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Design and performance evaluation of a LoRa-based mobile emergency management system (LOCATE)

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A R T I C L E I N F O

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A B S T R A C T

Smartphone devices can play a key role on emergency scenarios thanks to their pervasiveness, and the possibility to convey emergency requests from the involved people to the rescue teams. At the same time, the effective utilization of such devices on critical scenarios with limited mobile Internet access is challenging. As an alternative, several recent research studies have proposed Emergency Communication System (ECS) based on short-range Device-to-Device (D2D) solutions available on Commercial Off The Shelf (COTS) devices (e.g. Wi-Fi Direct); however, the target of these solutions is constituted by small indoor areas, since the scalability on large-scale environments is often a problem. In this paper, we overcome such issue by proposing LOCATE, a novel phone-based ECS enabling long-range communication among survivors and rescue teams over critical environments where 3/4G cellular connectivity is not available and the traditional geo-localization technologies (e.g. the GPS) provide only partial coverage of the environment. The proposed system consists of a mobile application connected to a LoRa transceiver via Bluetooth Low Energy (BLE); through the app, users can send emergency requests that are re-broadcasted by other peers until reaching a rescue personnel who is able to handle the emergency. Three novel contributions are provided in this paper. First, we provide extensive measurements of the LoRa technology, and investigate its suitability for ECS-related applications. Second, we describe the LOCATE prototype and the enabling algorithms; specifically, we propose a novel multi-hop dissemination algorithm which maximizes the probability to deliver an emergency request to the destination (e.g. rescue personnel) within a user-defined temporal threshold, while minimizing the number of message re-transmissions. Third, we extensively evaluate the LOCATE performance through OMNeT++ simulations, assessing the capability of the dissemination protocol to spread out the emergency requests over large-scale scenarios, and through experiments, assessing the capability of LoRa-based trilateration technique to provide accurate GPS-free localization. The results demonstrate that the LOCATE protocol is able to minimize the time required to handle the emergency when compared to other dissemination strategies (e.g. flooding, continuous, once-per-contact), and they highlight the considerable improvement provided by the LoRa technology over other D2D solutions available on COTS smartphones (e.g. Wi-Fi Direct).

1. Introduction

Among the countless enabling technologies of the Internet of Things (IoT), Low-Power Wide Area Networks (LP-WANs) are gaining significant interest thanks to their potential to deploy large-scale monitoring systems with limited installation costs and high energy efficiency [1,2]. The LoRa and LoRaWAN technologies can be considered one of the most popular LP-WANs solutions available on the market; more in details, LoRa defines the proprietary PHY wireless layer, while LoRaWAN is an open standard released by the LoRa Alliance and specifying the MAC layer operations and the network architecture [3]. At present, the LoRa Alliance includes more than 500 companies and deployments on more than 100 countries [3], while the number of use-cases is constantly growing, and ranges from precision agriculture [4–6] to city monitoring and industrial automation [7,8], just to name a few. Most of those deployments are based on the legacy LoRaWAN star topology, i.e. edge sensing LoRa devices transferring data toward an Application Server (e.g. a cloud service) via intermediate gateways. Complementary to the LoRaWAN network architecture, several recent studies are investigating the deployment of mesh topologies where the communication among LoRa transceivers occurs in a device-to-device (D2D) mode without intermediate gateways, and the data can be disseminated over multi-hop links thanks to LoRa-specific routing algorithms [9,10]; most of these solutions is based on the

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findings that synchronized collision problem on LoRa links is alleviated by the time- and frequency- domain energy spreading effect described in [10–12]. D2D LoRa links might complement/extend the coverage of a LoRaWAN deployment, e.g. allowing to connect distant nodes in a viable and cost-effective way; moreover, they might enable long-range communications on critic scenarios characterized by the absence or by the temporal unavailability of the LoRaWAN infrastructure.

To this purpose, the list of communication blackouts occurred worldwide during emergency events caused, e.g. by natural disasters or criminal activities, is quite long and has fueled the research on infrastructure-less Emergency Communication Systems (ECSs) [13,14]. Since 2000s, several studies have investigated the utilization of multi-hop Mobile Ad Hoc Networks (MANETs) in order to provide spontaneous connectivity on critical scenarios like the post-disaster ones, although the number of real-world deployments is limited [15]. More recently, the diffusion of end-user mobile devices, like smartphones and tablets, has paved the way toward next-generation ECS able to leverage the pervasiveness of such devices, and the availability of context-information about the emergency and the user [16], provided by the embedded sensors (e.g. GPS, accelerometer). Regarding the network connectivity, it is worth remarking that most of Commercial Off-The-Shelf (COTS) smartphones do not enable the creation of MANETs for security reasons; however, they are equipped with Device to Device (D2D) communication technologies, like the Bluetooh Low Energy (BLE) [17] or the Wi-Fi Direct [18], enabling data exchange with other peers in the 1-hop neighborhood. Emergency-related mobile applications supporting opportunistic dissemination of alert messages on the 2.4 GHz ISM band have been proposed, among others, in [19–21]; similarly, routing schemes for multi-hop D2D phone-networks are described in [16,22,23]. At the same time, the target of these studies is often constituted by indoor scenarios where the distance among the users is assumed short (i.e. in the order of tens of meters), due to the poor wireless range of the technologies mentioned above, and the number of hops limited, due to the complexity of implementing inter-group data exchange, as we also reported in [24]. On the opposite, D2D solutions on cellular bands allow addressing the coverage problem, however they still require the support of the base stations for the device discovery and resource allocation [25]; hence, they are not suitable for ECS on infrastructure-less scenarios.

In order to overcome such limitations, we describe in this paper how to deploy next-generation phone-based ECS by using the LoRA technology for long-range, multi-hop communication among people involved in the emergency (and requesting any kind of help) and rescue teams. To this purpose, we describe LOCATE, a wearable IoT system composed of a LoRa transceiver and an Android application, communicating through a BLE connection (the prototype is depicted in Fig. 10(b)). The LOCATE system enables opportunistic, multi-hop dissemination of alert messages over generic emergency scenarios where traditional infrastructures (e.g. 3/4G networks) are not physically available, like in rural areas, or temporally unavailable, like in post-disaster scenarios. Thanks to the exceptional propagation condition of the LoRa PHY layer, LOCATE users can exchange minimal, yet vital information like their current position and the type of help needed with other peers in a range of hundreds of meters; moreover, a novel anycast protocol - implemented by the LOCATE mobile app- allows the effective dissemination of the emergency messages over the scenario, by taking into account the sporadic connectivity among the users, their current position, the mobility effect, and some key performance metrics, like the time for the emergency resolution, the network overhead, and the impact on the device lifetime. Moreover, a LoRa-based trilateration algorithm is included within the LOCATE application, in order to allow the users' geolocalization even when moving over areas with poor GPS coverage. More in details, we propose four main contributions in this study:

- We characterize the suitability of LoRa technology with respect to the ECS requirements, by performing extensive measurements on two different scenarios, i.e. an *Urban* environment and a *Wood* area. On both cases, we derive analytical models of the LoRa link for ground-to-ground (GtG) communication, which represents the default scenario for the operations of the LOCATE platform. We remark that most of the existing LoRa measurements proposed in the literature (e.g. [26–28]) focuses on deployments where high-gain LoRa antennas are placed on rooftops (i.e. Air-to-Ground propagation conditions), or they are in Line of Sights (LoS). Although our experimental results indicate a much lower transmission range compared to these studies, they still demonstrate the possibility to disseminate emergency messages with minimal -but still adequate- payload, with a considerable performance gain compared to other D2D technologies available on today's smartphones.
- Based on such results, we devise the LOCATE platform, through which the user can broadcast geo-tagged help requests on the LoRa link: the message is disseminated by other LOCATE users until reaching a rescue personnel, denoted as the emergency solver. A wearable LOCATE prototype has been developed, including the mobile application and the IoT device, composed of LoRa and BLE modules, and powered via battery and a solar panel.
- We propose a novel data dissemination scheme for the LOCATE messages, which includes biased contention-based mechanisms (e.g. [29]) and probabilistic store-and-forward mechanisms derived from Delay Tolerant Networks (DTNs) [30]. An analytical framework is proposed for the optimal tuning of the DTN phase: more specifically, we derive the optimal transmission probability that guarantees that the emergency is completely solved within a user-define temporal threshold[1], while the network overhead - computed as the number of message re-transmissions- is minimized.
- We investigate the performance of the proposed LOCATE system through a twofold evaluation. The performance of the dissemination scheme over large-scale emergency scenarios is tested via OMNeT++ simulations. The simulation results demonstrate that the proposed scheme is able to guarantee the best trade-off between emergency resolution time and network overhead when compared with other multi-hop message dissemination schemes, or with the legacy Wi-Fi technology. Moreover, the energy consumption of the IoT device and the localization accuracy of the LoRa-based trilateration algorithm are tested through test-beds and experimental results.

A preliminary version of LOCATE has been presented in [31]. Here, we significantly extend the research work, including novel algorithms for the message dissemination and position estimation, novel measurements and performance results, and a completely revisited presentation. The rest of the paper is structured as follows. Section 2 reviews the state of art on LoRA research and on phone-based ECS. Section 3 provides experimental results for a LOCATE single-hop test-bed, and characterizes the utilization of LoRa technology for ECS applications. Section 4 describes the network architecture and the main operations performed by the LOCATE framework. The enabling data dissemination and localization algorithms are presented in Section 5. The LOCATE implementation (prototype device and mobile app) is described in Section 6. The evalu-

[1] As better explained later in the paper, we consider an emergency to be solved when an emergency request generated by user A has reached a rescue personnel, and the corresponding acknowledgment has been delivered back to the user A.

ation through simulations and experimental results is presented in Sections 7 and 8, respectively. Conclusions follow in Section 9.

2. Related work

At the best of our knowledge, no LoRa-based ECS has been proposed so far in the literature. However, several recent studies investigated the performance of LoRA technology over wide area deployments; we review them in Section 2.1. Similarly, in Section 2.2, we focus on the existing approaches and technologies for the implementation of phone-based ECS. The novelties provided by the LOCATE system compared to the literature are discussed in Section 2.3.

2.1. Literature on lora systems

Existing LoRa-related studies can be grouped into three main categories: (*i*) experimental test-beds, characterizing the performance of LoRa links and LoRaWAN networks; (*ii*) novel applications of LP-WAN technologies on the IoT domains, and (*iii*) enhancements to the LoRaWAN network architecture. The first group includes experimental measurements aimed to evaluate the LoRa technology with respect to link and system performance, like the communication range, the network scalability and the energy consumption: for instance, the authors of Petäjäjärvi and Mikhaylov [26] performed an extensive evaluation of LoRa links, and observed a maximum communication range of more than 15 Km on both ground and water scenarios. The scalability of LoRaWAN in dense scenarios has been investigated by means of theoretical framework and simulation studies respectively in [32] and [33]; in particular, this latter work demonstrates that the goal of connecting hundreds of devices to the same gateway -while still guaranteeing a high packet success rate- is feasible. A comprehensive analysis on how the packet loss of LoRa links is affected by operative conditions like the transmit power, the payload length and the antenna orientation has been provided in [27], while an empirical path loss model derived from signal measurements in the 433 MHz and 868 MHz ISM bands has been discussed in [34]. The trade-off between energy consumption and achievable data rate for different configurations of the LoRa transmitting profile has been investigated, among others, in [35]. Performance of LoRA links and of LoRaWAN networks are evaluated in [28] via simulations and experimental measurements: the results show that the transmission range of LoRa devices can be up to 10 Km under perfect Line of Sight (LoS) conditions, although the network capacity can be severely affected by the Spreading Factor (SF) in use (lower SF values translate into longer transmission times, and hence into a lower network capacity). For this reason, the authors of Feltrin et al. [28] indicate the utilization of multiple gateways as the preferable solution for the coverage of large urban areas.

Regarding the LoRa applications, these are clearly focused on outdoor large-scale environments, where the requirements of the monitoring system fit the characteristics of the wireless technology, i.e. long range-communication but with reduced throughput and potentially high communication delay. Smart agriculture constitutes one of the reference use-cases: experimentation involving LoRa sensors for smart irrigation and soil moisture measurements are described respectively in [4] and [5] and are also the goal of several international research projects (e.g. the H2020 SWAMP project [6]). In [27], the authors describe the implementation of an air-quality monitoring system that is composed of LoRa sensors operating at the rooftop of a campus building. A similar LoRa-based monitoring system is described in [7,8]: here, the sensor node is designed to be wearable, and self-powered through a solar energy harvester.

Among the several enhancements proposed in the literature to the LoRaWAN architecture, we focus on the studies investigating how to support multi-hop communication among LoRa devices without LoRaWAN gateways. This solution might reduce the network installation cost on dense urban areas, and also extend the network coverage in rural scenarios where gateways cannot be easily deployed. The feasibility of LoRa multi-hop networks has been demonstrated, among others, by Lee and Ke [10], Zhu et al. [11] and Liao et al. [12]. More specifically, the authors of Zhu et al. [11] show that LoRa transceivers can cope with the interference originated from time-synchronized packets transmitted by multiple transmitters using the same SF. In addition, the authors of Liao et al. [12] show that a timing offset is a simple yet effective solution to mitigate the self-interference problem before each packet re-transmission on multi-hop topologies. In [10], the authors describe the design and implementation of a mesh, multi-hop LoRa network; interestingly, the performance analysis shows considerable improvements compared to the legacy LoRaWAN star topology in terms of achievable throughput. Data dissemination and routing protocols for multi-hop LoRa networks are investigated, among others, in [9,36] and [37]. Due to the short packet length in LoRa, MANET routing protocols must be properly adapted to the LoRa stack; this is implemented in [9] for the case of the HWMP and AODV protocols, while [36] proposes to use RPL routing protocol with a path selection metric based on end-to-end time-on-air estimations. Finally, the authors of Ayele et al. [37] present a LoRa-based data dissemination scheme for wildlife area monitoring; the proposed solution involves the utilization of LoRa/BLE sensors deployed as collars on the animals to be monitored. Given the sporadicity of peer-to-peer communication among the sensor nodes, and their intrinsic mobility, a simple DTN store-and-forward mechanism is proposed, which takes into account the inter-contact time among devices and a cost function for the data replication.

2.2. Literature on phone-based ECS

Phone-based networks pose unique challenges compared to traditional MANETs, including the need to cope with the users' mobility, and the impossibility to use the Wi-Fi radio in ad-hoc mode, which is often disabled on most of COTS devices. Regarding the second issue, while waiting for the large-scale introduction of D2D cellular systems [38], several recent studies investigated solutions to support dissemination of emergency data over short-range, D2D links. In [14], the authors identify five major items of multi-hop D2D communication, and describe a field experiment over the area experienced by the Japan's heartquake of 2011. Performance and protocol extensions of Wi-Fi Direct in multi-group scenarios are described in [16,22,23]. In particular, the authors of Casetti et al. [23] propose a distributed algorithm aimed to build a connected graph over a phone-network, by properly setting the role of each device as client, relay or Group Owner (GO). In [16], the authors propose SENSE-ME, a phone-based infrastructure-less ECS providing multi-hop connectivity (via Wi-Fi Direct), sensing data sharing (via information centric networking), and distributed data processing for emergency detection (via consensus algorithms). As an alternative to Wi-Fi Direct, the authors of Franke et al. [39] propose a loosely synchronization mechanism, through which mobile phones alternate between client and hotspot mode, and are hence able to transfer data without any external access point; a similar mechanism is described in [40], by taking into account the mobility factor of each device in the switching strategy. In [41], an advertisement mechanism for post-disaster scenarios is proposed; the system consists of BLE beacons worn by users, and smartphones gathering the advertisements and uploading them to an emergency management headquarter. To overcome the range problem of BLE and Wi-Fi systems in outdoor emergency scenarios, the authors of

Chen et al. [42] propose to integrate FM radio transmitters into a smartphone, and deploy a novel app to broadcast emergency messages that are coded through the popular Morse scheme.

Beside the communication technology, another key issue of phone-based network is the strategy used to disseminate data among devices when considering the intermittent connectivity and the likely presence of network partitions. For this reason, MANET reactive routing protocols are often preferred over proactive ones, and enhanced with DTN mechanisms like carry-and-forward and mobility-aware epidemic data exchange [43,44]. In [45], and AODV-like protocol is proposed to support the dissemination of vital sensor data from patients to paramedics in the neighborhood. In [19,20], an integrated platform for smartphone connectivity in disaster recovery is described; the proposed system, called TeamPhone, supports both the creation of energy-efficient spontaneous groups among survivors, and a multi-hop messaging system between survivors and rescue teams, integrating AODV and opportunistic routing mechanisms. Interesting variations of alert dissemination strategies are proposed in [21] and [46]. In particular, the authors of Koumidis et al. [46] propose greedy dissemination strategies that take into account the neighbourhood density and the residual battery level of each smartphone. In [21], each emergency message is forwarded to the best matching neighbour, according to a classification system which takes into account the content of the request as well as the profile of each user (i.e., the kind of help s/he can provide).

2.3. Novelties of LOCATE platform

Our solution starts from the findings in [10,11] and [12] regarding the LoRa multi-hop mechanisms, however designing a different solution that combines timing offsets and Delay Tolerant Networking (DTN)-based mechanisms in order to maximize the data delivery over emergency scenarios. Vice versa, with respect to generic MANET-based ECS, the LOCATE platform introduces the following elements of novelties: (*i*) it is composed of smartphone devices transmitting over LoRa links, by means of the equipment shown in Fig. 10(b); (*ii*) it supports opportunistic message dissemination without any additional overhead for the topology control and the network setup; (*iii*) it exploits the advantages of LoRa (i.e. long-range and reduced energy consumption), while adapting the system design to the technology constraints discussed in Section 3 (e.g. supporting broadcast communication with very short messages containing only minimal information).

3. Motivations

In this Section, we provide a preliminary experimental evaluation of D2D LoRa communication scenarios. As widely discussed in the previous Section, several recent studies have provided extensive evaluation of LoRA links and LoRaWAN systems. Differently from them, our evaluation focuses on different goals, i.e.: (*i*) to derive proper statistical models and threshold values, which are used to tune the simulation model presented in Section 7; (*ii*) to understand the feasibility of LoRa technology for emergency-related applications, running on COTS mobile devices and executed on uncontrolled environments with Ground-to-Ground (GtG) links. To this aim, we consider an Adafruit Feather M0 RFM96 LoRa Radio (433MHz), connected to an Android smartphone via a BLE connection (the characteristics of the prototype are described later in this document on Section 6). We deployed a novel Android application for testing purposes, which allows to: (*i*) tune the parameters of the LoRa transceiver, i.e. the Spreading Factor (*SF*), Bandwidth (*BW*), Transmit Power (*TP*), Coding Rate (*CR*), Packet Size (*PS*); (*ii*) inject network traffic according to a Constant Bit Rate (CBR) application model; (*iii*) compute network statistics for each experiment, like the mean delay, the mean Received Signal Strength (RSS), the throughput and the Packet Delivery Ratio (PDR); (*iv*) display the results on a map, including the GPS data. We ran multiple experiments for single-hop D2D GtG communication, considering two different environments: (*i*) an *Urban scenario*, located in the downtown area of Bologna, close to the Department of Computer Science and Engineering of our university; (*ii*) a *Wood scenario*, located in a wooden area outside Bologna. In all the experiments, we consider a mobile user -transmitting data while walking within the scenario- and a fixed user -receiving data and sending the acknowledgment packets. Fig. 1(a) and (b) shows the scenario map for a specific test, as displayed by the mobile application. The blue marker denotes the position of the LoRa receiver, while the other colors denotes the quality of the Packet Delivery Ratio (PDR), from high (green markers) to poor (red markers). Every λ seconds, the source device transmits a message, and waits to receive the corresponding application ACK.

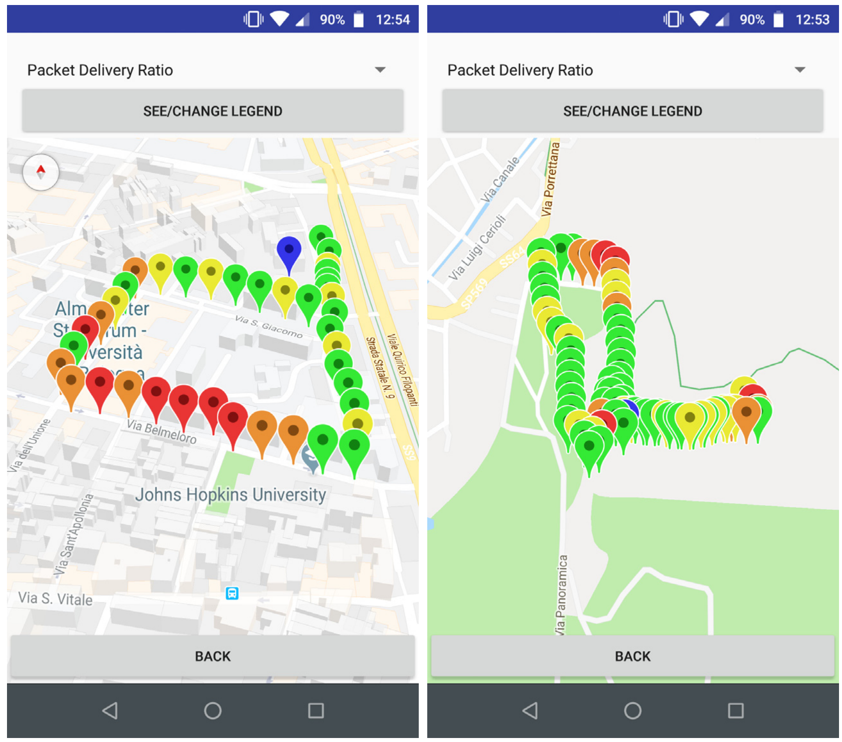
Figs. 2(a), (b) and 3(a) show the measured performance metrics for the *Urban scenario*. More in details, Fig. 2 depicts the PDR over distance, when considering the following configuration: $SF = 128$ c/s, $BW = 125$ KHz, $CR = 4/5$, $\lambda = 3$ s, and varying the *TP*. Using such configuration, the maximum achievable range is around 500 m, which is a quite lower value compared to the results in the literature, e.g. those presented in [26,28]. However, we should consider that: (*i*) tests have been performed by using low-cost, small antennas (+5dbi) as the one used in mobile emergency scenarios; (*ii*) all the configurations refer to GtG communication links, while most of the previously cited works considers LoRa deployments where the transmitters are located on rooftops, or in Line of Sights (LoS). We demonstrate the remarkable impact of the altitude from ground of the devices later in this Section. In any case, it is easy to notice that the LoRa range is considerably larger than other D2D communication technologies used for ECS applications (e.g. the Wi-Fi Direct [16]). In Fig. 2(b), we depict the PDR for different values of the *SF, BW* and *CR* parameters ($TP = 10$ db); as expected, the transmission range increases when using larger values of the *SF* (i.e. 4096). Fig. 3(a) shows the mean delay, for the same configuration of Fig. 2 and different values of *PS*: we can notice that the delay increases considerably with *PS*, and it exceeds 1 s for $PS > 40$ bytes.

Fig. 4(a) depicts the PDR for the *Wood* scenario; we considered the two configurations of the LoRA devices associated respectively to the maximum range (Fig. 2(b)) and minimum delay (Fig. 3(a)) in the *Urban* scenario, and two values of *TP* (10 dBm and 20 dBm). Despite a slight performance increase compared to the results in the *Urban* scenario, the dense presence of foliage and trees significantly contributes to attenuate the LoRa signal, quite similarly with the shadowing effect determined by urban buildings. This is made evident in Fig. 3(b), which depicts the experimental Path Loss (PL) over the link distance: two set of points are depicted for the two scenarios described so far. The regression line follows the *log-normal shadowing path-loss* Equation:

$$PL(d)[dB] = PL(d_0)[dB] + 10 \cdot a \cdot \log_{10}\left(\frac{d}{d_0}\right) + \chi_\sigma \tag{1}$$

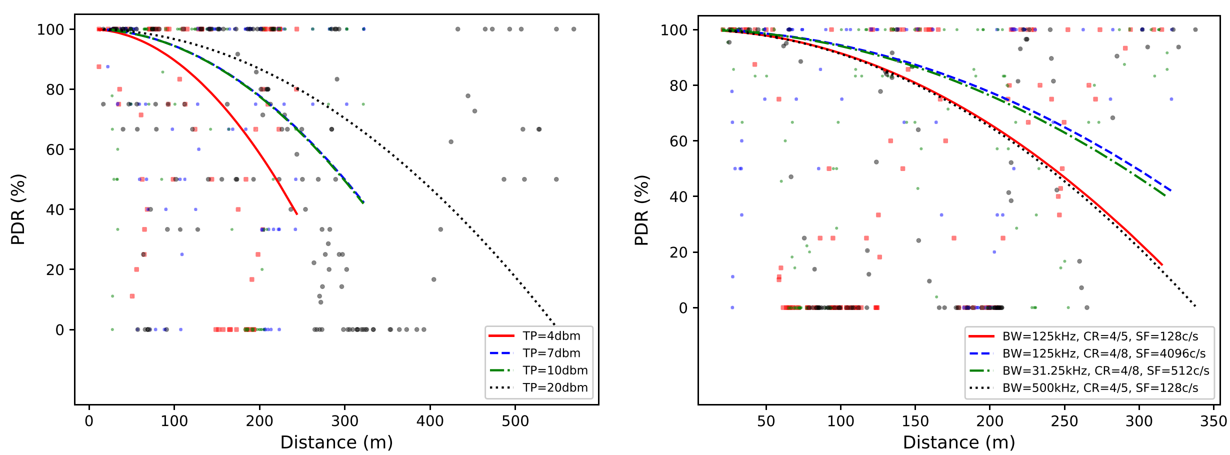
where a is the path-loss exponent that indicates the rate at which the path-loss increases with the distance d, $d_0 = 10$ m is the reference distance, $PL(d_0) = 56$ dB is the path loss at the reference distance d_0 measured experimentally and χ_σ is a Gaussian random variable with zero mean and standard deviation σ. The points depicted in Fig. 3(b) are the path-loss values calculated experimentally. In this case we executed $N_{\exp}$ transmission tests and computed the actual path-loss $PL_{\exp_i}$ for the *i*th experiment through the following Equation:

$$PL_{\exp_i}[dB] = \mathrm{TP}[dBm] + G_{Tx}[dBi] + G_{Rx}[dBi] - RSS_i[dBm] \tag{2}$$



(a) (b)

Fig. 1. The maps of the experiments for the *Urban* and *Wood* scenarios are depicted in Fig. 1(a) and (b), respectively. The blue marker denotes the position of the LoRa receiver, while the other color denotes the quality of the Packet Delivery Ratio (PDR), from high (green markers) to poor (red markers). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

Fig. 2. *Urban scenario*. The PDR as a function of the transmission power and for different LoRa configurations are depicted in Fig. 2(a) and (b), respectively.

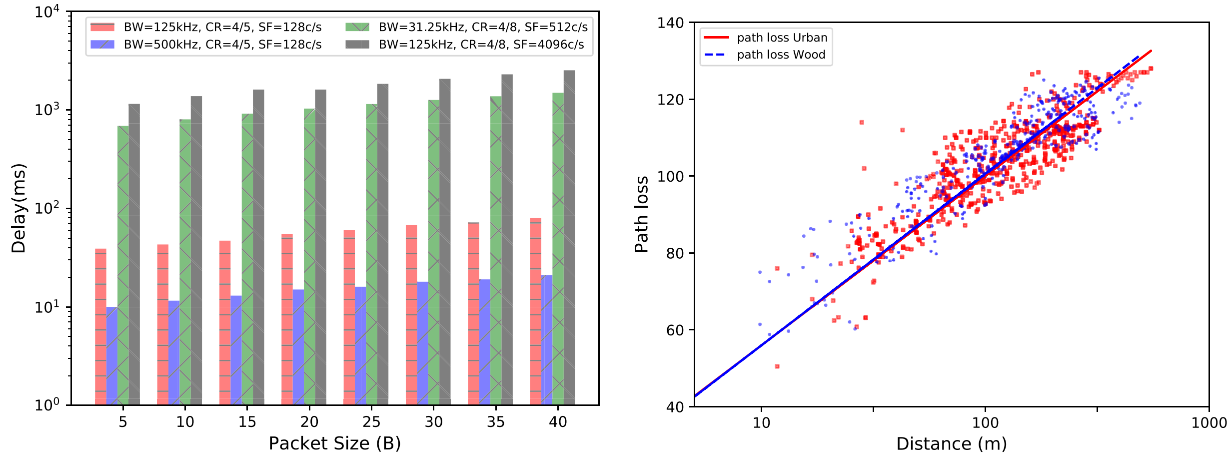
where $G_{Tx}[dBi] = G_{Rx}[dBi] = 5dBi$ is the gain of the used antenna for the transmitter/receiver nodes and RSS_i is the Received Signal Strength calculated at the receiver node during the ith experiment when the distance between transmitter and receiver is equal to $d_{\exp_i}$. Moreover, the σ value for the Gaussian noise is then calculated as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N_{\exp}} \left(PL_{\exp_i} - PL(d_{\exp_i})\right)^2}{N_{\exp} - 1}} \tag{3}$$

The regression model is finally determined by $a = 4.405$, $\sigma = 7.31$ in the *Urban* scenario, and $a = 4.464$, $\sigma = 7.99$ in the *Wood* scenario, defining pretty similar behaviours in both cases. We use the PL model of Eq. (1) in the simulation study presented in Section 7.

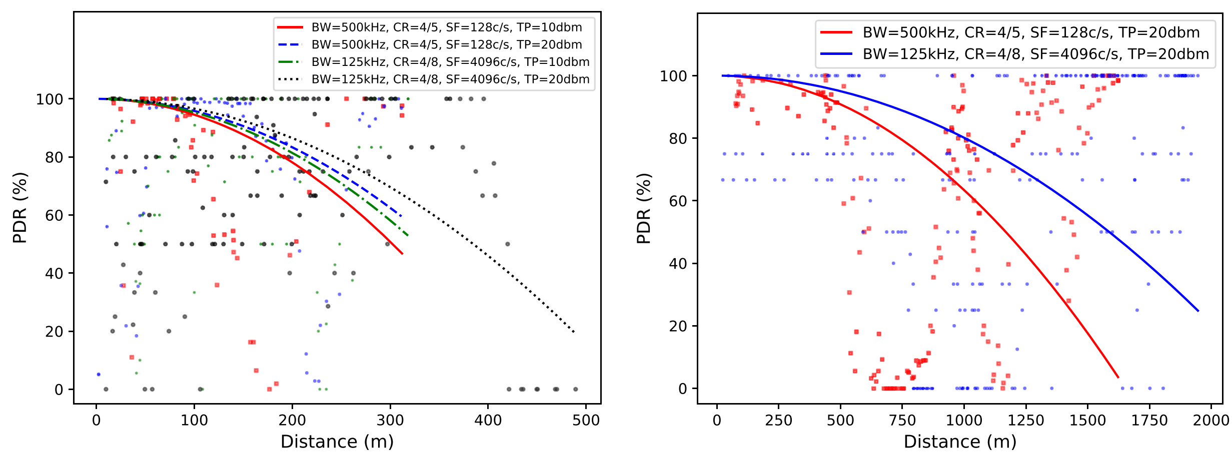
Finally, with Fig. 4(b) we conclude the evaluation by repeating the same analysis of Fig. 2(b) over the same *Urban* area of Fig. 2(a), but placing the LoRa receiver at the sixth floor of a building. As expected, the transmitting range is increased up of six time compared to the previous results. This is quite in line with the analysis reported in [27] and [28], and confirms the impact of the antenna altitude from ground and orientation on the LoRa performance.

From the results shown so far, we can conclude that: (*i*) due to the high delay, ECS with strict real-time requirements cannot be supported; (*ii*) similarly, the limited *PS* size does not allow implementing most of the emergency services proposed so far (e.g. chat



(a) (b)

Fig. 3. *Urban scenario*. The delay as a function of the Packet Size is shown in Fig. 3(a). The Path Loss model over distance for the two scenarios is reported in Fig. 3(b).



(a) (b)

Fig. 4. The PDR as a function of the transmission power and for different LoRa configurations in the *Wood scenario* is depicted in Fig. 4(a). The PDR for the same *Urban scenario* of Figs. 2–3(a) when the LoRa receiver is placed at the sixth floor of a building (hence, in GtA conditions) is shown in Fig. 4(b).

like [16,21]), however it is enough to support the exchange of minimal, yet vital information (e.g. the GPS coordinates); (*iii*) although the transmission range in GtG links is considerably lower than LoRaWAN deployments where the LoRa gateways are placed on rooftops or in LoS conditions, it is still up to ten times those of the Wi-Fi Direct, and hence message dissemination over a large-scale scenario could require only a limited number of re-transmissions.

4. LOCATE: network architecture

We consider a generic emergency scenario, characterized by the absence of mobile Internet coverage, and by the consequential presence of offline smartphones: this might be the case of rural areas or post-disaster environments, where the cellular infrastructures have been damaged or temporarily unavailable due to the excessive traffic load [14]. Without loss of generality, let L be the length in meters of the scenario (assumed square), and N be the number of user devices moving over it. Each device consists of a smartphone connected to a LoRa module, via an USB cable (Fig. 10(a)) or via a BLE connection (Fig. 10(b)), and running the LOCATE application in background. In order to increase the realism of the use-case, and also the generality of the proposed solution, we assume that: (*i*) only a fraction of the N devices, i.e. $\xi \cdot N$, with $0 < \xi \leq 1$ are able to geo-localize themselves through the GPS sensor embedded within the smartphone; (*ii*) the area is not covered by LoRaWAN gateways, hence each LOCATE device can only communicate with other peers in its LoRa range. The goal of this work is to enable the multi-hop dissemination of alert messages over the scenario, while guaranteeing the Quality of Service (QoS) of the end-to-end delivery process.

More in details, we assume the presence of three kinds of users/nodes: (*i*) emergency sources (*ES*), i.e. users needing some kind of help (e.g. requesting medical assistance), who will start an emergency procedure via the LOCATE mobile app; (*ii*) emergency solvers (*EV*), i.e. users having the expertise (e.g. medical personnel) or the possibility (e.g. having a feasible path toward the *ES*) to provide their help once notified; (*iii*) emergency relays (*ER*), i.e. users who are not able to act directly on the emergency, but can facilitate the search for a solver in their neighbourhood. We highlight that the previous roles are purely logical, i.e. the same user can serve as *ES, EV*, or *ER* at different instants, or for the different emergency requests. Any node can become an *ES* by broadcasting an Emergency Request (E−REQ) message, containing the following fields:

$$< request_{id}, position, type, user_{id}, device_{id} > \quad (4)$$

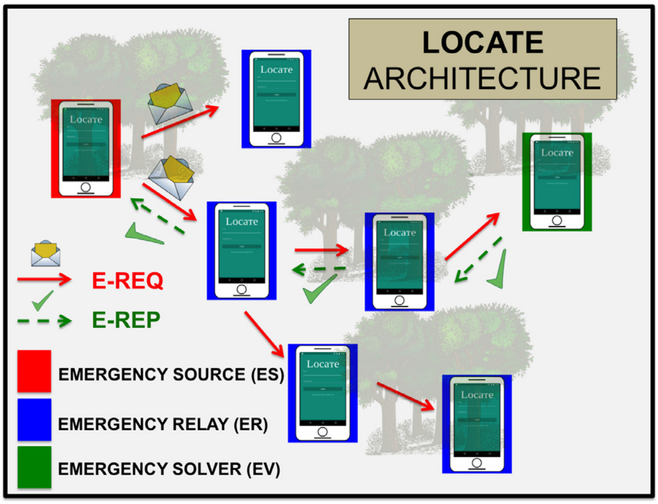


Fig. 5. The LOCATE network architecture [31].

Here, $request_{id}$ is a 2 bytes sequence number; *position* is an 8 bytes field containing the (latitude, longitude) coordinates of the *ES; type* is a 1 byte field, characterizing the nature of the emergency (e.g. rescue help, medical help, ...) and the type of the message (E−REQ or E−REP); $user_{id}$ (2 bytes) is the unique user identifier, generated when downloading the app the first time; $device_{id}$ (6 bytes) is the unique address of the transmitting LoRa device. The current position can be retrieved by the GPS (if available), or estimated through the procedure detailed in Section 5. Any user receiving the E−REQ message can: (*i*) accept to handle the request, hence becoming an EV; or (*ii*) serve as *ER*. The acceptance is performed manually through the app GUI, as described in Section 6. Vice versa, the election to the role of *ER* is always performed automatically; in this case, the E−REQ message is broadcasted according to the dissemination protocol described in Section 5.1, by copying the local address into the $device_{id}$ field. When becoming an *EV*, the node broadcasts an Emergency Reply (E−REP) message having the same structure of the E−REQ, except for the *type* field. The E−REP message is automatically re-broadcasted by each *ER*, until reaching the *ES*. We do not further elaborate on the way the emergency is managed at this stage, since it is out of the scope of this study. Fig. 5 shows an example of emergency scenario and of the LOCATE network architecture, for the case with 1 *ES*, 4 *ER* and 1 *EV*.

In Section 5 we describe the dissemination and localization algorithms, while the implementation details (i.e. the LOCATE application and IoT device) are provided in Section 6.

5. LOCATE: dissemination protocol

5.1. Dissemination protocol

The goal of the dissemination protocol is to optimize the Emergency Resolution Time (*ERT*), defined as the time interval from when the *ES* transmits the E−REQ message to when it receives the corresponding E−REP from any *EV*. This has to be achieved while limiting the network overhead, i.e. the re-transmissions of the E−REQ and E−REP messages, so that: (*i*) the system is able to operate correctly also in presence of multiple emergencies, and hence of concurrent dissemination procedures; and (*ii*) the battery of the LOCATE device can be saved as much as possible. In the following and for easy of disposition, we describe the case with a single emergency although the LOCATE dissemination scheme is not affected by the presence of multiple *ES*.

Let $U = \{u_1, u_2, \ldots, u_N\}$ be the set of the *N* user-owned LOCATE device available in the scenario. The protocol works in two main phases: (*i*) a dual, biased contention phase in which nodes become aware of the emergency for the first time, and forward the corresponding E−REP or E−REQ messages, becoming an *EV* or an *ER* (based on whether they are able to solve the emergency or not); and (*ii*) a DTN-inspired phase in which each EV implements a store-and-forward mechanism, until receiving an E−REP message from one of its neighbor. Fig. 6 depicts the state chart containing states and transitions of the node handling the *i*th emergency.

The goal of the contention phase is twofold, i.e. to let the possible solvers handle the emergency as soon as possible or, if there are no solvers around, to make the E−REQ cover the longest distance without flooding the network. Let CW_{acc} be the acceptance contention window, such that:

$$CW_{acc} = CW_{\max} \cdot (1 - \frac{1}{e^{\delta}}) \tag{5}$$

$$\delta = \gamma \cdot \frac{d(a_s, a_j)}{1 + \frac{d(a_s, a_j)}{R}} \tag{6}$$

where $CW_{\max}$ represents the asymptotic value for the delay, γ is a steepness factor, $d(u_s,\ u_j)$ is the distance between the *emergency source* u_s and the *receiver* node u_j, and *R* is the approximated maximum communication range (the parameter is tuned according to the experiments reported in Section 3). When receiving the E−REQ message for the first time, each node starts the *acceptance timer*, which is set to a random value uniformly distributed between 0 and CW_{acc}. It is easy to notice that nodes closer to the E−REQ source will have more chance to win the contention, since they might be able to reach the physical location of the *ES* quicker than the other nodes. If the nodes receiving the E−REQ did not send or overhear any E−REP message after a $CW_{\max}$ time interval, they start a second contention phase, aimed to detect the best candidate to forward the E−REQ message. Let CW_{ft} be the forwarding contention window, such that:

$$CW_{ft} = CW_{\max} \cdot \frac{1}{e^{\delta}} \tag{7}$$

The value of the *forwarding timer* is random and uniformly distributed between 0 and CW_{ft}. The formulation of the *acceptance timer* (Eq. (5)) and of the *forwarder timer* (Eq. (7)) is quite similar: however, the goals are opposite, since the *forwarding timer* gives higher priorities to nodes farther from the E−REQ transmitter, so that the emergency is spread out as fast as possible.

In the second phase of the protocol, after the *forwarding timer*, nodes enter in a DTN-like state until receiving an E−REP message. To this purpose, we assume the time to be divided into slots of equal duration, i.e. T_{slot}, set to 1 s in our experiments. Every T_b seconds/slots, each node in the DTN state re-transmits the E−REQ message with probability equal to p^*. In order to avoid collisions with other peers, we introduce random delay at the starting of each slot. When receiving an E−REP message, the node exits the DTN phase, and stops broadcasting the E−REQ message, while setting the emergency state as solved. From this time, the node will reply with an E−REP message to all received E−REQ messages. We consider different storage policies for the two messages, i.e: (*i*) the E−REQ message is stored by an *ER* till the corresponding E−REP is received while (*ii*) the E−REP message is stored for a maximum time-to-live T_{ttl} which can be manually configured by each user through the mobile app. The dissemination procedure automatically ends when all the nodes that have become aware of the emergency (i.e. they have received and re-broadcasted the E−REQ message) are informed about the presence of a solver handling it (i.e. they have received the corresponding E−REP message). The computation of p^* is clearly a trade-off between the *ERT* metric

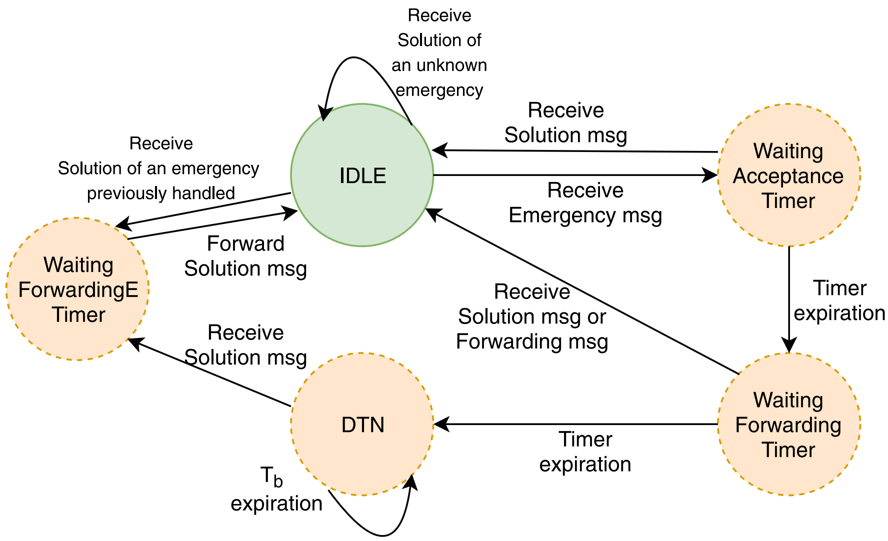


Fig. 6. State chart of the LOCATE dissemination protocol.

previously introduced and the bandwidth utilization, i.e. high values of p^* might minimize the *ERT*, although causing more collisions and directly increasing the overall network overhead. We discuss how to set this value in the Section below.

5.2. Protocol tuning via analytical results

In order to derive the optimal p^* value, we model the protocol scenario by extending the epidemic diffusion model proposed in [47]. In this study, the authors consider a generic mobile DTN scenario, where nodes exchange data each time they enter in the transmission range of each other, and approximate the dissemination function $D(t)$, i.e. the number of nodes reached by the message at time t, as follows:

$$D(t) = \frac{N \cdot e^{\beta \cdot N \cdot t}}{N - 1 + e^{\beta \cdot N \cdot t}} \tag{8}$$

where N is the node population, and β is the inter-contact rate between two nodes, assumed to follow an exponential distribution.

Let N denote the number of user-owned LOCATE devices available in the scenario, randomly distributed over a square area of length equal to L meters. Let $S < N$ be the number of *EV*s in the scenario, with $\phi = \frac{S}{N}$. All the nodes are assumed to move with random speed, uniformly selected within range $[v_{\min}, v_{\max}]$. For ease of disposition, we assume a simple disk diffusion propagation model of range equal to R (again, this value can be tuned according to the experimental results shown in Section 3). We model separately the two steps of E−REQ and E−REP message dissemination, assuming they are performed sequentially, i.e.:

- (*Phase1*). First, the *ES* emits the E−REQ message, which is disseminated until reaching at least one *EV*; this is achieved at time T_{phase1}. Let M be the number of nodes reached by the E−REQ message at this stage.
- (*Phase2*). Then, the *EV*s that have received the E−REQ message during *Phase1* reply with an E−REP message, which again is disseminated over the scenario. The propagation is completed when all the M nodes have received the corresponding E−REP: let such event occur at time T_{phase2}.

It is easy to notice that the assumptions above model the worst-case scenario where the E−REQ and E−REP messages are disseminated sequentially (the *EV*s are the last nodes to be notified about the occurrence of the emergency) rather than proceeding in parallel. The optimization problem can be formulated as follows: we want to determine the optimal p^* such that the network overhead is minimized, while the *ERT* value is kept below a user-defined safety threshold T_{MAX}, i.e.:

$$\begin{aligned} &minimize(O(T_{phase1} + T_{phase2})) \quad s.t. \\ &\qquad T_{phase1} + T_{phase2} \leq T_{\text{MAX}} \end{aligned} \tag{9}$$

where $O(t)$ is the total number of E−REQ and E−REP messages exchanged until time t. Let $D(T_{phase1})$ be the number of LOCATE devices that have received the E−REQ message after T_{phase1} seconds. We extend Eq. (8) by introducing a probabilistic mechanism. Let p the probability that a message dissemination is performed at each node contact, i.e.:

$$D(T_{phase1}) = \frac{N \cdot e^{\beta \cdot N \cdot T_{phase1} \cdot p}}{N - 1 + e^{\beta \cdot N \cdot T_{phase1} \cdot p}} \tag{10}$$

We impose that $D(T_{phase1}) > N - S$, i.e. at least one EV has received the E−REQ message, from which we derive T_{phase1} as a function of p:

$$T_{phase1} > \frac{log(\frac{(N-S)\cdot(N-1)}{S})}{\beta \cdot N \cdot p} \tag{11}$$

We model the dissemination of E−REP messages in a similar way, except that: (i) the initial population is given by M, and can be computed as $M = N - (S - 1)$ (ii) at the initial of *Phase2*, approximately $\lfloor \phi M \rfloor$ nodes start disseminating the E−REP message. Since *Phase2* will end when all the M nodes have received the E−REP message, we impose that $D(T_{phase2}) > M - 1$, i.e.

$$\frac{M \cdot e^{\beta \cdot M \cdot T_{phase2} \cdot p}}{M - \phi \cdot M + e^{\beta \cdot M \cdot T_{phase2} \cdot p}} > M - 1 \tag{12}$$

from which we derive T_{phase2} as a function of p:

$$T_{phase2} > \frac{log((M-1)\cdot(M-\phi \cdot M)}{\beta \cdot M \cdot p} \tag{13}$$

By substituting Eqs. (11) and (13) into Eq. (9), we derive p as follows:

$$p = \frac{log\Big(\frac{(N-S)\cdot(N-1)}{S}\Big) \cdot M + \log((M-1)\cdot(M-\phi \cdot M)) \cdot N}{T_{\text{MAX}} \cdot N \cdot M \cdot \beta} \tag{14}$$

where we set the symbol ‘ = ’ instead of ‘≥’ because we want to find the probability p satisfying the constraint defined in Eq. (9) while minimizing the total number of exchanged messages. This is equivalent to ensure that the emergency is solved exactly

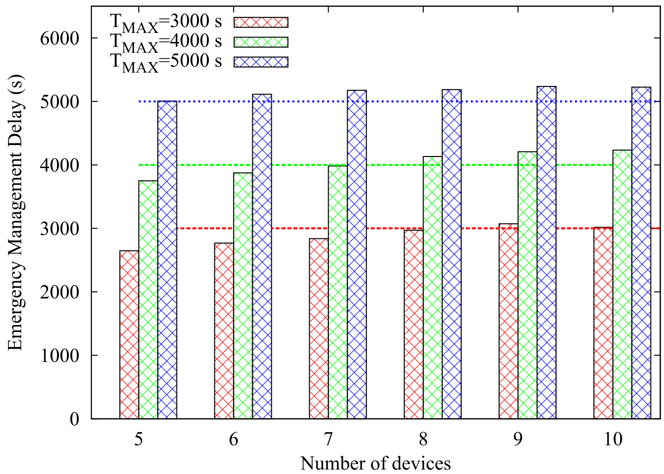


Fig. 7. The comparison between the analytical and simulated LOCATE models is proposed here, for different configurations of N and T_{MAX}.

at the time threshold T_{MAX}. We now compute p^*, i.e. the *per-slot transmission probability*, from p, i.e. the per-contact probability. Let T_c be the average contact time between nodes, and T_b the broadcast interval; this implies that at each contact, two nodes have at least $\lfloor \frac{T_c}{T_b} \rfloor$ opportunities to disseminate the E-REQ or E-REP messages. The per-contact dissemination between two nodes occurs when there is at least one transmission during the contact time, i.e.:

$$p = 1 - (1 - p^*)^{\lfloor \frac{T_c}{T_b} \rfloor} \tag{15}$$

Finally, from the Equation above we derive p^* as follows:

$$p^* = 1 - \sqrt[\lfloor \frac{T_b}{T_c} \rfloor]{1 - p} \tag{16}$$

We remark that the optimality of the p^* value holds under the assumptions introduced at the beginning of this Section, i.e. (*i*) the inter-contact rate follows an exponential distribution; (*ii*) nodes move with random (constant) speed; (*iii*) a disk diffusion propagation model is used.

The exact formulation of β (average inter-contact rate) and T_c (average inter-contact duration) depends on the mobility model in use, and has been computed in other studies [48,49]. For instance, for the Random Waypoint model, β and T_c can be estimated as follows [49]:

$$\beta = \frac{8 \cdot \omega \cdot R \cdot v}{\pi L^2} \tag{17}$$

$$T_c = \frac{\pi^2 \cdot R}{8 \cdot v} \tag{18}$$

where $\omega = 1.3504$ and assuming $v = v_{\text{min}} = v_{\text{max}}$.

In Figs. 7, 8(a) and (b) we validate the analytical model through simulations, and we provide insights on the protocol behaviour for different scenarios and configuration parameters. More specifically, in Fig. 7, we depict the *ERT* metric for the analytical and simulated LOCATE protocol, under varying values of N (x-axis), and of the emergency resolution threshold T_{MAX} (different bars). Compared to the original protocol described in the previous Section, the simulation model has been tuned in order to make *Phase1* and *Phase2* happen sequentially, i.e. *EVs* do not reply with an E-REP message during *Phase1* (with duration equal to T_{phase1}), and, similarly, each *ER* stops broadcasting E-REQ messages during *Phase2*. Again, we remark that these assumptions correspond to the worst case message dissemination for our protocol, where only the DTN phase is considered and p^* is tuned according to Eq. (16). Unless stated otherwise, we consider a simulated scenario with the following parameters: $L = 4000$ m, $R = 400$ m, $S = 1$, $v = 3$ m/s. For each configuration, we executed 10,000 different runs, by randomly placing the node at each run within the scenario. We can notice that -for all the configuration of N and T_{MAX}, the simulation results match quite closely the analytical model (i.e. the horizontal line corresponding to the wanted *ERT*), hence validating its accuracy. Fig. 8(a) shows the values of p^* as a function of N (x-axis) and T_{MAX} (on the y-axis). As expected, the transmission probability decreases quite smoothly when increasing T_{MAX} and/or the number of nodes participating to the dissemination procedure. Similarly, Fig. 8(b) shows the values of p^* as a function of the nodes' speed (on the $x-$axis) and of the scenario length L (on the $y-$axis), for $N = 8$ and $T_{\text{MAX}} = 3000$. The dark values (where p^* is set to 0) correspond to the case where Eq. (16) does not produce a result, i.e. there is no valid probability ensuring that the dissemination procedure can be completed within T_{MAX} seconds. It is easy to notice that the scenario size produces a higher impact on the p^* values than the nodes' speed, i.e. the probability is sharply increased on sparse network environments.

5.3. Localization technique

The protocol described so far assumes that LOCATE devices are able to self-locate, and to add their location information to the E-REQ and E-REP messages. The current latitude and longitude are retrieved via the GPS embedded sensor of the smartphone if available, or, as an alternative, through trilateration methods with other peers. In this second case, the LOCATE u_i device will periodically broadcast COORD-REQ messages, requesting the current location from other peers in its neighbourhood. All the nodes receiving such message will reply with a COORD-REP message, including the following info:

$$< id_i, lat_j, long_j, time > \tag{19}$$

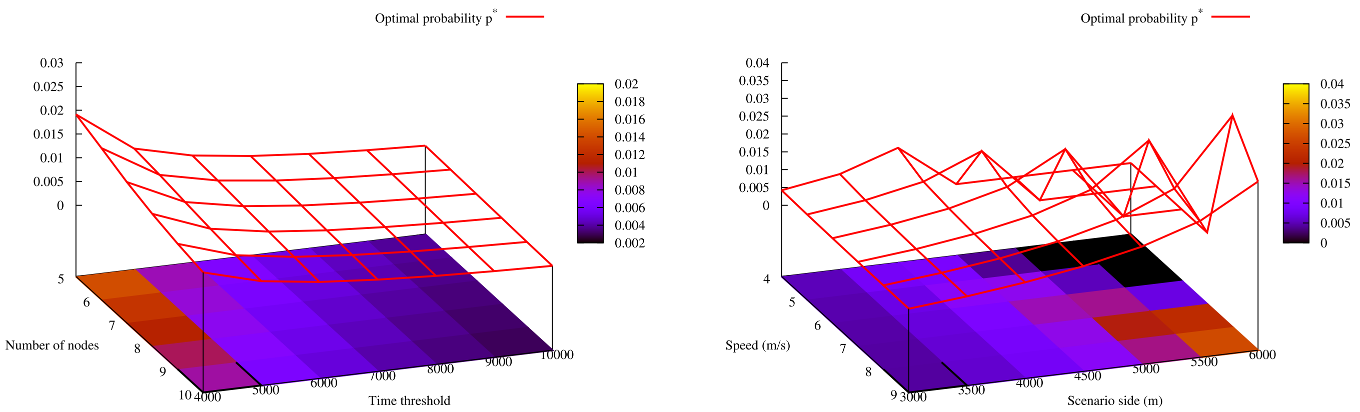
where id_i is the identifier of u_i, *time* is the current timestamp and $lat_j/long_j$ are the coordinates of the replying node u_j. Based on the measured RSS, and on the path-loss model represented in Fig. 3(b), node u_i estimates the current distance from node u_j. When gathering at least three COORD-REQ messages, node u_i computes its current location by employing a trilateration method. This latter has been implemented via the NonLinearLeastSquaresSolver algorithm made available by the lemmingapex library.[2] We remark that few works so far have investigated effective geolocalization through LoRa-based trilateration techniques (e.g. [50]). The accuracy of our method is evaluated in Section 8.

6. LOCATE: mobile application and IoT device

The LOCATE client is composed of an Android mobile application and of an external IoT device. We describe the two components in the following.

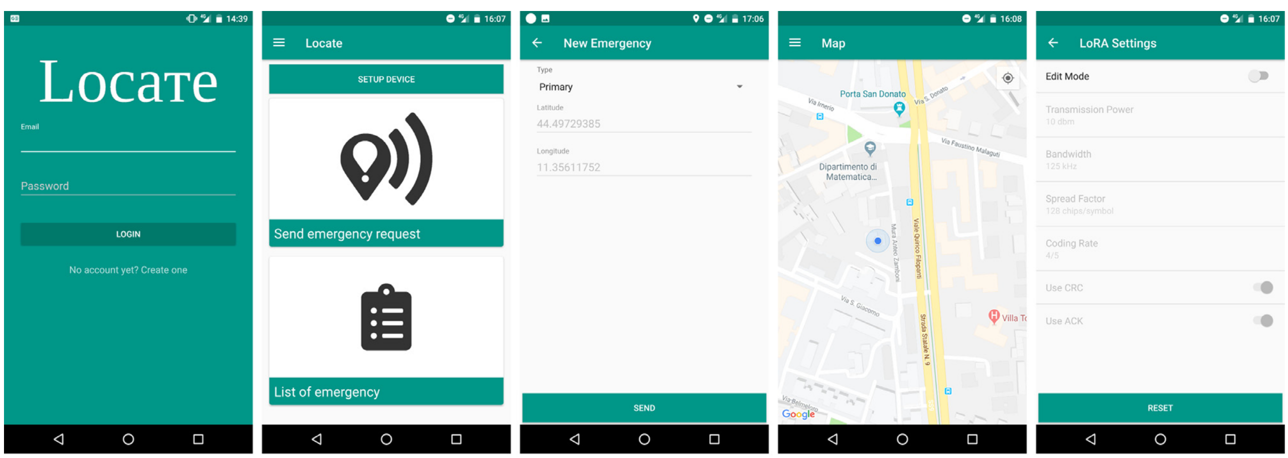
The LOCATE app runs on Android (version > 5.0) smartphones. Before using it on a real emergency scenario, users are requested to register themselves (Fig. 9(a)) by obtaining a unique identifier. The GUI of the app (Fig. 9(b)) provides three main functionalities: (*i*) it allows starting a new emergency procedure, simply clicking on the corresponding button (Fig. 9(c)); (*ii*) it allows tracking the ongoing emergency procedures (e.g. the received E-REQ messages) on the map (Fig. 9(d)); (*iii*) it allows tuning the settings for the LoRa module (Fig. 9(e)). Moreover, the app implements the multi-hop dissemination protocol described in the previous Section, and it runs in background when the main Android Activity state is not visible. When receiving an E-REQ message, a notification is displayed to the user, who can decide whether to accept or not the

[2] https://github.com/lemmingapex/trilateration/.



(a) (b)

Fig. 8. The values of the transmission probability p^* computed through Eq. (16) as a function of N and T_{MAX}, and of L and v, are depicted in Fig. 8(a) and (b), respectively.



(a) (b) (c) (d) (e)

Fig. 9. Some screenshots of the LOCATE mobile application: the registration Activity (Fig. 9(a)), the main Activity (Fig. 9(b)), the send emergency Activity (Fig. 9(c), the map Activity (Fig. 9(d)) and the setting Activity (Fig. 9(e)).

emergency; in case of acceptance, the device sets its role to *EV*, and sends backs an E−REP message. Otherwise, in case of explicit denial, or in case there is no user action within a time limit, the device sets its role to *ER*, and keeps disseminating messages for that emergency without requiring any further manual interaction.

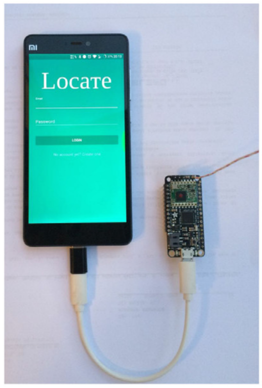
In [16], we described a proof-of-concept deployment, where the LOCATE device is connected to a LoRa transceiver through an USB cable (see Fig. 10(a)). Clearly, this solution has some practical limitations when adopted on a real-world scenario, in terms of maneuverability (e.g. the presence of a cable), and energy autonomy. We addressed both the limitations, by devising an improved LOCATE device, composed of an Adafruit RFM96W LoRa radio transceiver, operating on the 433 MHz band, and of a HM-10 Bluetooth Low Energy (BLE) module. This latter is paired with the smartphone, and enables a bidirectional communication channel between the smartphone and the LoRa transceiver. Due to energy and computational constraints, the whole process of message filtering, parsing and disseminating according to the multi-hop dissemination protocol described in the previous Section is implemented on the mobile app rather than on the LoRa transceiver. In Fig. 10(b), the IoT module is powered by a small LiPo battery (3.7 Volt), which can be charged by an external, wearable solar panel (1 Watt, 5.5 Volt). We evaluate the energy consumption of the current prototype in Section 8.

7. Simulation results

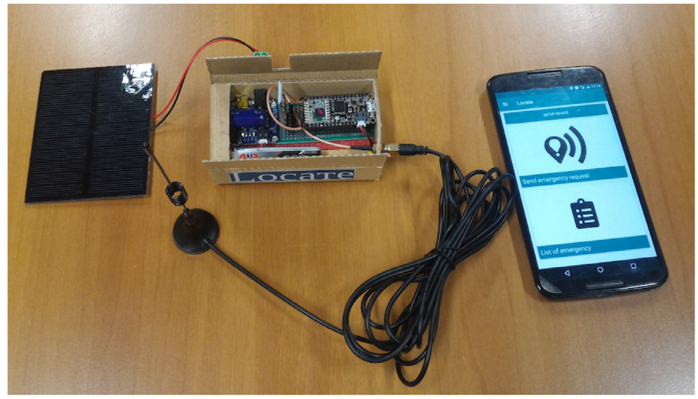
In this Section, we evaluate the performance of the LOCATE platform via simulations, focusing on the capability of the dissemination scheme to favour the effective multi-hop broadcasting of E−REQ and E−REP messages over large-scale emergency scenarios. All tests have been performed through the OMNeT++ tool, by using the FLORA framework[3] to model the LoRa operations at the PHY layer. To this purpose, we used the PDR and Path Loss model derived from the measurements reported in Section 3, and more specifically in Eq. (1) and in Fig. 2(a) and (b). When not stated otherwise, we adopted the simulation parameters reported in Table 1.

We consider a square area of $L = 5000$ m length, with $N + 1$ LOCATE devices randomly placed over it. Let ϕ denote the percentage of *EV*s available in the scenario. At the simulation start, one *ES* starts broadcasting the E−REQ message. The simulation runs until: (*i*) the *ES* receives the corresponding E−REP message sent by one *EV* (and possibly relayed by other *ER*); or (*ii*) the simulation time

[3] https://flora.aalto.fi/.



(a)



(b)

Fig. 10. The LOCATE proof-of-concept implementation: the prototype with the USB cable connection described in [16] is shown in Fig. 10(a), while the current version featuring a BLE connection between the app and the IoT device is represented in Fig. 10(b).

Table 1
Simulation Parameters.

Parameter	Explaination	Value
N	number of nodes	{5...45}
ϕ	% of solvers	{5...30} %
L	scenario length	5000 m
v	mean node speed	1.5 m/s (pedestrian mobility)
M_{type}	Mobility model	Random Waypoint
P_{time}	Pause time	0 s
T_{MAX}	*ERT* threshold	{6000...10000} s
T_b	broadcast interval	5 s
N_{runs}	number of runs	1000
$T_{simLength}$	max simulation length	Set equal to T_{MAX}

exceeds the maximum duration $T_{simLength}$. For each configuration, we ran 1000 repetitions, and averaged the values of the following performance metrics:

- *Emergency Resolution Time* (*ERT*), defined as the average time which is needed to solve the emergency, and computed as the time interval from when the *ES* broadcasts the E−REQ message for the first time, to when the first corresponding E−REP message is received by the *ES*.
- *Emergency Resolution Ratio* (*ERR*), defined as the percentage of cases in which the emergency is solved, i.e. the *ES* receives an E−REP message within the simulation time.
- *Emergency Overhead* (*EO*), defined as the total number of E−REQ messages sent by LoRa nodes during the entire simulation.

We compare five multi-hop message dissemination schemes:

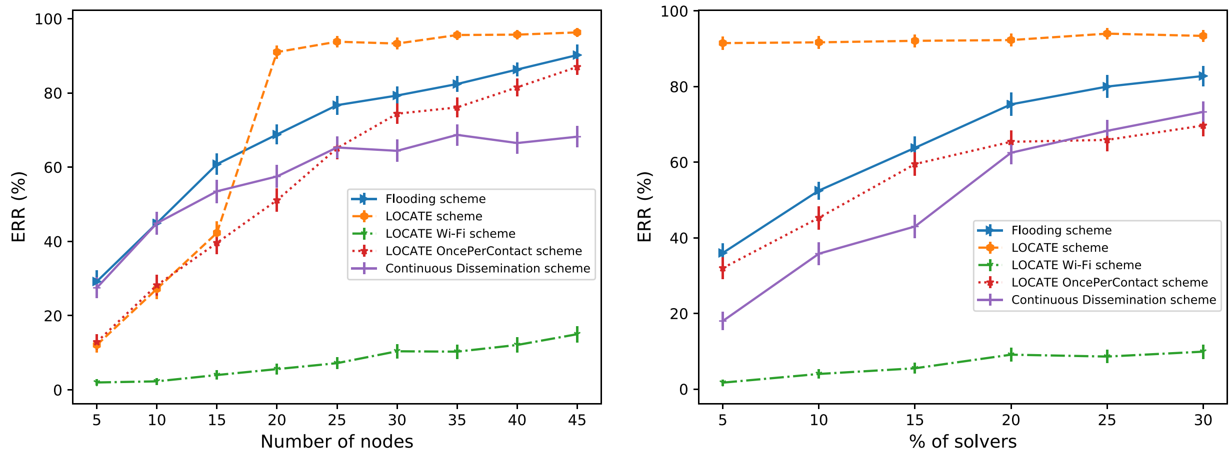
- *Flooding*: this is a basic dissemination strategy, where a node rebroadcasts each received message (both E−REQ or E−REP) after a random timing offset, uniformly distributed between [0, 20] s. Nevertheless, we add the following mechanism for fair comparison: if a node receives an E−REQ message for an emergency already marked as solved (i.e. it has already received the corresponding E−REP message), it avoids to forward the E−REQ and immediately sends back the E−REP. No DTN mechanism or message re-transmissions are employed, with the exception of the ES node that retransmits the E−REQ message each 15 s on the average, until the reception of the E−REP message. Hence, the *Flooding* provides the lower baseline in terms of network overhead on sparse network environments.
- *Continuous Dissemination*: this uses the same probabilistic dissemination scheme of the LOCATE protocol, but without employing the analytical model described in Section 5.2. Rather, the transmission probability p^* is set to 1, i.e. message dissemination is always performed at each broadcast interval. The configuration above provides the upper baseline in terms of network overhead.
- *OncePerContact*: similarly to the previous case, this is a probabilistic dissemination scheme where $p^* = \frac{1}{T_c}$, where T_c is the mean contact time defined in Eq. (18). Hence, nodes perform message exchange once for contact (on average).
- *LOCATE Wi-Fi*: this is the LOCATE dissemination protocol implemented over the 802.11 Wi-Fi technology (assuming the ad-hoc mode is enabled) rather than on the LoRA technology. Since LoRa is not integrated yet within smartphones, the *LOCATE Wi-Fi* scheme is considered as reference for state-of-art phone-based ECS.
- *LOCATE*: this is the LOCATE dissemination algorithm as described in Section 5. We set T_{MAX} equal to $T_{simLength}$ i.e. the LOCATE dissemination protocol adjusts p^* in order to guarantee the emergency resolution within the simulation duration. We set $p^* = \frac{1}{T_c}$ for those configurations where Eq. (16) does not return a valid result (i.e. there is no probability value ensuring that the emergency will be solved within the T_{MAX} interval).

Through the first three schemes (i.e. *Flooding, Continuous Dissemination* and *OncePerContact*) we evaluate the effectiveness of the *LOCATE* protocol when compared with basic dissemination techniques; vice versa, the comparison with *LOCATE Wi-Fi* allows understanding the gain provided by the communication technology (i.e. LoRa vs Wi-Fi) when considering the same software suite.

Four different analysis are considered, i.e.: *(i) Node Analysis*, where we vary the number of users/devices (N) within the scenario while keeping constant the percentage of solvers; *(ii) Solver Analysis*, where we do the opposite, i.e. varying ϕ for a fixed value of *N; (iii) Time Analysis*, i.e. where we investigate the performance of LOCATE for different T_{MAX} values, i.e. varying the user requirement on the emergency resolution; *(iv) Grid Analysis*, i.e. where we investigate the system performance in presence of static GtG repeaters that participate to the message dissemination.

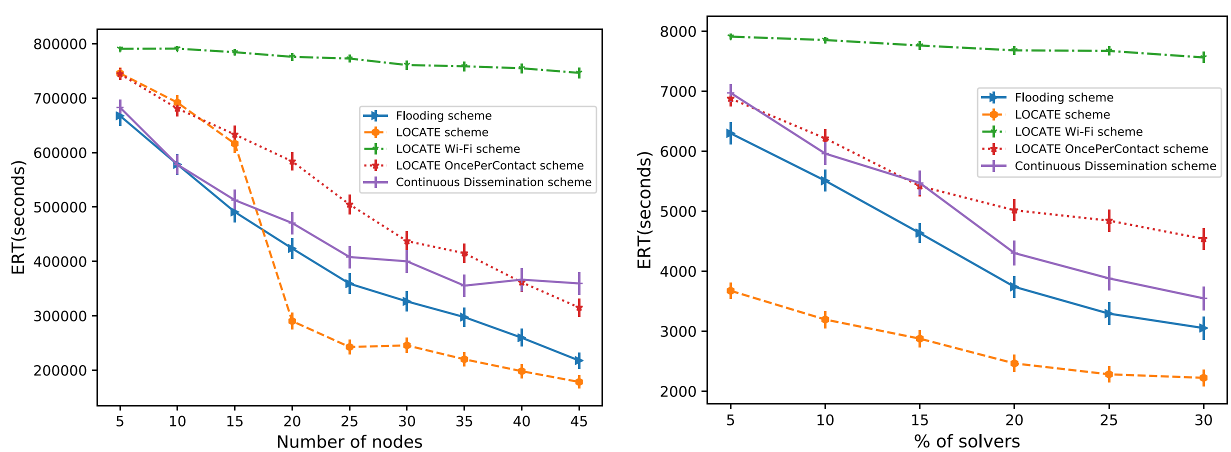
7.1. Node analysis

Figs. 11(a), 12(a) and 13(a) depict the *ERR, ERT* and *EO* metrics when varying the numbers of users/devices (N) available in the scenario. We kept constant the percentage of *EV* devices, set equal to $\phi = 20\%$. From Fig. 11(a), we can notice that the *LOCATE Wi-Fi* scheme guarantees emergency resolution only in a very low percentage of cases, due to the limited transmission range, and



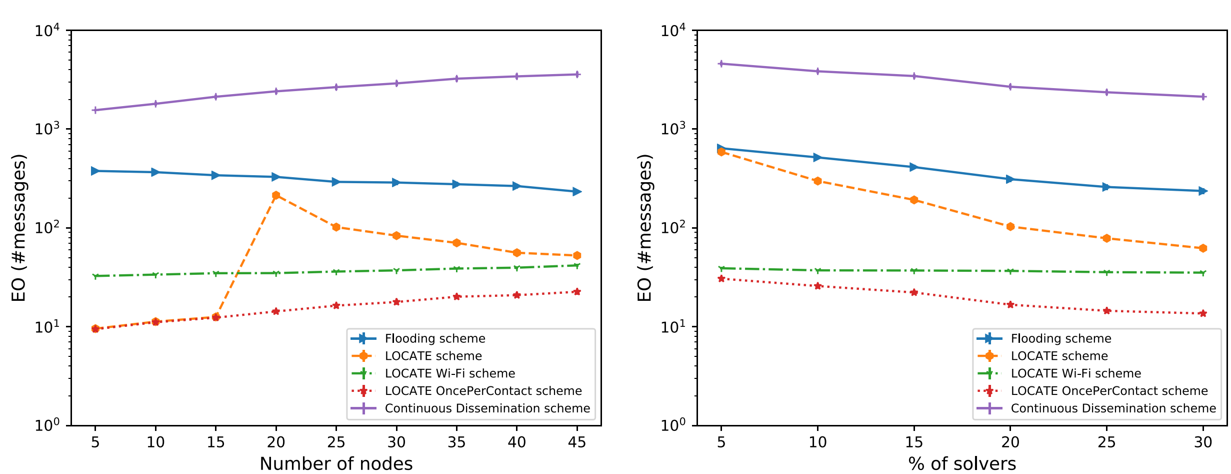
(a) (b)

Fig. 11. The *ERR* metric when varying the number of users/devices with $\phi = 20\%$ is depicted in Fig. 11(a), and when varying the percentage of solvers (ϕ) with $N = 25$ is depicted in Fig. 11(b).



(a) (b)

Fig. 12. The *ERT* metric when varying the number of users/devices with $\phi = 20\%$ is depicted in Fig. 12, and when varying the percentage of solvers (ϕ) with $N = 25$ is depicted in Fig. 12(b).



(a) (b)

Fig. 13. The *EO* metric when varying the number of users/devices with $\phi = 20\%$ is depicted in Fig. 13(a), and when varying the percentage of solvers (ϕ) with $N = 25$ is depicted in Fig. 13(b).

the sparseness of the environment; the performance difference with the other schemes demonstrates the improvement provided by LoRa technology, and hence further justifies its usage for ECS applications. The *Continuous Dissemination* scheme incurs in synchronous collision problems when increasing the values of N. The LOCATE system is sub-optimal for $N < 15$ since no valid probability value (p^*) exists according to Eq. (16); we recall that in these cases the same probability of the *OncePerContact* approach is used. However, for $N \geq 20$, the LOCATE system overcomes all the other competitors, and guarantees emergency resolution on almost 95% of the cases. The same improvement can be observed on the *ERT* metric in Fig. 12(a). The *OncePerContact* scheme provides the highest delay for the emergency resolution since the number of transmissions is too low to guarantee effective dissemination among the nodes. As before, when $N \geq 20$, the LOCATE system provides the best performance in terms of *ERT*; it is also easy to notice that the average time for the emergency resolution is greatly below the requested threshold T_{MAX} (equal to 8000 s). The performance gain on the *ERR* and *ERT* does not come at the expense of the network overhead, depicted in Fig. 13(a). As expected, the *Continuous Dissemination* introduces the highest overhead compared to the other schemes. The LOCATE system performs identically to the *OncePerContact* algorithm for $N < 15$, has a peak for $N = 20$, and then decreases for higher values of N, matching the trend of the transmission probability p^* depicted in Figs. 8(a) and 8(b). We remark that the *EO* values of the LOCATE system are considerably lower than the *Flooding* and *Continuous Dissemination* schemes, and pretty close to the *OncePerContact* algorithm; however, the performance gain introduced by our solution in terms of *ERT* and *ERR* metrics is significant, hence confirming the effectiveness of the analytical model used to tune the transmission probability.

7.2. Solver analysis

Figs. 11 (b), 12(b) and 13(b) depict the *ERR, ERT* and *EO* metrics when varying the percentage of solvers ϕ, for $N = 20$. The *ERR* of the LOCATE scheme is close to 100%, and is only marginally affected by the increase of the ϕ parameter, being nearly optimal even for the configuration with the lowest density of solvers ($\phi = 5\%$). The performance of the other schemes increases with ϕ, although they are considerably lower than our scheme for all the configurations. Similar behaviours can be observed in Fig. 12(b); on average, the LOCATE scheme is able to solve the emergency 2000 s before the *Flooding* scheme for the configuration with $\phi =$ 5%. Finally, in Fig. 13(b), we can notice that the LOCATE scheme introduces only a slight additional overhead compared to the *OncePerContact* algorithm, and that such difference decreases significantly when increasing ϕ, since the transmission probability p^* is adjusted correspondingly.

7.3. Time analysis

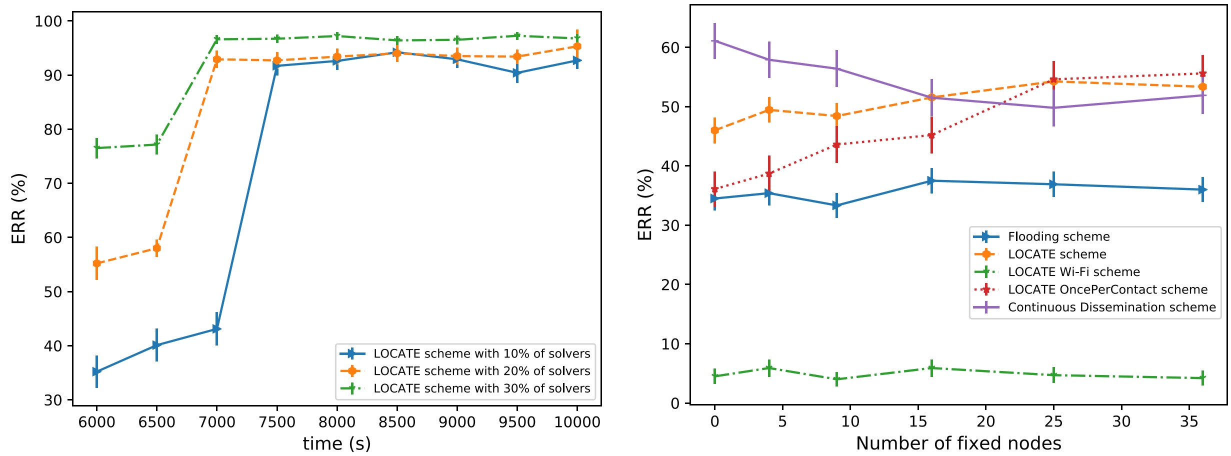
Figs. 14(a), 15(a) and 16(a) depict the *ERR, ERT* and *EO* metrics when varying the emergency time resolution threshold T_{MAX}, for $N = 25$. We considered three configurations of the percentage of solvers, i.e. $\phi = 10\%$, 20% and 30%. In this analysis, for fair comparison reasons, we only evaluate the performance of the LOCATE scheme since the other solutions do not take into account the time threshold in their protocol operations. For low values of T_{MAX} and ϕ, no valid probability exists for the computation of p^*, and the *OncePerContact* algorithm is used. This justifies the poor *ERR* values in the left part of Fig. 14(a); however, after reaching a threshold point that guarantees the existence of a valid p^* value (equal to 7000 s for $\phi = 20\%$ and 30%, and 7500 s for $\phi = 10\%$), the *ERT* values approach the 100%. This also explains the trend of the *ERT* metric in Fig. 15(a); we can notice that, for values of T_{MAX} greater than the threshold points previously indicated, the *ERT* increases since our algorithm automatically decreases the transmission probability p^* in order to guarantee convergence within a larger time interval. The network overhead is depicted in Fig. 16(a); we can notice that the *EO* values significantly decrease when $\phi >$ 10%, and when relaxing the wanted threshold T_{MAX}.

7.4. Grid analysis

Figs. 14 (a), 15(b) and 16(b) depict the *ERR, ERT* and *EO* metrics for $N = 5$ and $\phi = 20\%$. On the x-axis, we vary the number of static ground devices placed in the scenario at fixed distance one from each other. Since the distance exceeds the LoRa transmission range on all the configurations tested, the nodes do not form a connected mesh network. However, each static device can participate to the message dissemination, serving as a repeater. We can notice that the *ERR* metric considerably decreases when increasing the number of repeaters for the *Continuous Dissemination* protocol, due to the impact of synchronous collisions. Conversely, both the LOCATE and the *OncePerContact* schemes are able to exploit the increasing density of repeaters; for the case of LOCATE, this also translates into an effective reduction of the *ERT* index (depicted in Fig. 15(b)), which is considerably lower than all the other competitors. Fig. 16(b) provides further evidence of the fact that our solution is able to handle the emergency resolution through a proper tuning of the transmission probability, since the network overhead is comparable with the *OncePerContact* scheme, and considerably lower than the *Continuous Dissemination* and *Flooding* schemes.

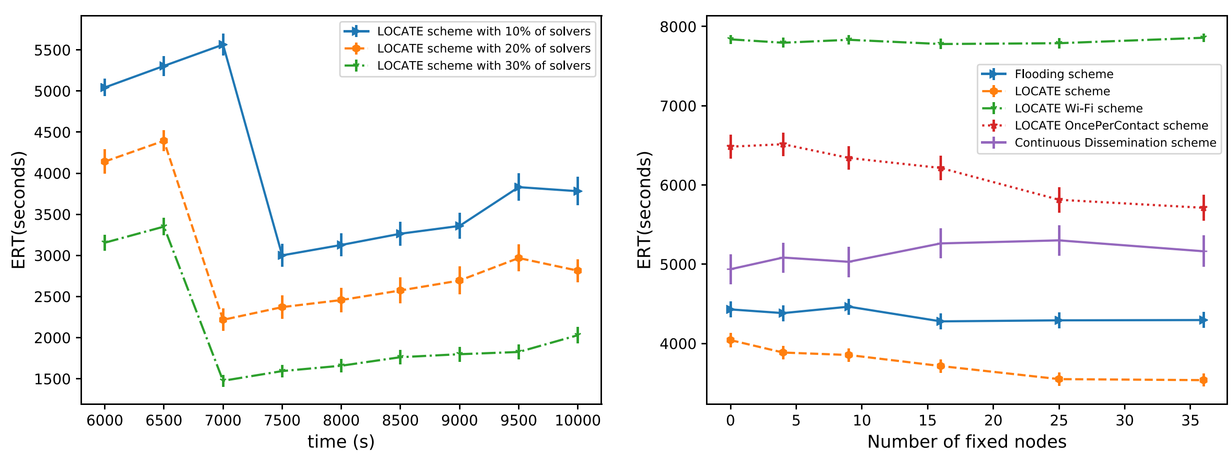
8. Experimental results

In this Section, we provide further experimental results on the LOCATE system. We tested the networking capabilities at the link layer via measurements in Section 3, and at the system layer via simulations in Section 7. Here, we analyze the accuracy of the LoRa-based localization procedure described in Section 5.3, and the energy-efficiency of the LOCATE device. Regarding to the first point, we depict in Fig. 17 the results of localization test performed in the *Urban* scenario, and including a mobile LOCATE transmitter and a static LOCATE receiver; the mobile client periodically broadcasts the COORD-REQ message and waits to receive the COORD-REP message from the static device, as explained in Section 5.3. The x-axis represents the GPS-distance between the nodes, while the y-axis represents the estimated RSS-distance, computed through Eq. (1). Each dot indicates the result of a localization test, after a COORD-REQ-COORD-REP message exchange; the dotted line in green denotes the optimal distance estimator where the GPS distance on the x-axis coincides with the RSS-based distance on the y-axis. The line in blue indicates the performance of the RSS-based distance estimator, computing the mean estimated distance for each GPS sample, and further aggregating the results with a spatial resolution of 10 m. We can notice that the RSS-based estimator is quite precise when the distance is lower than 70 m, or higher than 140 m, also due to the characteristics of the tested environment: in any case, we can notice that the error on the distance estimation is always lower than 90 m, as also demonstrated by Fig. 18(a), which depicts the CDF of the distance error. Based on such results, we evaluate in Fig. 18(b) the accuracy of the LoRa-based triangulation localization algorithm when varying the number of static anchors with known GPS positions. To this purpose, we run multiple simulations by varying the positions of the mobile LOCATE client and of the static anchors within the same area of Fig. 17; for each run, we estimated the distance between the client and each anchor according to the average and standard deviation values of the measured RSS distance estimator of Figs. 17 and 18(a). We can notice that the localization



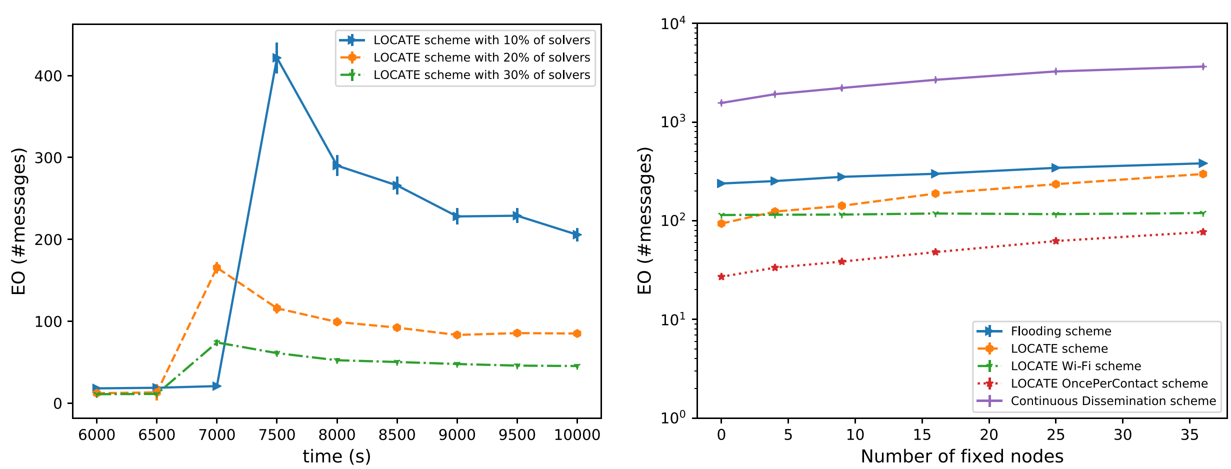
(a) (b)

Fig. 14. The *ERR* metric when varying the T_{MAX} threshold with $N = 25$ and three values of ϕ is depicted in Fig. 14(a), and when varying the number of fixed nodes with $N = 5$ and $\phi = 20\%$ is depicted in Fig. 14(a).



(a) (b)

Fig. 15. The *ERT* metric when varying the T_{MAX} threshold with $N = 25$ and three values of ϕ is depicted in Fig. 15(a), and when varying the number of fixed nodes with $N = 5$ and $\phi = 20\%$ is depicted in Fig. 15(b).



(a) (b)

Fig. 16. The *EO* metric when varying the T_{MAX} threshold with $N = 25$ and three values of ϕ is depicted in Fig. 16(a), and when varying the number of fixed nodes with $N = 5$ and $\phi = 20\%$ is depicted in Fig. 16(b).

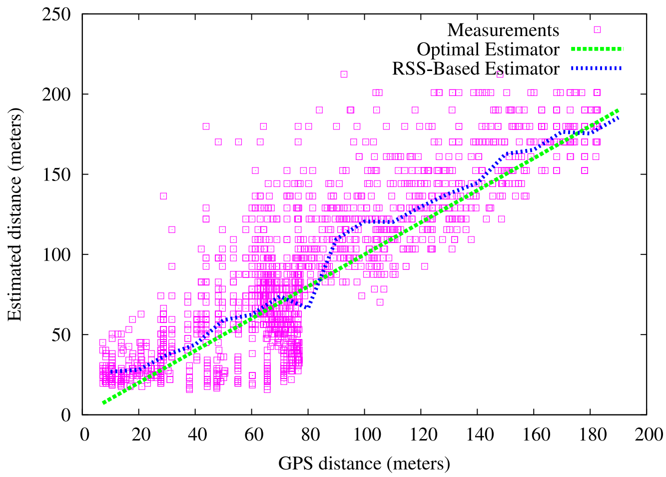


Fig. 17. The accuracy of the LoRa RSS-based distance estimator.

error reduces with the number of available anchors transmitting the COORD-REP message, and that is lower than 70 m on 90% of the cases, for each number of anchors.

Next, we analyze the energy consumption of a LOCATE device, focusing on the LoRa transmitter, and investing the impact of different configurations on the mean energy consumption. In Fig. 19 we show the experimental result where we measured the power consumption of a LoRa device while transmitting data. Clearly, in any wireless communication system, the power consumption is a function of the transmission power; however, in this analysis, we fixed *TP* to 20 dBm while we focused on evaluating the LoRa-specific configuration parameters, showing that these latter can have a remarkable impact on the energy efficiency of the IoT device. To this purpose, we varied the LoRa transmission profile and the traffic load during the experiment, i.e.: from 7 to 42 s we used $BW = 125$ kHz, $CR = 4/5$ and $SF = 128c/s$ to transmit 6 kB; from 52 to 84 s we used $BW = 500$ kHz, $CR = 4/5$ and $SF = 128c/s$ to transmit 1.5 kB; from 94 to 121 s we used $BW = 31.25$ kHz, $CR = 4/8$ and $SF = 512c/s$ to transmit 6 kB; finally, from 131 to 175 s we used $BW = 125$ kHz, $CR = 4/8$ and $SF = 4096c/s$ to transmit 30*B*. We can notice that the power absorption due to the transmission phase is quite similar over all the tested configurations (see Table 2 for the exact values).

Moreover, Table 2 shows the energy efficiency of the different configuration. We can notice that the energy consumed for bit is

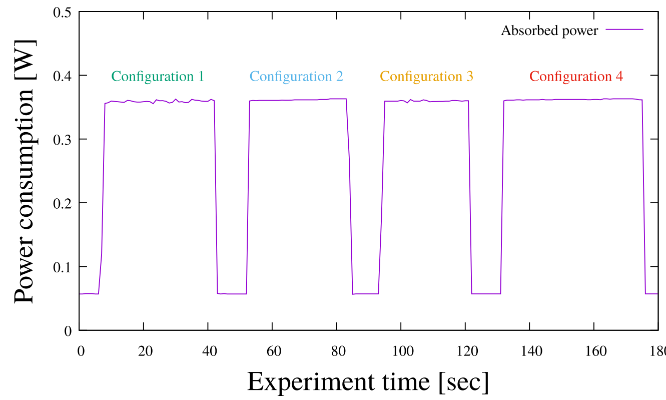


Fig. 19. Energy consumption while transmitting with different configurations.

Table 2
Energy consumption.

Configuration	Power consumption (W)	Energy efficiency (mJ/bit)
No transmission	0.0586	–
BW=125kHz, CR=4/5, SF=128 c/s	0.3699	0.2736
BW=500kHz, CR=4/5, SF=128 c/s	0.3676	0.9681
BW=31.25kHz, CR=4/8, SF=512 c/s	0.3770	0.2160
BW=125kHz, CR=4/8, SF=4096 c/s	0.3747	68.697

dependent on the system configuration. In fact, the fourth configuration ($BW = 125$ kHz, $CR = 4/8$, $SF = 4096c/s$) is highly inefficient with his 68.697 mJ/bit compared to the third one ($BW = 31.25$ kHz, $CR = 4/8$, $SF = 512c/s$) having only 0.216 mJ/bit as energy efficiency. In fact we sent only 30*B* with the fourth configuration compared to the third one where we were able to send 6 kB, using only the double of transmission time (see Fig. 19); at the same, it guarantees considerably longer coverage range, as shown previously in Figs. 2(b) and 4(a). Hence, the choice of the LOCATE configuration should take into account the optimal trade-off between the energy consumption of the device, and the range of the link; reasoning in terms of the target use-case, this is a trade-off between temporal duration of the emergency process, and speed of dissemination of the emergency messages. The automatic configuration of the transmission parameters, considering both

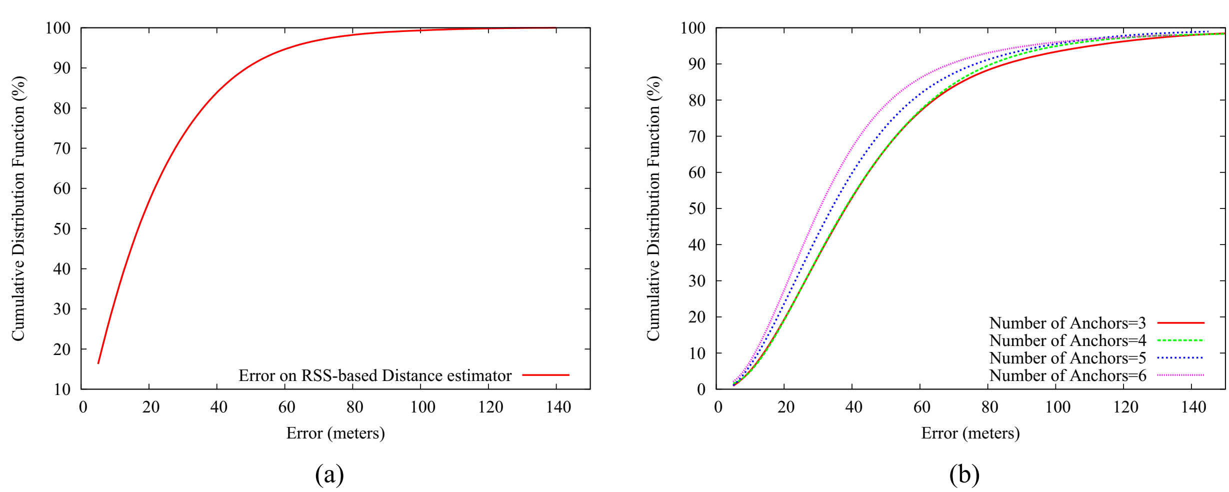


Fig. 18. The CDF on the distance error is shown in Fig. 18(a). The CDF on the localization error via triangulation techniques when varying the number of static GPS anchors is shown in Fig. 18(b).

energy-related and coverage-related performance, is left as future work.

9. Conclusions

In this paper, we investigated how to deploy effective, large-scale Emergency Communication System (ECS) on user-owned smartphone devices. To this purpose, we proposed the LOCATE system, a novel hardware/software platform enabling multi-hop dissemination of alert message containing minimal vital information regarding the location of users requesting help, and the type of the emergency. The alert message -generated by the user through the mobile app- is transmitted through an IoT module which includes a LoRa transceiver. We described the LOCATE prototype and the enabling algorithms, i.e.: a self-localization algorithm implementing a trilateration technique, and a multi-hop dissemination scheme which combines probabilistic DTN and biased-contention mechanisms. An analytical model has been proposed in order to derive the optimal transmission probability of the dissemination protocol, by taking into account the emergency resolution time, and the network overhead. A threefold, extensive performance evaluation has been proposed. First, we investigated benefits and drawbacks of LoRa technology for ECS applications through measurements on two target scenarios (called *Urban* and *Wood*). Second, we analyzed the performance of the LOCATE dissemination scheme over simulated emergency scenarios, when compared against other dissemination protocols and D2D technology (Wi-Fi). The OMNeT++ simulation results demonstrate that the LOCATE scheme is able to guarantee emergency resolution within the time threshold, and to produce higher *ERR* and lower *ERT* values compared to other DTN-based approaches, and to the same algorithm implemented over legacy Wi-Fi technology. Third, we presented additional experimental results on the LOCATE localization technique and on the energy-consumption of the IoT module. We can hence conclude that the LOCATE platform represents a cost-effective and efficient solution to deploy phone-based ECS, while waiting for the integration of LoRa module within COTS mobile devices.[4] Future works include the porting of the LOCATE mobile application on IOS devices, the extension of the analytical model by taking into account the optimal range-energy trade-off, and the experimental evaluation over additional scenarios.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

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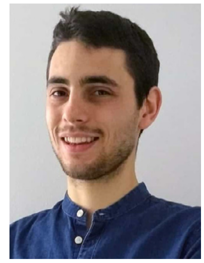

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