency response communications networks using various communication technologies including Cellular, Bluetooth, WiFi, and LTE ProSe. The proposed solutions considered different situations such as earthquakes, floods, and landslides, and addressed various aspects of disaster management, including data usage in situation awareness and prediction, networking, security, real-time communications, QoS, etc.

A typical approach for constructing these post-disaster networks is building them on top of D2D technology relying on multi-hop communication, thereby relaxing the need for a preexisting infrastructure and providing a timely setup in emergency situations.

Several of the proposed solutions have been built on top of WiFi as the main D2D wireless technology. In [25], the authors proposed TeamPhone which consists in making use of smartphones to form a replacement network relying on WiFi Direct to create Peer-to-Peer (P2P) connections for sending and receiving emergency messages between these smartphones. In [26], the authors developed a D2D smartphone relay prototype that could send emergency information using WiFi ad-hoc mode to enable sharing of information among people gathered in the evacuation center. In [27], the authors described a smartphone-based ad-hoc network architecture using WiFi tethering mode for post-disaster scenarios. The objective of such network architecture is to connect smartphones from the disconnected area (as a result of cellular network damage) to either emergency communication equipments deployed in the disaster area or to other smartphones located in a covered area.

Although WiFi technology is widely adopted and supported by practically all smartphones, implementing these solutions for field tests requires modifications to the firmware of the transceiver driver [27] for the use

of WiFi Direct and root access to the kernel, or jailbreaking devices [25] for the use of WiFi ad-hoc mode. Additionally, due to the short range of WiFi, a rescue team member would need to walk through collapsed buildings to effectively find people potentially under the wreckage. This procedure can significantly slow down the rescue process and introduce risks to rescue team members by requiring them to be around potentially dangerous areas while looking for people.

In more recent studies, there has been a shift towards LTE ProSe, which is a long-range D2D wireless technology introduced by 3GPP in its 12th release. This promising standard allows two devices to communicate directly, independently of the core network [28]. One of the earliest attempts to exploit such technology for emergency networks was presented in [20]. In their solution, health-related information is collected from wearable devices and body sensors using a victim's smartphone. Then, the collected information is broadcast to nearby smartphones using ProSe to reach more people. However, their solution is only limited to one-hop broadcast communication and can only be used in situations where a partial-coverage telecommunications infrastructure is available to enable D2D direct communication, which limits the applicability of this solution in large-scale disasters. In addition to these limitations, their solution did not take into account the energy cost of LTE ProSe broadcasts. Unlike [20], the authors of [6] and [7] have addressed the massive energy cost of LTE ProSe broadcasts and proposed clustering techniques to extend the lifetime of the entire network, and energy-aware routing algorithms have been proposed to further reduce the energy consumption of cluster heads. However, it was observed that the presented clustering techniques put a heavy load on the near-coverage devices, as they are repeatedly selected for cluster-head roles. This drains their energy resources prematurely and consequently affects the lifetime of the entire network. Alternatively, to clustering techniques, the authors of [21] introduced a hierarchical architecture containing two types of nodes: relays and clients. In their proposal, the authors developed three algorithms for relay node selection, where the selected nodes retransmit data to all other remaining nodes. The selection process reduces the number of broadcasting nodes, thus producing higher performance than direct broadcast to all nodes (i.e., flooding over ProSe). Although the resulting architecture helped reduce LTE ProSe broadcast cost, it heavily depended on the availability of special equipment called a Group Application Server (GAS) that initiates the network construction, collects relevant information about nodes, and selects relay nodes, which limits its wider applicability.

The solutions mentioned above focused on the communications network problem, but overlooked the integration of various IoT technologies into them. To cope with such a limitation and provide solutions with better situational awareness and effective decision-making, solutions need to consider IoT hardware constraints, data rates, protocols, etc. Examples of such solutions include the work proposed in [29] where the authors considered integrating WSN protocols such as the Routing Protocol for Low-Power and Lossy Networks (RPL) in an emergency communication network. Furthermore, in [30], the authors propose an end-to-end system for connecting on-body sensors of trapped victims to the command center. They introduced two types of nodes: mobile nodes (carried by victims, survivors, and even public safety officers), and tactical nodes installed by rescuers in some places to act as relays. They propose to construct an ad-hoc network that connects these two types of nodes and on-body sensors. The purpose of this network is to collect data from the sensors and push it to the command center using the MQTT protocol. Although these solution integrates IoT technology, they require additional hardware, for example, HF modules or LoRa gateways in [31, 32], which might not be practical in extreme situations.

Despite these efforts, optimizing the constructed emergency network for IoT data and services has not been well addressed in the literature. Efforts have been made in [19] to propose a basic architecture for flood data collection and visualization using IoT services with three layers: application, network, and perception. Additional work has been presented in [18] where the authors proposed a middleware to prioritize IoT data in an emergency network. Their approach consisted in associating each IoT device with a priority depending on the type of disaster, then in the routing phase, each relay node classifies data depending on its priority. The authors claimed that when tested on smart buildings and firefighting scenarios, significant improvements can be obtained compared to traditional techniques. However, it is to be noted that the proposed scheme still depends on the 4G network infrastructure, which reduces its applicability in the absence of a cellular network.

| Paper | Technology | Energy Considered | IoT Integration | Telecommunication coverage | Requires Extra Hardware | Validation |
|------------------|-------------------------|-------------------|-----------------|----------------------------|-------------------------|---|
| [6] | ProSe | ✓ | ✗ | Partial coverage | ✗ | Matlab Simulation |
| [7] | ProSe, WiFi, Cellular | ✓ | ✗ | Partial coverage | ✗ | Formal modeling, Omnet++ simulation |
| [18] | N/A | ✗ | ✓ | Partial coverage | ✓ | Formal modeling, Python-based Simulation |
| [20] | ProSe, BLE | ✗ | ✓ | Partial coverage | ✗ | Qualcomm SDK and simulator |
| [21] | ProSe | ✓ | ✗ | Partial coverage | ✓ | Matlab simulation |
| [25], [26], [27] | WiFi | ✗ | ✗ | Out of coverage | ✗ | Tested on real devices |
| [29] | WiFi, BLE, Zigbee, NVIS | ✗ | ✓ | Out of Coverage | ✓ | Prototype |
| [30] | WiFi, BLE, Zigbee, WBAN | ✗ | ✓ | Partial coverage | ✓ | Tested on devices |
| [31], [32] | WiFi, BLE, LoRa | ✓ | ✓ | Out of coverage | ✓ | Prototype Simulation for routing protocol |
| Our work | ProSe, WiFi, BLE, WBAN | ✓ | ✓ | Out of coverage | ✗ | NS3 Simulation Code made publicly available |

Table 1: Recent studies on post disaster communication networks

A summary of the related work is shown in Table 1 where several features have been considered to characterize the studied solutions including the wireless technology employed, whether the study addressed the issue of energy consumption, the integration of IoT devices and services, the radio coverage demonstrating the solution’s dependence on conventional telecommunication systems, whether the solution necessitates additional hardware, and finally the validation method employed in the study.

We conclude that previous research efforts have mainly focused on either suggesting the deployment of additional hardware for long-range communications, which can be difficult to obtain, expensive, and time-consuming, or on providing an alternative infrastructure to the main damaged one by trying various technologies, primarily WiFi or LTE. Most of these solutions considered partial coverage and attempted to reach the covered area to relay emergency messages and ignored the case of complete out-of-coverage situations. Most importantly, more research is still needed on how to integrate IoT technology into emergency communication networks, and effective optimization techniques are not yet established. For instance, consider the case where a command center or a public safety officer needs to query/access a certain ser-

vice provided by multiple IoT devices (temperature readings offered by temperature sensors), existing LTE ProSe-based solutions use flood routing to deliver queries and responses [20]. This leads to significant energy waste and creates additional network overhead, especially with LTE ProSe. To cope with this situation, we introduce a multipath forwarding scheme on top of a constructed virtual network and focus on determining the optimum path that connects all IoT devices providing the same service, which makes services from various IoT devices efficiently available to rescuers.

3. Problem Formulation and Network Model

3.1. Network Model

We consider the case of a smart city hit by a full-scale natural disaster resulting in damage to buildings, leaving many victims in need of assistance, and destroying almost the entire communications infrastructure and power lines. We assume that there are many IoT devices (smart sensors, smartwatches, wearables, cameras, smartphones) that are battery-operated and which continue to function for some time even in the absence of the main power supply network.

We focus on the problem illustrated in Figure 1, in which a Base Station (BS) is fully damaged and victims are unable to use the wireless network to communicate their health status and request help. In these situations, the user equipment (UE) should be able to automatically switch to disaster mode when no control signals are received from the BSs for a specific period of time [33, 27]. In disaster mode, a UE sends and listens to hello messages to build its neighborhood cache. In contrast to previous solutions [34, 35, 36], we consider the case where nodes do not rely on an external entity to obtain instructions on how to build a network. Instead, they actively participate in the construction of the network hierarchy.

In the rest of the paper, we distinguish between the following terms *Device*, *Station*, *Relay*, and *Node*.

A *Device* can be any small thing capable of performing sensing or actuating operations. It is typically very constrained in storage, processing, and communications resources. Every device has a type assigned to it depending on the services it provides.

A *Station* is a higher capacity communicating object, typically a smartphone equipped with LTE technology and held by rescuers, volunteers or victims. In our case, we assume that it also implements D2D ProSe.

A *Node* is a general term that is used to refer to a device or a station.

A *Relay* is a station involved in the forwarding of data from a node to other nodes.

We also assume the following:

- Rescuers, volunteers, and victims have smartphones enabled with LTE D2D ProSe.
- Users have already pre-installed an emergency application that allows their devices to start the construction and use of an emergency network.
- The application can be activated by a special emergency message sent by a special agency or by not detecting an RRC SYNC message for a certain period of time.
- We assume that rescuers and volunteers are mobile, whereas victims are stationary waiting to be rescued.
- All stations are equipped with a USIM, providing all the preconfiguration and authorization necessary for the LTE D2D ProSe communications specified in [11].
- Each station in the disaster area is equipped with multiple wireless technologies including LTE ProSe, WiFi, and BLE.
- Each relay node will serve k nodes and will be connected to I other relay nodes.
- Each relay uses only LTE ProSe to communicate with one or more relay nodes (RN).

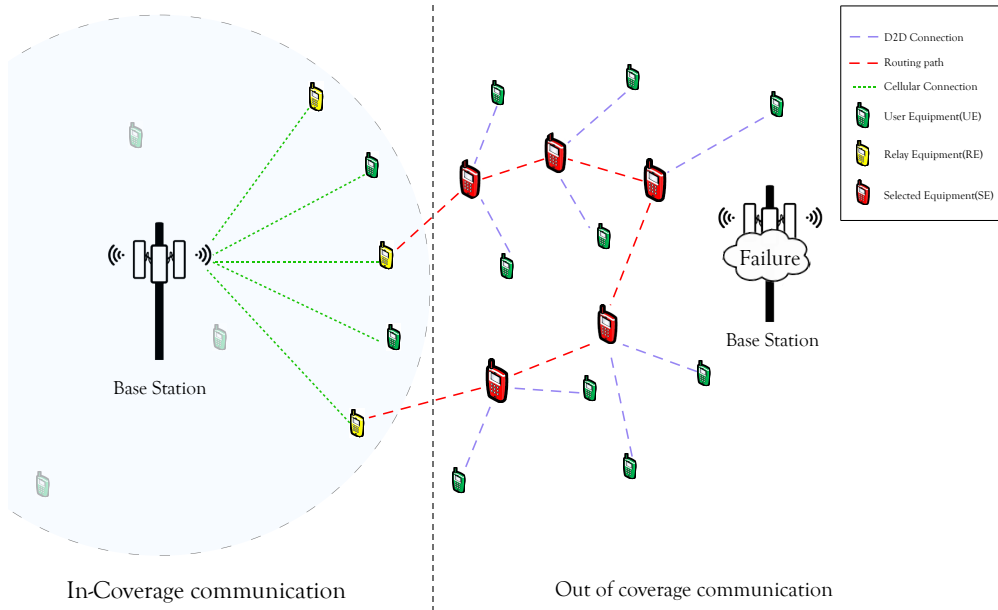


Figure 1: Out-of-coverage communication in partial telecommunication failure

- We assume that mobility is low and victims are mainly waiting to be rescued.
- We assume that traffic is heavy due to file sharing, video and audio flows being exchanged.
- Each IoT device has only one interface and each smartphone has many.
- Communications between smartphones occur through the LTE ProSe interface. The selection of LTE ProSe is motivated by its qualities over other wireless technologies as shown in [37, 38, 20]

We model the network in a disaster-affected area without cellular coverage as a graph $G(S, D, E)$ where S is the set of stations that are typically smartphones held by rescuers, volunteers, or victims. D is the set of IoT devices (e.g., vital signs monitoring devices, smartwatches, wearable devices, wireless cameras, temperature sensors, presence sensors, etc.). E is the set of edges where E_{ij} denotes a direct wireless link from i to j , such that i and j belong to $S \cup D$.

subsectionProblem Formulation In previous work, [39], we tried to build an emergency network that facilitates communications between victims and public safety workers. The purpose of this system is to help victims acquire instructions on where to find the first necessity items, how to get to the nearest shelter safely, and most importantly, the presence of healthcare personnel in the vicinity. It also helps public safety workers gather information on trapped victims and the state of their location (is it safe? is it on fire? is it fragile? is there a gas leak? etc.). We achieve this, by considering IoT devices as one of the most important sources of information, we then integrated these devices into a pre-built emergency network of smartphones, operating in out-of-coverage LTE ProSe mode. The presented architecture allowed both rescuers and victims to query a group of devices (certain type) simultaneously. In this paper, we extend our previous architecture with a multi-path routing based on existing IoT service types for further optimization and utilization of IoT technology.

3.2. Problem Statement

Given the network graph $G(S, D, E)$ of stations S and IoT devices D connected via wireless links E . Let the cost of ProSe, denoted $P\{n_s, n_d\}$ be the cost incurred by any transmission of a request/response packet from a source node n_s to a destination node n_d through multihop broadcast, such that n_s and n_d belong to $S \cup D$. In our previous work, we tried selecting an optimal set of relay nodes without taking into consideration

the type of services covered by these relays. By neglecting this selection criterion, several relay nodes may remain active during traffic routing unnecessarily, resulting in faster battery depletion. To minimize the ProSe cost for any communicating pairs n_s and n_d , the emergency network should be constructed taking into account the following criteria: (i) the use of a minimum number of relay nodes that can broadcast any packet from source n_s to destination n_d , (ii) the selection of the optimal set $M \in S$ of relay nodes that ensure network connectivity, (iii) the use of all smartphone candidates that cover a maximum number of IoT devices, and (iv) for any communicating pairs n_s and n_d , we build a sub-network for each type of service consisting of devices of the same Type T and intermediary nodes that are necessary to connect these devices.

The described problem is NP-complete, we prove this by showing that the above problem is similar to the minimum Connected Dominating Set (CDS), which is already known as NP-complete [40]. However, considering two types of nodes (Station and IoT Devices) in the network, and constructing a subnetwork for each type of service makes the problem more complex. In the following section, we discuss in detail the proposed heuristic to tackle the aforementioned problem.

4. Service-Oriented Efficient D2D Broadcast

In this section, we provide a solution to the problem mentioned above. First, we discuss a simple yet effective heuristic for building a reliable and robust emergency network based on LTE ProSe. The objective is to select a minimum number of station relays in such a way that the overall cost of ProSe is minimized. The proposed heuristic operates in three phases: Discovery phase, Distributed Relay Selection phase, and Service-oriented Efficient D2D Broadcast.

4.1. Discovery Phase

In the first phase, each smartphone (station) starts discovering its surrounding devices and neighboring smartphones.

Algorithm 1 Periodic Stations Discovery

```

1: BroadcastHelloMsg(id, energy, NA(u)) ▷ On the LTE D2D ProSe Interface
2: Switch to Receive mode for  $t$  seconds
3: Listen for Hello Messages
4: for each Msg Received do
5:   Let  $V$  be Sender of msg containing sender Id, EnergyLvL, Set of Neighbors  $N^A(v)$ 
6:   if  $V \in N^S(U)$  then
7:     Update  $V$  in  $N^S(U)$ 
8:   else
9:      $N^S(U) \leftarrow N^S(U) + V$ 
10:  end if
11: end for
12: for each neighbor  $W \in N^s(U)$  do
13:   if  $Now - D^t \text{ of } W > \text{threshold}$  then ▷ Remove  $W$  from neighbors list if its not rediscovered in a given period
14:      $N^S(U) \leftarrow N^S(U) - W$ 
15:   end if
16: end for

```

4.1.1. Periodic Station Discovery

In this phase, every station sends a discovery message to neighboring stations through periodic transmissions. The discovery message contains information related to energy level, neighbors list, and the degree of connectivity which are necessary parameters for the next phases. Although 3GPP specifies a direct device-to-device (D2D) discovery protocol that allows for a station to discover its neighbors, the ProSe discovery mechanism works only in coverage and in partial-coverage modes and requires the presence of an LTE core network. Furthermore, the ProSe specification imposes a certain message structure and a limited size. Therefore, including the aforementioned discovery information in ProSe discovery messages is not

practical. To enable station discovery, we propose another mechanism based on ProSe broadcast communications, where stations periodically broadcast hello messages containing the aforementioned information. Algorithm 1 presents the discovery phase of surrounding stations over LTE ProSe direct communications.

Algorithm 2 Periodic Device Discovery

```

1: Switch to Transmission Mode
2: for each Available Interface do
3:   Broadcast(HelloMsg)
4: end for
5: Switch to Receive Mode for  $t$  seconds
6: Listen for Responses or Push Notifications on all Available Interfaces
7: for each Msg Received do
8:   Let  $D$  be Sender of Msg
9:   if  $D \in \mathbf{N}^d(U)$  then ▷ Station  $D$  has already been discovered
10:    Update  $D$  in  $\mathbf{N}^d(U)$  ▷ update the Station  $D$  information(energy level, covered devices, ...) in local table
11:   else
12:     $\mathbf{N}^d(U) \leftarrow \mathbf{N}^d(U) + D$ 
13:   end if
14: end for
15: for each neighbor  $W \in \mathbf{N}^d(U)$  do
16:   if  $Now - \mathbf{D}^t \text{ of } W > threshold$  then ▷ Remove  $W$  from neighbors list if it is not rediscovered in a given period
17:     $\mathbf{N}^d(U) \leftarrow \mathbf{N}^d(U) - W$ 
18:   end if
19: end for

```

4.1.2. Periodic Device Discovery

To ensure maximum coverage of IoT devices, stations periodically discover their surrounding devices. The number of devices discovered by a station is an important factor during the selection of relay stations. In fact, smartphones support a wide set of wireless interfaces (WiFi, LTE, Bluetooth, ZigBee, ANT+, NFC, QR, etc.) [41]. In addition, smartphones are capable of communicating with different types of smart objects such as devices used in smart homes, healthcare systems, wireless cameras, or other ProSe-enabled smartphones. Stations discover devices in two modes; (i) listening to hello messages from devices that support push mode (e.g. Google Eddystone, iBeacon, AliveCor [42]), or (ii) broadcasting a message 'Who is there?' to discover devices operating in pull mode (e.g. wireless cameras). A station has to constantly switch between interfaces to send discovery messages. A station, stores discovered devices, services, communication modes, and interfaces in a table. Algorithm 2 presents the device discovery phase.

4.2. Distributed Relay Selection

Using discovery results obtained from Phases I and II (station and device tables), we construct a network backbone. Stations that belong to the backbone are referred to as broadcasting nodes or as relay nodes, and are the only nodes responsible for data forwarding. After the previous discovery phases, each node is aware of its neighboring stations and devices. If a station detects that two of its neighbors are not connected directly, then the station becomes a relay station. If two stations S_1, S_2 with a set of neighbors $\mathbf{N}^A(S_1), \mathbf{N}^A(S_2)$ respectively, and $\mathbf{N}^A(S_1) \subset \mathbf{N}^A(S_2)$ then S_1 is considered a simple station, otherwise S_1 becomes a relay station. In the case where $\mathbf{N}^A(S_1)$ is equal to $\mathbf{N}^A(S_2)$, we favor the station with the highest residual energy. After this, each selected station is assigned a set of devices that it manages. A device can connect to more than one station. This phase is repeated periodically over a fixed time interval, network changes can also be considered as a triggering factor, by monitoring the changes ratio of every local table, and if it exceeds a selected threshold value then a selection process will be triggered. Algorithm 3 shows the periodic selection process.

Algorithm 3 Station Selection

```
1: //State variable set to false if node U is selected. Otherwise, it is set to true.
2: covered  $\leftarrow$  false
3: //Iterate over discovered stations
4: for  $i = 0$  to  $N^s$  do
5:   //Station  $i$  covers all neighbors of station  $U$ 
6:   if  $N^d(U) \subset N^d(i)$  then
7:     //Current Station  $U$  is not Selected
8:      $covered^U \leftarrow true$ 
9:     Break
10:  else if Station  $U$  and Station  $i$  have the same neighbors then
11:    if  $Energy^U > Energy^i$  then
12:      Select Station  $U$ 
13:    else
14:       $covered^U \leftarrow true$ 
15:      Break
16:    end if
17:  end if
18:  If there is a combination of neighboring stations that can cover the current station's neighbors, then the current station becomes covered by these neighboring stations.
19:  for  $j = i$  to  $N^s$  do
20:    if  $N^d(U) \subset N^d(i) \cup N^d(j)$  then
21:       $covered^U \leftarrow true$ 
22:      Break
23:    else if  $N^d(U) = N^d(i) \cup N^d(j)$  and  $i^{energy} > U^{energy}$  and  $j^{energy} > U^{energy}$  then
24:       $covered^U \leftarrow true$ 
25:      Break
26:    else
27:      Select Station  $U$ 
28:    end if
29:  end for
30:  if  $covered^U = true$  then
31:    Break
32:  end if
33: end for
```

4.3. Broadcast

We assume that we have n stations and m services on the network. A station could be in three states: acting as a relay, not acting as a relay, and undecided. We define the relay state matrix $\mathbf{R} = r_{ij}$ for $i \in \{1, \dots, n\}$ and $j \in \{1, \dots, m\}$ where the state of each station i is as follows:

$$r_{ij} = -1 \text{ initial state or undecided} \quad (1)$$

$$r_{ij} = 0 \text{ if Station } i \text{ is not a relay for Service } j \quad (2)$$

$$r_{ij} = 1 \text{ if Station } i \text{ is Relay for Service } j \quad (3)$$

Note that our solution is distributed, where every station keeps a list of covered services and calculates its state for each service j . First, we neglect the type of service and proceed with the relay selection. The result is a set of relays for general traffic, where no service type is specified. Then, every relay station calculates its states in regard to the service i and removes all other services from its list of neighbors, and runs the selection algorithm again with the updated neighbors' list. If it is selected again as a relay, then $state\{i\} = 1$. The relay station must forward all traffic of service type i , otherwise, $state\{i\} = 0$ and the station ignores any packet of service type i . As shown in the example depicted in Figure 2, the relay station UE6 remains inactive if the request is for a heart monitoring service. Algorithm 3 shows the periodic selection process for general traffic, while Algorithm 4 shows the service-oriented relay selection process.

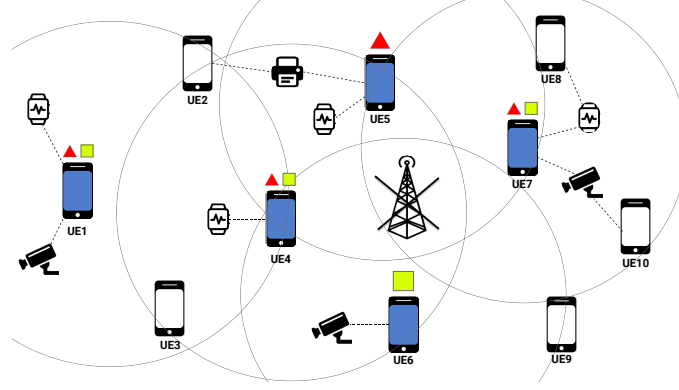


Figure 2: Sub-network identification for different types of services in a full out-of-coverage scenario

Algorithm 4 Service-Oriented Efficient D2D Broadcast

- 1: State[1..n] table of size n where \mathbf{State}^i is set to true if node U participates in routing traffic for service type i , false otherwise
 - 2: Iterate over types of services
 - 3: **for** $i = 0$ to n **do**
 - 4: $\mathbf{N}^D(u) \leftarrow$ list of neighbor devices of type i
 - 5: Remove all devices of type i from the list of neighbors $\mathbf{N}^A(u)$
 - 6: $\mathbf{N}^R(u) \leftarrow \mathbf{N}^A(u) \cap \mathbf{N}^D(u)$
 - 7: $\mathbf{State}[i] \leftarrow \text{CalculateState}(U, \mathbf{N}^R(u))$ ▷ Using Algorithm 3
 - 8: **end for**
-

4.4. Routing

When receiving a request/response message, a relay node starts by checking the service type embedded in it. If the relay node is allowed to forward traffic of this type of service $state\{i\} = 1$, then it broadcasts the message to its destination, else it drops the message. Algorithms 5 shows the procedure for routing requests and responses according to the type of service.

Algorithm 5 Request/Response Routing

- 1: *Receive(Msg)*
 - 2: Let \mathbf{S} be the Sender of Msg
 - 3: Let \mathbf{D} be the Destination of Msg
 - 4: Let \mathbf{t} be the Type of the Requested Service
 - 5: Let \mathbf{id} be the ID number of Msg
 - 6: **if** $\mathbf{id} \in \mathbf{SeenIds}()$ **then**
 - 7: *Drop(Msg)*
 - 8: **else if** $\mathbf{State}[\mathbf{t}] = \mathbf{true}$ **then**
 - 9: **if** $\mathbf{D} = \mathbf{U}$ **then**
 - 10: Create Response Message
 - 11: *Broadcast(Response)*
 - 12: **else if** $\mathbf{D} \in \mathbf{N}^d(U)$ **then**
 - 13: *Send(Msg)ToD* on the Proper Interface
 - 14: **else**
 - 15: *Multicast(Msg)* On LTE D2D Interface
 - 16: **end if**
 - 17: **end if**
-

5. Evaluation Methodology and Scenarios

In this section, we present an evaluation of the proposed solution through simulation in the discrete event Network Simulator NS-3[43]. We used version 3.22 of NS3 which we ran on a simulation station equipped

Table 2: Simulation Configuration

| Parameters | Values |
|--------------------------|--------------------------------------|
| Environment | |
| Number of UEs | 20,30,40,50 |
| Number of Devices | 20,30,40,50 |
| Area Size | 500m * 500m |
| Stations Mobility | random walk |
| IoT Device Mobility | stationary |
| Simulation Duration | 200s |
| Rounds per Scenario | 100 |
| LTE | |
| Number of Resource Pools | 1 |
| SideLink Bandwidth | 50 resource blocks |
| Resource Block Size | 4 |
| Carrier Frequency | 700 MHz |
| Discovery Period | 0.32 s (Default value for LTE ProSe) |
| PSCCH Length | 8 resource blocks |
| UE Transmission Power | 23.0 dBm |
| Propagation Loss Model | Cost-231-Hata |
| WiFi | |
| Phy | 802.11n |
| Rx Gain | 10 dB |
| Tx Gain | -1 dB |
| Propagation Loss Model | Cost-231-Hata |
| Mac | Ad-hoc WiFi Mac |

with an Intel Core i7-7700K processor and 16GB of RAM and operates on a 64bit Linux Ubuntu 20.04. We implemented our scenarios on top of the LTE D2D ProSe module provided by NIST [22].

Nodes were deployed in an area of 500m*500m randomly following a uniform distribution and divided into two groups, stations, and devices. Stations are mobile and have a variety of wireless interfaces, namely LTE, 802.11 (WiFi), and 802.15.4. Each station is equipped with an energy source of 10,000J. The rest of the nodes (IoT devices) are stationary and randomly deployed across the simulation area. IoT devices only support 6LoWPAN over 802.15.4 and operate on a small-size energy source of 100J. We use the COST 231 Hata [44] propagation model across all our simulation scenarios, which is considered one of the best-suited models for wireless communications in a disaster situation [45, 46, 47].

In our simulation, only stations perform the selection process. Data traffic consists of request/response packets and follows a Poisson process. We run extensive simulations considering different network sizes. Table 2 summarizes the simulation configuration.

5.1. Methods Considered

To evaluate the energy efficiency achieved by the Service-oriented Energy Efficient D2D Emergency Network (**SEEDEN**), we test our work against the following approaches:

- (i) **aN Energy-awarE D2D communication scheme (NEED) [7]**: is based on clustering. We choose this work to compare with as a representative of most clustering techniques used for emergency networks.
- (ii) **NEED-ProSe**: This work is our re-implementation of the NEED protocol [7] described above using LTE ProSe instead of WiFi. It is worth mentioning that this task was not trivial, as it required changing the synchronization and message broadcast timing to suit the periodic messages transmission of LTE ProSe.

- (iii) **ProSe-based File Distribution (PFD) [21]:** This work focuses on minimizing the ProSe cost of file sharing in an emergency situation. Their solution is based on Connected Dominating Sets for minimizing the number of relay nodes.
- (iv) **TeamPhone [25]:** an emergency network for disaster situations based on WiFi direct using victims' smartphones.

5.2. Metrics Considered

To evaluate the performance of our proposal compared to the methods described above, we performed extensive simulations. Each scenario was repeated 100 times, with the simulation duration set to 200s. We considered the three following configurations :

- (i) **Varying Network Size:** In the first set of simulations, we vary the number of stations as well as the number of devices, to assess the effect of network size on energy efficiency with the considered approaches. Since our technique is service-oriented, we vary the number of IoT devices from 50 to 200. The objective here is to test the effect of network size on energy consumption.
- (ii) **Varying Network Traffic:** The type of traffic that needs to be routed throughout the network is important. We changed the destination of service requests from (station and devices) to devices only. In this configuration, we assume that users are only interested in reaching IoT devices and their services. We also changed the number of service types in the network.
- (iii) **Varying Mobility Speed:** The network topology has a significant effect on the performance of the solutions. To measure this, we tested the proposed technique in various mobility speed configurations from low mobility 1 m/s to high mobility 10 m/s.

6. Simulation Results

We simulated five algorithms, we refer to them as PFD, TeamPhone, NEED, NEED_Prose, and SEEDEN. Note that we had to modify TeamPhone and NEED to make them work with LTE ProSe. We measured the performance of previously mentioned algorithms according to the following metrics:

6.1. Delivery Ratio

The main goal in an emergency situation is to send critical messages to their destination to ask for or provide help. Any proposed algorithm must guarantee a high packet delivery ratio. Figure 3 shows that our adaptation of the NEED protocol achieves the highest delivery ratio compared to all other algorithms, and also shows that it scales well with the size of the network. However, the original NEED protocol running on WiFi shows the lowest packet delivery ratio, slightly over-performed by our proposed algorithm SEEDEN running on WiFi. This shows that WiFi downgrades the performance of the algorithms tested. The performance of SEEDEN over ProSe shows a high delivery ratio, not as high as the NEED over ProSe, but nearly 70% of packets are delivered successfully.

6.2. Energy Consumption

Delivering packets is not the only important thing. In fact, the energy consumed by the nodes while delivering packets is also important, as it affects the performance of the entire network. A power-hungry algorithm results in a rapid depletion of the precious battery of the nodes. In Figure 4, we show that our adaptation of the NEED protocol is a power-hungry algorithm. Despite the fact that the NEED algorithm uses unicast transmissions and a hierarchical architecture known for minimal energy consumption, when using ProSE, the transmission becomes multicast, using the L2 group address. This makes it clear why WiFi-based solutions consume less energy than ProSe-based ones. The energy saving techniques provided by PFD were indeed effective, compared to the adaptation of NEED to ProSe, where it shows a better performance, but Figure 4 shows that SEEDEN consumes less than PFD and is almost comparable to WiFi-based techniques. This proves that constructing for each type of service a subnetwork responsible for delivering packets related to this service is effective in reducing energy consumption by putting irrelevant nodes (to the service being requested or delivered) to rest.

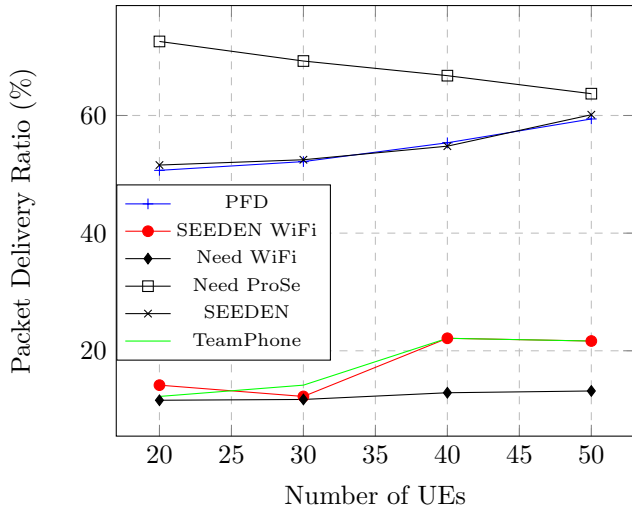


Figure 3: Packet delivery ratio in function of network size

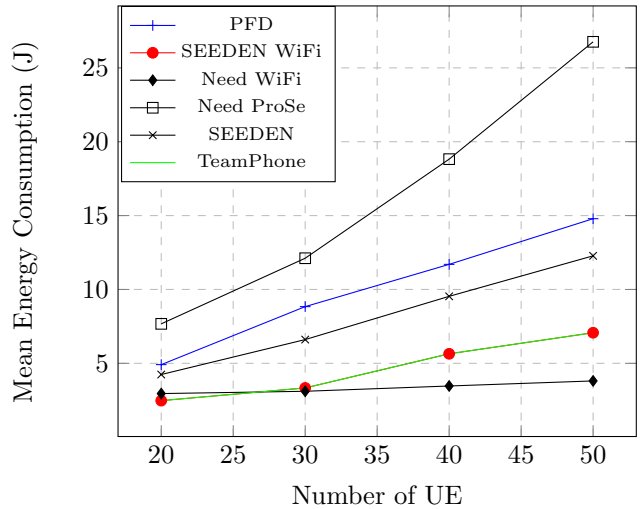


Figure 4: Mean energy consumption in function of network size

6.3. Energy Efficiency

The results of the two previous graphs are not decisive, because if we favor the packet delivery ratio, then the NEED_ProSe adaption is the better choice, but if we choose energy consumption, then the clear choice is SEEDEN. The question here is: which is better and more efficient? To decide on this, we define energy efficiency as the packet delivery ratio per consumed energy and then compare the obtained results. Figure 5 shows the energy efficiency of each algorithm, and as expected WiFi-based algorithms are not that efficient due to their low delivery ratio. It also shows that the proposed SEEDEN is the best long-term solution. This is shown in Figure 10 as well, where we tested our proposed solution with different types of services from a few types to many. Clearly, one of the biggest advantages of our proposed solution is that it scales well with the number of services in the network, and it is clear that the performance of SEEDEN improves when the number of services increases, which is not the case for PFD and the other remaining algorithms.

6.4. Network Lifetime

To better assess the effect of each algorithm on the performance of the entire network, we measured the lifetime of the network, where we set the residual energy of the smartphones at 20J and run the simulation until 20% of the nodes are dead. The network lifetime gives a good indicator of network efficiency in terms of energy consumption and load balancing, meaning that the more the network load is balanced, the longer the network remains active, and vice versa. Figure 7 shows the significant advantage of short-range WiFi-based solutions over others in term of low energy consumption, which confirms the results seen in Figure 4. Nonetheless, the performance of SEEDEN is clearly better than the remaining solutions. This shows the effectiveness of service oriented multi-path routing in reducing the energy cost of LTE ProSe compared to cluster-based routing .

6.5. Load Balancing

We use this metric to test the fairness of all algorithms, defined as the amount of load attributed to each node in the network. We measured it by the amount of energy consumed by each node, then we calculated the standard deviation of these values. Figure 6 shows that NEED_ProSe does not provide good results for load balancing metric, meaning that the performance of the entire network relies on a set of nodes well connected and near the sink node. These nodes do most of the packet forwarding, which results in their batteries depleting faster than the other nodes, which remain inactive most of the time. In contrast, SEEDEN achieves better load balancing, distributing the load across all nodes.

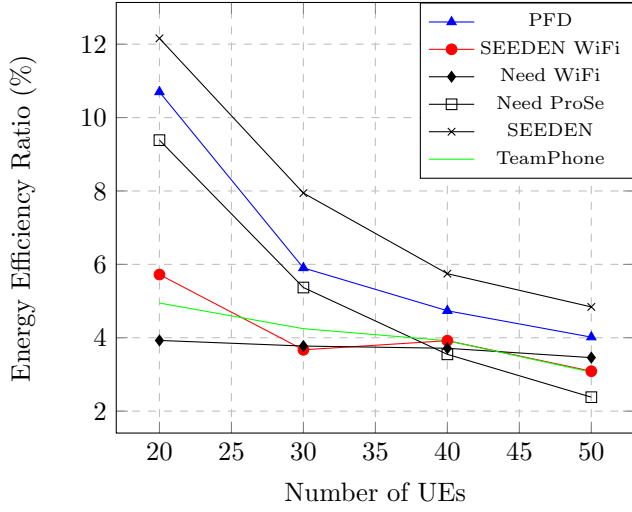


Figure 5: Energy efficiency in function of network size

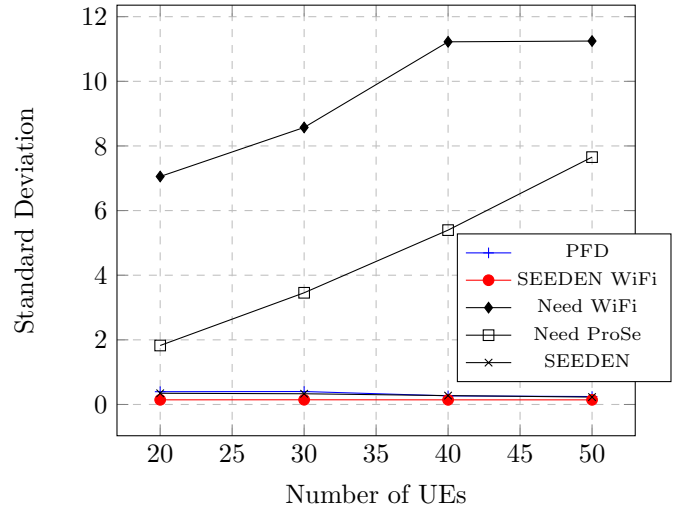


Figure 6: Energy consumption and load balancing

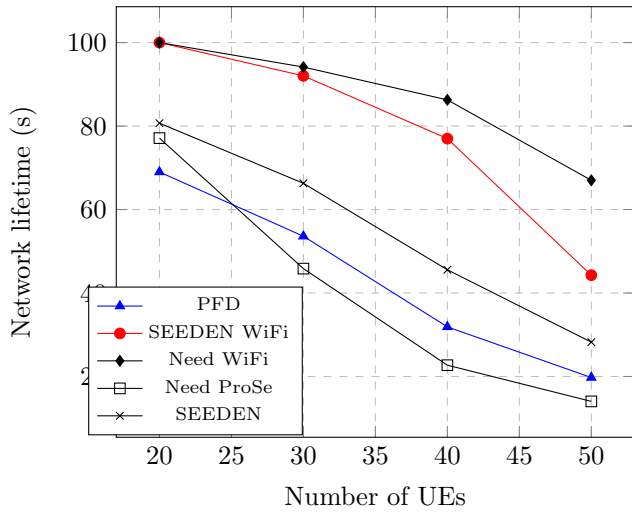


Figure 7: Network Lifetime (until 80% of nodes die)

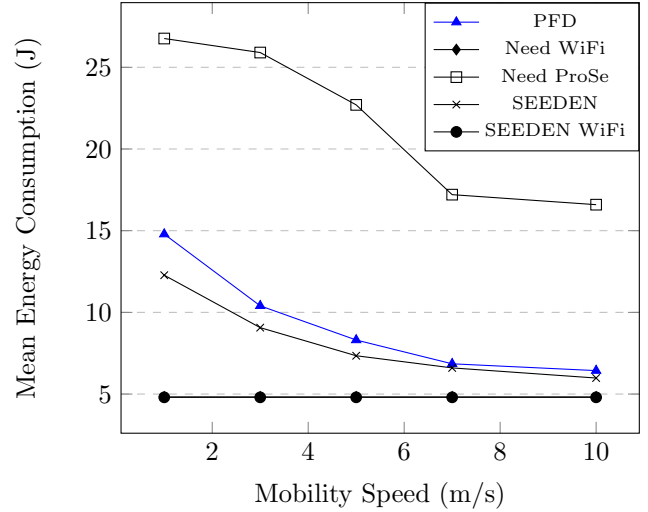


Figure 8: Energy consumption in a dynamic network

6.6. Mobility

In the case of a disaster, people move constantly, either looking for help or looking to help others, except for trapped victims who remain stationary. This means that any emergency network must handle the challenges that come with mobility. To reflect this situation, we varied the mobility speed of the nodes to simulate the behavior of the network in low- and high-mobility modes. As can be seen in Figure 8, the higher the mobility the lesser the energy consumption for PFD, NEED_ProSe, and NEED. However, in Figure 9 we notice a slight decrease in the performance of all simulated solutions in terms of the packet delivery ratio, especially in high mobility cases.

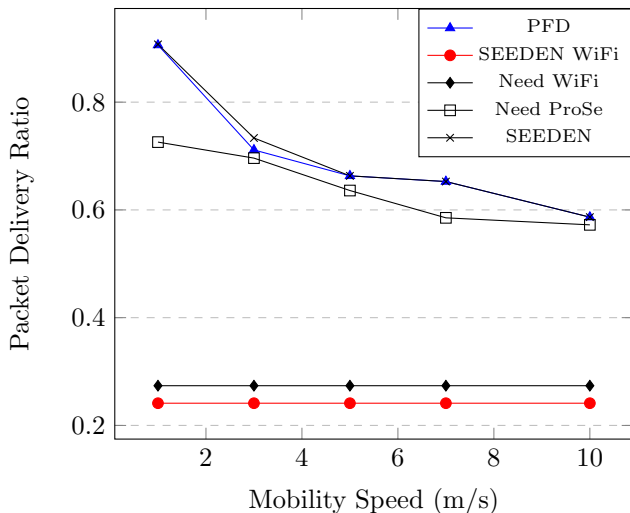


Figure 9: Packet delivery ratio in a dynamic network

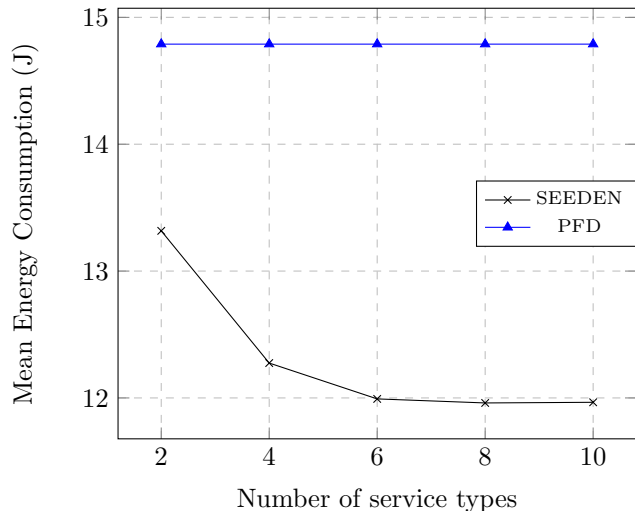


Figure 10: Consumed energy in function of the number of service types

7. Conclusion

Communication and quick access to accurate information pertaining to a disaster area are vital for the organization and success of rescue operations. In most cases, this requires the establishment of a replacement emergency communications system, as the main one would be severely damaged or completely out of order.

In this paper, we have presented how to establish and maintain such a system that we designed and implemented with the new and promising LTE ProSe technology, and optimized for various types of IoT services. Specifically, our system uses LTE ProSe to build a communication backbone, offering reliable message delivery, and a multipath routing technique, to optimize QoS for each IoT service available on the network. Implementation is a key feature in this paper, where we relied on realistic models, especially the LTE ProSe model offered by NIST, to implement both our solution and top state-of-the-art solutions. Our results showed that, unlike the cluster-based approaches, our method equally distributes the load between all nodes. As a consequence, the lifetime of the network is significantly extended. Further experiments also demonstrated that our approach has the lowest energy consumption of all ProSe-based solutions while still ensuring a packet delivery ratio close to 70%, thus achieving the highest energy efficiency when compared to other approaches. These advantages lead to a more efficient emergency communication network that can be deployed over wide areas. Translating the work presented in this paper into a deployable prototype can help public safety workers overcome the two major problems they face during a disaster situation: the absence of a communication system and the lack of relevant and up-to-date information on affected areas. With the availability of smart-phones equipped with ProSe D2D [48, 49], one of the most straightforward extensions of this work would be to consider the implementation and the evaluation approach under more realistic conditions. A more general extension requires the conduction of more research on how mobility affects the

performance of the emergency communication network, particularly in cases of high mobility. Additionally, due to the various standards, resource limitations, and communication stacks involved, it is often impossible to simply apply basic security standards to IoT technology. Therefore, when integrating heterogeneous IoT devices, more attention should be paid to security requirements, including authentication, integrity and confidentiality.

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