M-HELP - Multi-Hop Emergency Call Protocol in 5G

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***Abstract*—Wireless mobile networks are widely used during large catastrophes such as earthquakes and floods where robust networking systems are indispensable to protect human lives. The objective of this paper is to present a self-adaptive emergency call protocol that allows keeping potential victims connected to the core network through the available functional gNBs, when a fraction of gNBs in a network area are fully destructed with no access to other gNBs or the core network due to the disaster. Nowadays, the density of mobile devices and progress in outband device to device (D2D) communication provide the framework for the extension of both mobile and network coverage. We propose a novel, 3GPP compatible and completely distributed protocol called M-HELP for emergency call service for 4G/5G enabled mobile networks. We assess M-HELP efficiency under various scenarios representing different degrees of network destruction and different emergency call conditions. The tests demonstrate the significant performance of M-HELP in terms of transmission success rate, energy management, latency and control traffic load.**

***Index Terms*—multi-hop emergency call, outband D2D communication, network resilience, radio-mobile network**

I. Introduction

Recent catastrophes such as the Tsunami of the Indian Ocean in 2004, Hurricane Katrina in 2005, the Fukushima disaster in 2011 and Haiti Earthquake in 2010 have demonstrated that a robust networking system is indispensable to protect human lives. In such situations, mobile networks present a more resilient way to transfer urgent information and to coordinate the work of rescue teams compared to landline connections [1]. In these circumstances, the ubiquity of mobile phone devices and radio access infrastructure make mobile communication the default method of communication and can make positive contributions before, during and after the disaster. Besides, the citizen familiarity with mobile applications (SMS, voice call, chat) increases the frequency and the efficiency of their usage [2].

Currently, public safety services use a narrow band Terrestrial Trunked Radio (TETRA)-based systems that can only support voice services [3] and concern specific devices. 4G and 5G mobile technologies are leading the way to device to device (D2D) communications, which due to the mobile device density gives the tools for the extension of the terminal coverage when the network is damaged. Many applications and protocols [4]–[6] were proposed for public safety services based on global mobile network proximity service [7]. Since Release 11, the Third-Generation-Partnership-Project (3GPP) started to develop the specifications of new protocols and services for supporting public safety services. Figure 1 illustrates major 3GPP works related to safety service and emergency data communication. The success of such solutions depends on their relevance in terms of latency, availability, deployability, energy consumption, stability, compatibility with different technologies and security.

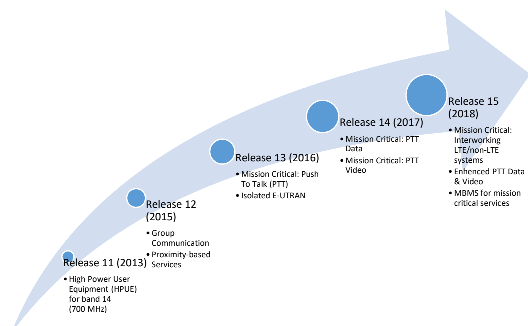


Figure 1: 3GPP works related to public safety services

The objective of this work is to investigate the emergency services deployment under catastrophic and unpredictable situations. The idea is to provide a self-adapting distributed mechanism that allow maintaining the connectivity of the out of coverage users and potential victims when the networking infrastructures are partially affected. In order to enhance the reliability of emergency information transfer, an optimized multi-hop emergency calls service in 5G mobile networks is proposed that allows autonomous transfer of emergency calls to the core network once a call has been initiated. Further, it is assumed that the network infrastructure is widely affected (see Fig. 3). The protocol is built on top of the 3GPP standardized D2D communication and push to talk (walkie talkie) technologies. The protocol is compatible in smart phones with hardware supporting 4G/5G. Thus, it can be used even in areas where 4G/5G is not fully deployed.

The remainder of this paper is organized as follows, Section II provides an overview to other related work, while Sections III and IV explain the system model and proposed design of the multi-hop emergency calls service protocol, respectively. Section V provides the performance analysis and comparison with an existing protocol and Section VI concludes the paper.

II. Related works

Deployment of safety and emergency service platform becomes a central preoccupation of modern societies. Major works in this field focus on the conception of networking systems able to guarantee the service accessibility anywhere, anytime instantaneously.

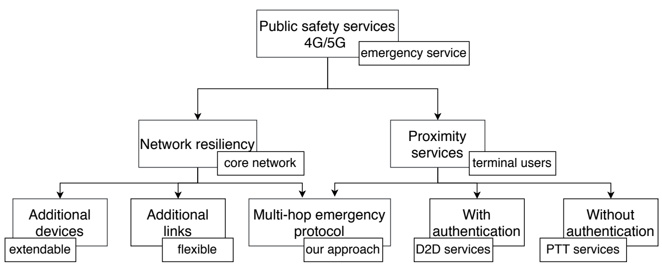


Figure 2: Taxonomy of public safety research works. Our approach using both the D2D technology and PTT aims to improve the network resilience.

Few works of the literature have dealt with the resilience and self-adaptation of the mobile networks after a disaster that touches the network infrastructure and causes a high amount of emergency calls. To achieve network resiliency, the use of additional infrastructure such as satellite or UAVs have been proposed. However, these have the drawback of higher cost of deployment and time needed for their deployment (responsiveness issue).

Further, these approaches envisage the use of movable physical units to rapidly work as a stand-in for damaged network facilities. In [8], the use of a satellite system in conjunction with a terrestrial mobile network is studied. In [9], the use of unmanned air vehicles (UAV) in the disaster-hit areas is investigated.

In [10], the authors proposed to reshape the mobile network architecture in order to relax the dependencies between UEs, base stations, and the core network. The objective is to provide more resilience against link disruptions. This kind of approach, based on virtualization/redundancy of links and functionalities, is efficient for localized perturbations and is inefficient when the disaster impact is larger. Other works such as [1] and [6] focus on the recovery aptitude of the networking system after a disaster. On the other hand, two main approaches have been proposed in literature to enhance transmission efficiency at the terminal user. First is extending the base stations coverage by using the D2D protocols [11], [12]. Second is the push to talk (PTT) service which support the group calling communication [5], [13], normally used in walkie talkies.

- *Push-to-talk communication* is described in TS 22.179 of 3GPP standard [14] and [15]. In push-to-talk protocol, the user requests permission to transmit at the touch of a button, then all subscribers of the PTT service receive the call. The user with the higher priority overrides the current talker to transfer its emergency message and speaking time is limited to prevent resource starvation.
- *Device to Device (D2D) communication* is a technology which enables direct communication between mobile devices, without passing through network infrastructure. D2D enhances service quality in densely populated networks by reducing the radio link distances. It was first introduced in the 3GPP release 12 [16], [17], and proposed for public safety proximity services (ProSe) [17], [18]. Further, D2D communication allows the use of short range radio technologies such as WiFi, bluetooth, Zigbee, LoRa, Thread, EnOcean, SIGFOX and others to communicate [19]–[22].

Both PTT and D2D protocols aim to extend communication possibilities to support proximity-based services. However, available research works using the D2D and PTT approaches are proposed for well-deployed networks and are not adapted to the sudden surge of network demand and to the network failures.

Even if dealing with disaster situations is well studied in ad hoc networks, the projection of those solutions over 4G/5G mobile standards is rarely studied. Indeed, the conception of emergency call service for 4G/5G networks requires taking into account the strict and closed 3GPP recommendations specifying what could be done or not. In addition, the user equipment (network nodes) not being owned by the system itself making the protocol possibilities more regulated and constrained than in private/community networks such as MANET, VANET systems. Therefore, the emergency call protocol has to be as light as possible with less control and redundancy traffic.

Amongst the rare works on the massive use of D2D mechanisms to overcome large disaster situations, mention may be made of FINDER protocol [23]. In FINDER algorithm, mobile devices organize themselves into hierarchical clusters and route emergency calls to working base stations. Here the whole region under the out of coverage area is divided into different clusters. Each cluster has a potential cluster head (CH) selected by the members of the cluster. The mobile nodes in each cluster sends the data to the CH and the CH aggregate the data and send it to the nearest active BS via multi-hop D2D communications, using neighboring CHs as a relay.

In this paper, we investigate the under-studied way of using the mobile devices to achieve both network resiliency and transmission efficiency during a sudden surge of emergency calls. The idea is to use the terminal devices as relay stations for directing the emergency calls to the fully functional base stations.

III. Multi-hop emergency call routing design

Let N be the set of the base stations composing the 4G/5G radio mobile network and M be the set of mobile devices distributed within the network area. Further, it is assumed that all the mobile devices of M are emergency service enabled devices. This means that the mobile subscriber has given the authorization for the use of the emergency service and for serving as a relay for such calls. Each user equipment $ue \in M$ knows its battery level, $\text{SoC}_{ue} \in [0, 100]$, its network coverage state, $\text{Ic}_{ue} \in \{0, 1\}$ by at least one base station and its localization accuracy, $\text{LocAcc}_{ue} \in [0.001, 1]$. An emergency call is generated either manually (by human will) or automatically (e.g. after a car accident detection or the reception of an emergency call). The emergency call includes information such as a voice, text, or video message from the human source, indicators about the emergency degree (level), device localization, etc. Once a node receives an emergency call, it adds its own localization to the relayed message. Both emergency source position and relay devices' positions help the public safety center to localize precisely the source of the emergency call.

The transfer of the emergency call to the public safety centers can cross a multi-hop path especially when the emergency call is due to a wide catastrophe over a large geographical area. The transfer of the emergency call can take two different forms:

1) When the sender is within the coverage of a base station (eNB or gNB), a classical data communication is performed.
2) When the sender is out of coverage, the emergency call is diffused, using the out of coverage D2D mode, to all the neighboring devices.

The two cases of emergency calls are illustrated in Figure 3. The figure shows that three devices within the disaster area diffuses its call to three relaying mobiles. The relay devices send the message to two different base stations. The transmission redundancy allows improving the reliability of the protocol. However, the number of copies of the same message have to be controlled to prevent the radio network saturation.

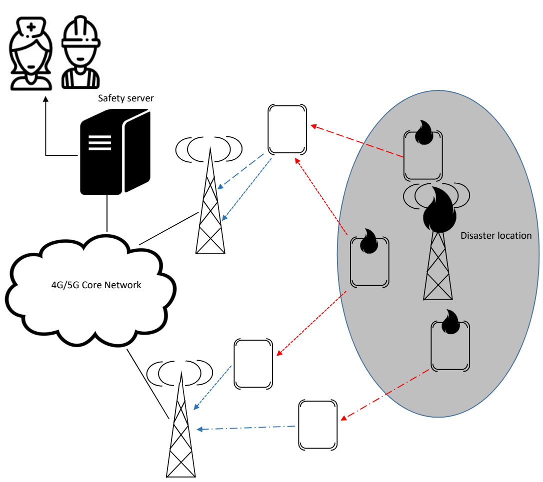


Figure 3: Safety service architecture. Red arrows represent the D2D communications and the blue arrows represent the classical uplink communications.

When the sender is out of coverage, the emergency call source or relay sends a control message via the physical sidelink control channel (PSCCH). The PSCCH serves, implicitly, to synchronize the sender with the potential receivers. It is used by ProSe-enabled devices to send the sidelink control information (SCI) that informs the mobile receivers about the data transmission parameters used during the next sidelink period: subframes and radio resource blocks [24]. More precisely, the PSCCH indicates the index of the used subframes (time), the used radio resource blocks (frequencies), the modulation and coding scheme, and the D2D group destination ID. Each UE listens continuously to the PSCCH channel to detect if another UE is transmitting in the current sidelink period. Once the PSCCH message is received, the relay node tunes to the corresponding resources in the physical sidelink shared channel (PSSCH) to receive the emergency data.

IV. Multi-Hop Emergency call protocol (M-HELP)

Due to the specificity of emergency call service under large disaster conditions, we aim for an emergency call protocol that is as light as possible. M-HELP protocol is a fully distributed protocol with a zero control charge. Here zero control messages means the proposed method does not add new control messages but utilize the control messages, as standardized by 3GPP, used for out-band D2D without a change. Thus, already existing control signals are taken use to implement the M-HELP and there are no additional control messages in the design. Its objectives are to maximize the probability that the emergency call reaches at least one base station with minimum delay and with a reasonable number of exchanged messages.

M-HELP procedures used by an emergency device and relay device are summarized in the algorithm 1 and algorithm 2 respectively. When a mobile generates an emergency call, the emergency service constructs a data message including the emergency data (rescue video, voice, or text), user ID, emergency class, eventually the mobile localization, eNB/gNB serving station ID and observed SINR. If the emergency source mobile is under the coverage of a given base station, then the emergency call is sent using the classical uplink communication (PRACH and PUSCH channels). Otherwise, a D2D communication procedure is started. First, a PSCCH message is sent announcing that emergency data will be sent during the next sidelink period. The parameters included in PSCCH inform the receivers about the subframes (TRP) and frequencies (RIV) used to transmit the emergency data over the PSSCH channel. The PSCCH includes a destination group ID equal to "ANY" to indicate that all the mobile phones are concerned. After sending the data over the PSSCH channel, the emergency source phone counts, during a period of T_0, the number of relay devices of its own message. If this number exceeds a given threshold $RS_{\text{threshold}}$, the phone considers that the emergency call is sufficiently relayed, otherwise the emergency call is resent until the maximum number of re-transmissions, n_0, is reached. In addition, the reverse communication time for the network to reach an emergency device is not evaluated and assumed to be negligible. Thus, the continuation of help requests even after a successful transmission is prevented.

Once an emergency call is received, the relay device r checks if the message was already received and processed. If the emergency message is not already processed, r computes a waiting time, T_r, according to (1). During the period T_r, the device r counts the number of times that the just received message is relayed by other devices. If this number, after T_r, is lower than $RS_{\text{threshold}}$, r relays the message after adding its own localisation. Similar to the emergency source phone, the relay device r checks whether it is under the coverage of an available base station or not to determine if it needs to send the message in a classical or D2D mode.

The computation of the waiting time T_r aims to prioritize the devices according to their current state. Devices with a lower state of charge (SoC), out of coverage, or with lower localization accuracy wait longer before taking the decision of relaying the received emergency call. Longer T_r allows the device to wait for the decisions of the devices with a better state. Therefore, a device relays an emergency call, only if the number of relay devices in a better state is not sufficient. To prevent a very long waiting time, a maximum waiting time T_{max} is defined. Further, the relay UE process one call at a time and ignores other calls received while it is busy. However, a single relay UE processes multiple call requests.

$$T_r = \min\left(T_{\text{max}}, \frac{1}{\text{LocAcc}_r + \delta} \times \frac{1}{\text{Ic}_r + \delta} \times \frac{\text{SoC}_{\text{max}}}{\min\left(\text{SoC}_{\text{r}}, \text{SoC}_{\text{max}}\right)} \times \text{T}_{\text{cycle}}\right) \qquad (1)$$

V. Simulation and Results

To assess the performance of the proposed multi-hop emergency call service, we implemented M-HELP using AnyLogic® software [25]. We studied a covered area of 7.5km$\times$10.5km. Under normal conditions, the mobile network presents 8 base stations and 100 emergency service enabled devices. For each scenario considered, in the simulation results, hundred different random replications were done, changing the position of the UEs and the devices at which emergency occurs. Finally, the average value of the outputs was obtained and plotted. Further, the emergency calls were generated at random time instances from a uniform distribution over the time interval considered. The base stations are numbered as shown in Figure 4 and get damaged in the order of 1 to 8, due to the catastrophe. The emergency data transfer takes T_{d2d} seconds. Mobile devices are considered monotasking, which means that during the emergency procedures (algorithms 1, 2), the device can not process other requests.

Algorithm 1: Emergency device

input data: emergency data, myID, T_0, $RS_{\text{threshold}}$, I_{TRP}, RIV, MCS, n_0
DATA.content = emergency data; DATA.srcID=myID
if I am out of coverage **then**
  nbAttempts=0
  repeat
    send PSCCH with I_{TRP}, RIV, MCS
    send DATA by PSSCH channel
    start=now()
    while now()-start $< T_0$ **do**
      if I receive PSSCH **then**
        mess=received data
        if mess.DATA.srcID==myID **then**
          $N_{RS}++$
        end if
      end if
    end while
    if $N_{RS} > RS_{\text{threshold}}$ **then**
      EXIT
    end if
    nbAttempts++
  until nbAttempts > n_0
else
  send DATA using ordinary link (RACH + PUSCH)
end if

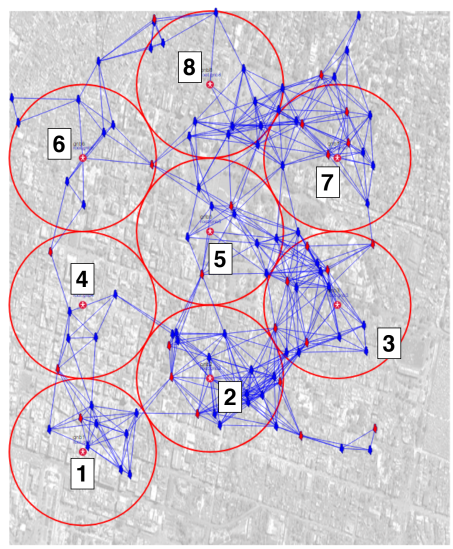


Figure 4: Screenshot of our anyLogic®simulator: studied scenario with 8 gNBs and 100 randomly distributed devices. Linked devices (resp. device-to-gNB links) represent D2D (resp. traditional) communication possibilities. Red circles represent the gNBs' covering areas.

A. Experiments

As depicted in Figure 4, mobile devices are randomly distributed over the network area. The fixed parameters used for the simulation are presented in Table. I. Further, the random numbers required for the random parameters were generated using a uniform distribution over the considered interval. Choosing values for T_{max}, threshold of relaying UEs

Algorithm 2: Relay device

```
input data: received data, LocAcc, SoC, T_max,
    RS_threshold, I_TRP, RIV, MCS
toRelayMess=received data
if (not already relayed message from
    toRelayMess.DATA.srcID) && (mode == idle) then
    compute T_r
    start=now()
    mode = busy
    while now()-start < T_r do
        mess=received data
        if mess.DATA.srcID==toRelayMess.srcID then
            N_RS ++
            if N_RS ≥ RS_th then
                EXIT
            end if
        end if
    end while
    if N_RS < RS_threshold then
        if I am out of coverage then
            DATA.content = toRelayMess.DATA.content +
                myLocation
            DATA.srcID=toRelayMess.DATA.srcID
            send PSCCH with I_TRP, RIV, MCS
            send DATA on PSSCH channel
        else
            send DATA using ordinary link (RACH +
                PUSCH)
        end if
    end if
    mode = idle
end if
```

($RS_{\text{threshold}}$) and upper limit of re-transmissions (n_0) was done empirically. However, the singular impact of those parameters will be discussed in depth for the different scenarios in the extended versions of this work.

To assess the performances of M-HELP protocol, we considered three quality metrics: success rate, the average number of D2D messages per node and emergency call latency (average and worst-case values). This latency is the delay of the call transmission from the end device to the network infrastructure. This includes all the delays caused by processing, buffering data during the waiting time latency, re-transmission and transfer times. The reverse communication from network to emergency device is not considered since it is assumed that the emergency aid providers communicate with the emergency device directly using the location information available on the emergency device. Thus, reverse communication and its delay are not evaluated. The *success rate* represents the ratio of the number of emergency calls that reach at least one base station. The performances of the protocol are evaluated by varying the number of functional base stations, the total number of emergency calls and the interval of time during

Table I: Simulation parameters

Parameter	**Value**
Network area	7.5×10.5 km^2
gNB coverage	1.5 km
Total gNB number	8
Total UE number	100
T_{cycle}	1 sec
UE's localization accuracy	RAND (0.001,1)
Initial UE's SoC	RAND(0,100) J
Maximum waiting time (T_{max})	120 sec (2 min)
Delay for emergency re-transmission, T_0	5 minutes
D2D link connection range	1.5 km
Data transfer delay per D2D link, T_{d2d}	60 sec (1 min)
Threshold of relaying UEs, $RS_{\text{threshold}}$	2
Upper limit of re-transmissions, n_0	3
Distribution of UE spread	RAND(7.5, 9.5) km^2
Number of emergency calls	variable
Emergency calls occurring interval, ETI	variable
Number of operational gNBs	variable [1..8]

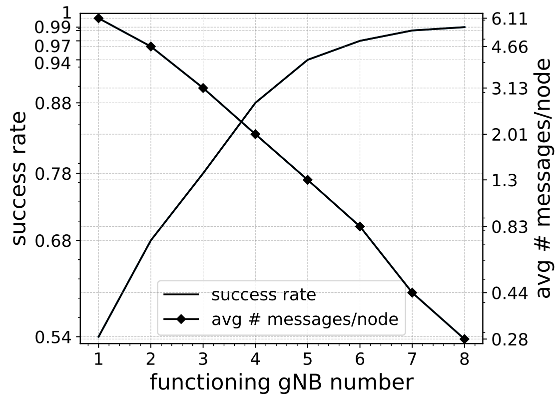
which emergency calls occur (ETI). The simulation of different numbers of base stations allows us to observe how the protocol performs under different degrees of damage.

B. *Performances analysis*

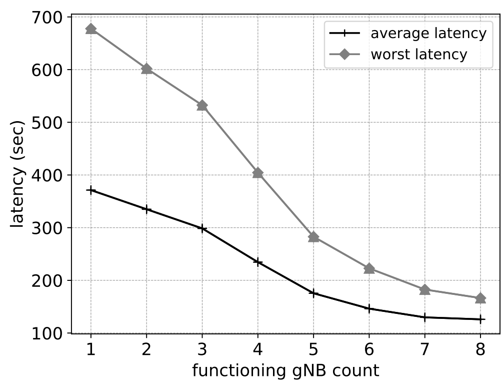
First, we studied the variation of the average number of sent messages per device and the success rate according to the number of operational base stations. Figure 5(a) shows that when there is just one functional base station, the success rate is above 50%. Furthermore, the success rate exceeds 85% when the number of functional base stations is bigger than 4. Also, we observe that the average number of call forwarding per node increases when the number of available base stations decrease. Indeed, the emergency calls need more hops to reach the few remaining base stations.

Figure 5(b) shows the variation of worst and average latency for the same scenario as Figure 5(a). According to the used $T_0 = 300s$ and $T_{\text{max}} = 120s$, the worst latency to reach the first base station is around 25 minutes when only one base station is working. The average latency reaches 13 minutes (800s) for the single working base station case.

Figure 6(a) shows the variation of the average number of sent messages per node and the success rate according to the number of emergency calls occurring in 1 hour. Two cases are tested: 1 functional gNB and 8 functional gNBs. As expected, the success rate is the highest when all the gNBs are working since the probability that the emergency source is close to a working station is high. This is reflected in the low number of sent D2D messages (less than 0.2 per node). However, for a single working gNB case, the success rate falls below 20% with 80 emergency calls. The success rate of M-HELP remains acceptable when the number of emergency calls is reasonable. We recall that devices are considered monotasking and during the processing of an emergency call, a device can not respond to another request. Therefore, the success rate of M-HELP protocol is highly underestimated, since current technological progress allows to manage several requests at the same time.

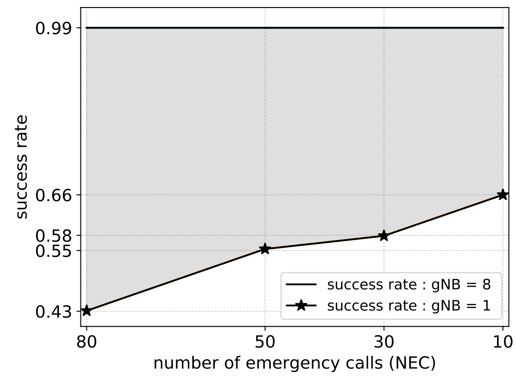


(a)

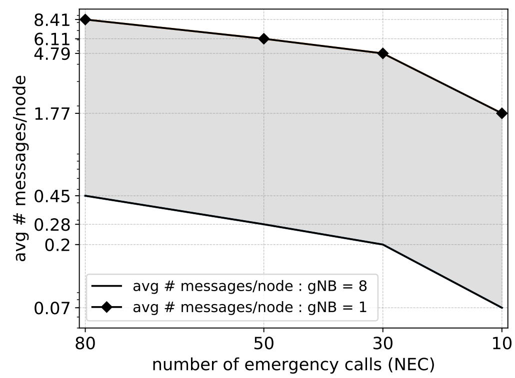


(b)

Figure 5: (a) Variation of the average number of D2D sent messages per node and the success rate according to the number of operational gNBs (b) Variation of the latency according to the number of operational gNBs. Parameters are: 50 emergency calls occurring during one hour.



(a)



(b)

Figure 6: (a) Variation of the success rate according to the total number of emergency calls (NEC) and (b) Variation of the average number of D2D messages per node according to the total number of emergency calls (NEC). Parameters are: emergency calls occur during one hour. Two cases considered : all gNBs are operational and only one gNB is operational

Figure 7(a) shows the variation of the average sent messages per node and the success rate according to the interval of time during which the emergency calls are generated. The number of generated emergency calls is fixed to 50 and the number of functional gNB is 2. Figure 7(a) shows that the success rate increases when emergency calls are spread over a longer interval period. Indeed, a relay device processes the first received emergency call and ignores the others until it finishes the algorithm 2. When the emergency calls arrivals are concentrated in a short interval of time, the probability that an emergency call is ignored increases leading to a lower success rate. In Figure 7(b), we observe that when the emergency calls are sufficiently spread over time, the risk that a relay device is in a busy state decreases, making that the number of exchanged messages increases too. Furthermore, we observe that messages exchanging finishes by around 5 to 30 minutes after the generation of the last emergency call due to the use of control thresholds, $RS_{\text{threshold}}$ and n_0. Most importantly, Figure 7(b) shows the network resiliency achieved by M-HELP. The network traffic is kept controlled such that the average data traffic per node reach a limit and remains constant with time.

Finally, we studied the auto stabilization process of M-HELP protocol. Figure **??** shows the variation of the average number of sent messages per node according to the number of operational gNBs under 20, 50, and 80 emergency calls. When the network is not seriously damaged, the D2D communication is rarely used. The intensive use of D2D appears when more than 50% of the network are damaged.

C. Comparison with FINDER protocol

In order to guarantee a fair comparison between the two protocols, the same values used for parameters in [23], that proposed the FINDER algorithm, were used in our simulation The results obtained are shown by Figures 9(a), 9(b) and 9(c). It is observed that M-HELP has a higher success rate and

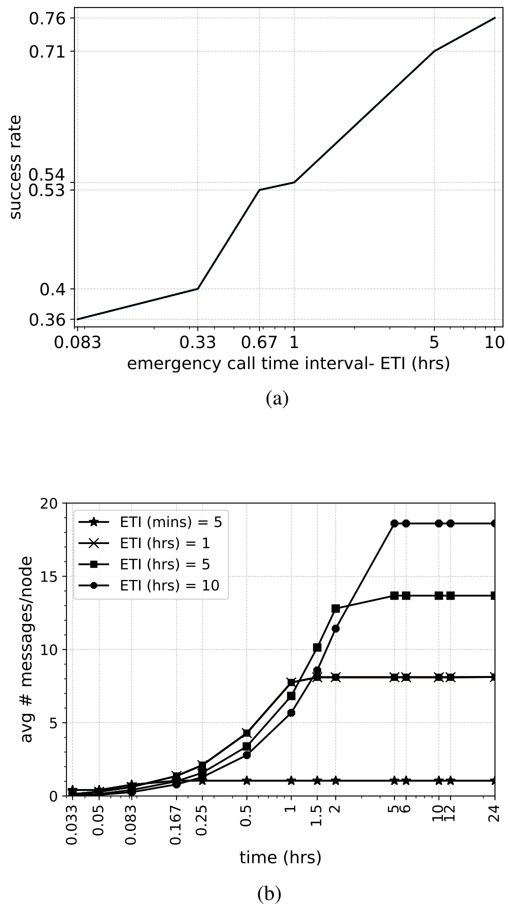


Figure 7: (a) Variation of the success rate according to the interval of time during which the emergency calls occur (ETI) and (b) Progression over time of the average number of D2D messages per node. Parameters are: 2 operational gNBs and 50 emergency calls. On the abscissa, the time is displayed in logarithmic scale.

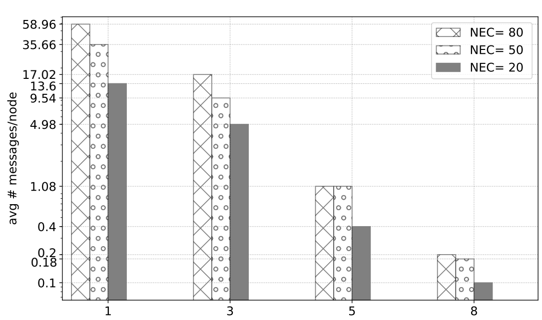


Figure 8: Average number of D2D messages per node after auto stabilization according to the number of operational gNBs. Parameters are: emergency time interval (ETI) is 5 hours, number of emergency calls (NEC) = 20, 50 and 80.

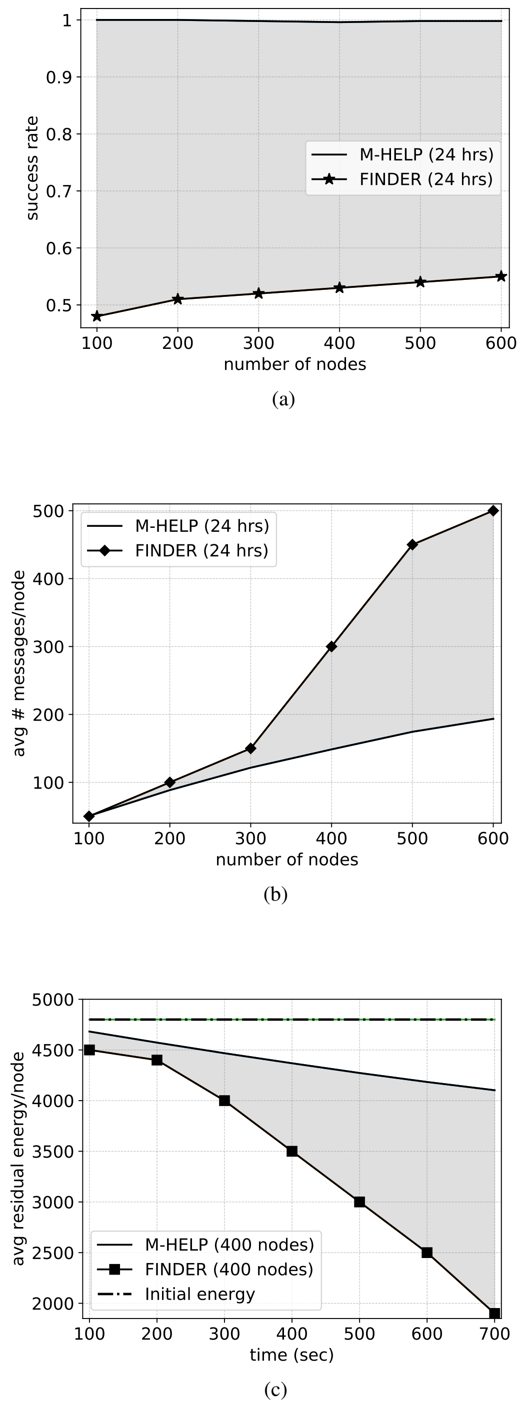


Figure 9: Comparison of our approach with FINDER protocol. (a) Variation of the success rate according to the number of nodes, (b) variation of the average number of sent messages according to the number of nodes (c) variation of residual energy according to the number of nodes. Parameters are: 1 operational gNB, energy to transmit a message = 0.08 mJ, energy to receive a message = 0.05 mJ, random number of calls occurring over 24 hours.

residual energy than FINDER protocol and provides a lower average messages per node. The reason is that devices, in FINDER protocol, relay the emergency call only to the cluster head (CH). The CH aggregates the received data and sends it to nearby CHs. This results in a high traffic concentration on CHs and reduces the success rate. Furthermore, CHs consume higher energy than ordinary devices.

Comparison to that, M-HELP adopts a massively distributed approach where there is no weight on a particular device to relay the emergency call to the gNB. Since the relay devices listen to the transmissions of the same emergency data, before transmitting it on their own, less traffic is generated in the network. Further, the stronger relay devices transfer the message before any other relay device in the neighborhood.

The computation of the waiting time T_r in (1) offers a dynamic and distributed way to select the stronger relay devices. This avoids high data congestion at one relay device, disperses the traffic among the network devices and conserve the energy of the intermediate relay devices. Comparing to FINDER, the lightness of the protocol adding less weight on the relay devices and utilizing the stronger devices to transmitting the emergency data are the major contributions of M-HELP. A drawback of M-HELP, is keeping the value of maximum waiting time, T_{max}, fixed which can effect the residual energy in the relays with low battery levels

VI. Conclusion

This work addressed the problem of connecting victims in out of coverage areas back to an operational network, during a large catastrophe where the 4G/5G network infrastructure is damaged partially.

Multi-hop emergency call protocol (M-HELP) is a distributed and fully 3GPP compatible protocol with zero additional control messages. M-HELP autonomously transfers emergency calls from out of coverage areas to base stations using device to multi-device sidelink communications. The idea is to propose a light, practically feasible protocol on top of the existing standardized technologies.

The performed experiments show the performance of M-HELP in terms of the success rate, latency and traffic redundancy management. Additionally, the performance of M-HELP is compared with FINDER protocol. Tests show that M-HELP provides a higher success rate, higher average residual energy per node and lower average number of sent messages per node than FINDER.

M-HELP protocol represents an efficient basis for emergency service implementation. However, the study of the impact of each used parameter ($RS_{\text{threshold}}$, n_0, T_0, T_{max}) on the protocol behavior should be done. Adaptive and dynamic mechanisms for setting the values of these parameters according to the number of detected emergency calls are under-study. The computation of the waiting time T_r has to be improved by introducing the SINR data. The objective is to avoid selecting a relay device farther from the operational network than the emergency device.

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