Adaptive Emergency Call Service for Disaster Management

Vishaka Basnayake, Hakim Mabed, Dushantha Nalin K. Jayakody, *Senior Member, IEEE*, Philippe Canalda .

Abstract*—Ubiquity and accessibility of cell phones make the cellular networks an indispensable tool for disaster management. Indeed, the density of cell phones and progress in device to device (D2D) communication protocols provide the ideal setting for the extension of the network coverage and the improvement of its resilience. In this paper we propose 5G-SOS protocol service to keep potential victims connected to the 4G/5G core network through relay user phones, even if a large fraction of the network infrastructure is fully destroyed. Unlike previous proposed services, 5G-SOS fulfils the criteria necessary for a real implementation of the protocol. In fact, 5G-SOS protocol ensures a minimal disturbance of the both end-user devices and the core network operation. In addition, the protocol dynamically adjusts its parameters according to the emergency call charge in order to optimize the success rate and the transfer time of the emergency calls. A densely populated Traverse city of Michigan, USA, with a 15000 population, was used to evaluate 5G-SOS. Extreme emergency scenarios were studied under 5G-SOS and compared with protocols namely, M-HELP and FINDER, in terms of transmission success rate, latency, network traffic control and energy management.

***Index Terms*—disaster management, emergency call protocol, latency, self-adaptive, transmission success rate, 4G/5G emergency service, 3GPP, D2D**

I. INTRODUCTION

A self-adaptive, efficient, and easy to access emergency call service is paramount during a large disaster. When such a disaster strikes, impacted people face the risk of not being rescued on time especially when the number of victims is high and disaster affects the network infrastructure itself. Although it is difficult to prevent natural disasters and pandemics such as Tsunami in 2004 and COVID-19, disaster management allows to mitigate their effects and improve the disaster impact assessment process and response actions [1]–[3]. As seen in Figure. 1, the collection of data about the victims, e.g., number of victims, degree of emergency, geographical distribution, and mobility conditions, provide some crucial information to calibrate and schedule the rescuing actions during the impact assessment phase. In this context, personal public communication systems play a key role and provide the easiest and fastest way to gather such data.

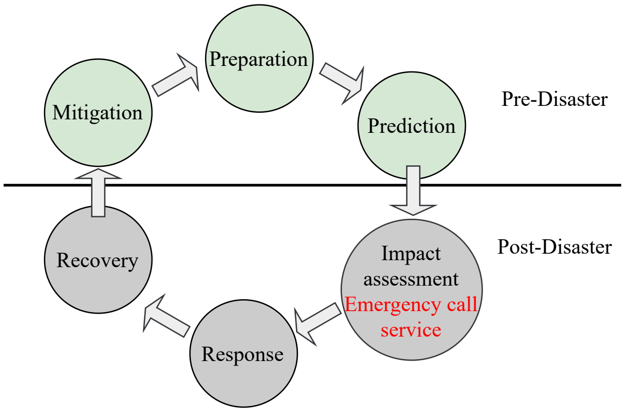

Figure 1. The actions performed before and after a disaster are given by the disaster management cycle. An efficient emergency call service is required to provide necessary information for the response and recovery phases in disaster management.

Cellular networks are particularly useful during the first minutes after a disaster: for both organizing and coordinating the response and impact assessment. The victims' identification and the coordination of emergency response teams are the keys to the success of the assessment and response phases of the disaster management action as shown in Figure. 1.

- *Response phase*: Public safety services coordinating the rescue actions use a narrow band terrestrial trunked radio (TETRA)-based systems that can only support voice services [4] and concern specific devices. Using cellular technology in public safety allows communication with much less cost and time constraints. Many applications and protocols [5], [6] were proposed for public safety services based on cellular network technologies [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. The evolution of such specifications with their respective 3GPP release are illustrated in Figure 2.
- *Impact assessment*: During the earlier minutes of the disaster, it is important to maintain connectivity with all users, .i.e, potential victims, in such a manner that all the emergency messages get collected. D2D mechanism allows to extend the radio coverage of gNodeBs (gNBs) by using the user equipment (UE)s as relay stations. D2D communications raise many questions concerning power control, resource allocation and interference man-

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agement [8]. Also it can compete with and impact the usual communications. However, this impact is negligible during a disaster situations where priority may be given to emergency calls.

Despite the works on D2D use during disaster scenarios, the real implementation of such solutions faces two major obstacles. The first obstacle is tied to the several challenges associated to the cohabitation of D2D communications and the traditional uplink/downlink communications [9]. Emergency call service should be light enough to not disturb the normal functioning of the user phones. Secondly, the proposed emergency call protocol should manage in fully distributed way, when the network infrastructure may be damaged, the traffic fluctuation and the radio resource access.

A lot of these works employ additional external devices which costs time and reduces the system responsiveness. The other works all adopt a clustering based topology that induces a huge control traffic to elect the cluster heads. Moreover, such approaches are not tolerant to the CH failing and make heavy demands on some devices, thereby ignoring the privacy of the phones.

The proposed emergency call protocol, called 5G-SOS (5G StandalOne Service), is at the best of our knowledge the first full 5G-NR compatible emergency call service with zero-control traffic and adaptive behavior to the emergency charge. These two characteristics argue for the real implementation of the protocol in 5G NR networks.

The remainder of this paper is organized as follows, Section II provides an overview of other related works, while Section 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 existing protocols and Section VI concludes the paper.

II. RELATED WORKS

The following review of the literature confirms that specific initiatives are required for emergency disaster management. Multiple performance metrics, e.g., end-end latency, availability, deployability, energy consumption, stability, security, determine the success of such solutions.

A. 3GPP works

Even if dealing with disaster situations is well studied in ad hoc networks literature [10]–[12], the projection of those solutions over 4G/5G cellular standards is rarely studied and remains difficult. Besides, the user equipment (network nodes) are not owned by the system itself making that the protocol possibilities are more regulated and constrained than in private/community networks such as MANET, VANET systems [13], [14]. Therefore, the emergency call protocol has to be as light as possible with less control and redundancy traffic.

Two main approaches in *Mission Critical services* were introduced by 3GPP group concerning proximity-based services in 4G/5G mobile networks; extending the gNBs coverage by using the D2D [15], [16] and supporting the group calling communication, also referred as, push to talk (PTT) service [5], [17]. PTT is described in TS 22.179 of 3GPP standard [18] and [19].

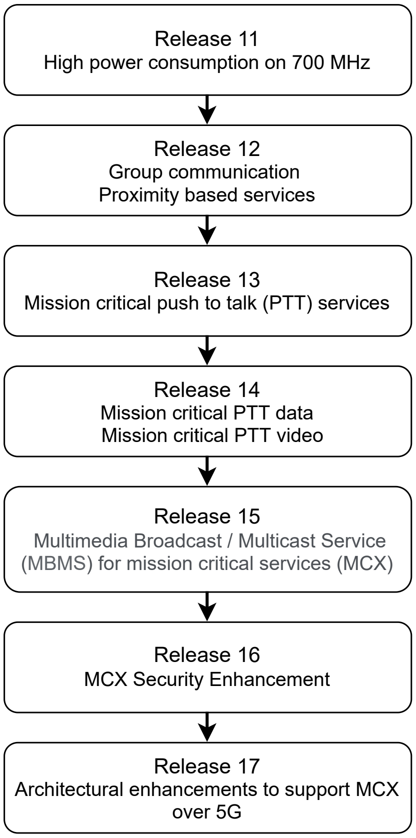

Figure 2. Evolution of the 3GPP specifications for missions critical/emergency scenarios using proximity-based services under each release from 11 - 17.

Although PTT and D2D mechanisms present a way to extend the network coverage and services, these technologies are conceived for well-deployed local mobile networks. An extended networking protocol using such mechanisms is required for implementing an emergency call service functional under extreme situations, i.e., a high number of emergency calls, the partial failure of the network, a large geographical area affected, to forward the calls reliably to the core network.

B. Wireless network recovery

Some works of the literature [6], [20], [21] addresses the resilience and self-adaptation of the mobile networks to face a disaster affecting the network infrastructure. In Table I, the research works on recovery solutions for wireless networks are presented. The extended architecture based approaches complicates the 3GPP compatibility in communications and add extra infrastructure costs. In this case, external or movable physical units such as satellite [22] or unmanned air vehicles (UAV) [23]–[26] are deployed to rapidly work as a stand-in for damaged network facilities.

Moreover, resilient architecture-based approaches are less disruptive to the 3GPP specifications. In [27], the authors proposed to relax the dependencies between UEs, gNBs, and the core network. The objective is to provide more resilience against link disruptions by using the virtualization/redundancy

Table I
ANALYSIS OF SELECTED NETWORK RECOVERY SOLUTIONS FROM THE LITERATURE.

work paper	ext. arch.	resilient arch.	resilient app.	resilient proto.	3GPP compa.	out of cov.
[24]	x					x
[25]	x					x
[22]	x					x
[23]	x					x
[21]		x			x	
[27]		x			x	
[28]			x		x	
[29]			x		x	
[30]				x		x
[31]				x		x
[32]				x	x	
[33]				x	x	
[34]				x	x	x
[35]				x	x	x

of the links and functionalities. Although this approach is efficient for localized perturbations, it remains inefficient when the disaster impact is over a large geographical area. The application-based approaches try to manage the reliability and the robustness issues on the service layer [28], [29]. The application has to detect the communication failure and has to adapt the transfer mode accordingly (use of other wireless technology, other coding schemes, data substitution, etc.).

Resilient protocol based approach is widely discussed for ad hoc networks [30], [31]. However, those protocols are incompatible with 5G network specifications. Some resilient based protocols compatible with 3GPP standard are proposed such as [32], [33]. Nevertheless, most of these protocols can not be used in an out of coverage situation when the disaster affects the network infrastructure.

However, FINDER protocol in [34] represents one of the rare works on the massive use of D2D mechanisms to overcome large disaster situations. In FINDER, emergency calls are forwarded to working gNBs by clustering and organizing the out of coverage mobile devices. There is a cluster head (CH) in each cluster that is selected by the members of the cluster. The CH receives emergency calls transmitted by mobile nodes within its cluster. The CH aggregate and transmit them across the neighboring CHs to the nearest active gNB via multi-hop D2D communications. The procedure suffers from the complexity of clusters computing and the lack of resilience against cluster head failure. On the other side, the use of personal UEs to serve as cluster heads is not practical.

On top of that, M-HELP [35] is another resilient protocol designed to address large disaster scenarios using D2D. M-HELP adds zero additional control messages to the network. Further, it has been shown that M-HELP has a better performance in terms of successful transmission reliability, network congestion and residual energy compared to FINDER. However, the robustness of M-HELP remains a challenge under scenarios with varying emergency call loads, scale of disaster, D2D transfer delays, UE densities. Hence, 5G-SOS is proposed to improve the robustness of M-HELP under such scenarios using available neighborhood data.

III. MULTI-HOP D2D FOR EMERGENCY CALL SERVICE

Let N be a set of gNBs composing the 4G/5G cellular network and M be the set of UEs distributed within the network area. In this work, it is assumed that all UEs $\in M$ are 4G/5G emergency service enabled. In such a network area, each UE can behave both as an emergency call initiator or a relay. Since a disaster scenario is evaluated, first it is assumed that the UEs are stationary and their location is fixed. The mobility of nodes is evaluated separately for a specific scenario in the simulation results section.

The two modes of emergency call transmission, D2D and classical, are illustrated in Figure 3. In this example, three UEs (orange, blue, and red) are in an emergency and are out of coverage due to the failure of the covering gNB. The orange UE sends a broadcast D2D message that is only received by one UE and then relayed in the classic mode to the operational gNB at the top of the figure. The emergency call of the blue UE is sent in D2D mode and is received by three UEs. The two relay devices in black transfer the emergency call to both working stations, while the red UE ignores the blue UE's emergency call because its RSSI is worse than the blue UE. The red UE diffuses its emergency call to the blue UE, which relays it to all neighboring UEs until the emergency call reaches the working station at the bottom of the figure. The transmission redundancy allows improving the reliability of the protocol. However, the number of copies of the same message has to be controlled to prevent radio network saturation.

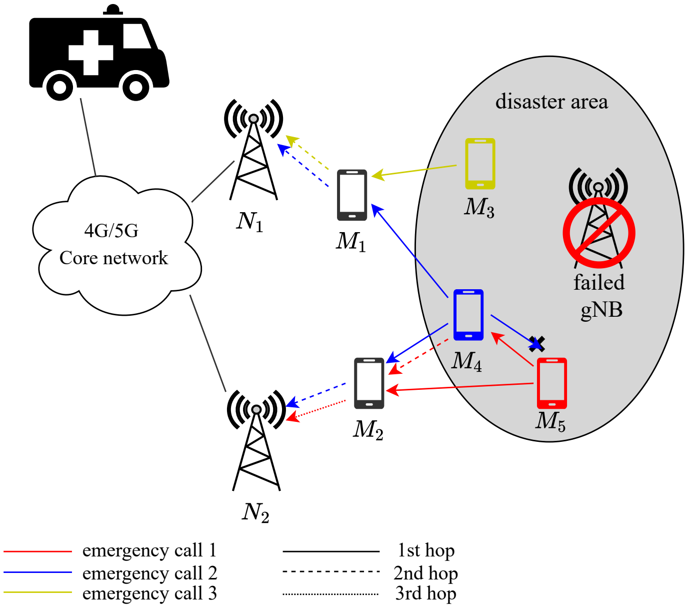

Figure 3. The proposed emergency call service architecture. Emergency UEs in the disaster area forward their calls in the direction of the functioning gNBs via relay UEs in the neighborhood. Distinct emergency calls generated by each emergency UE are represented by the color of the arrow. Solid lines indicate the D2D communication mode while dashed lines indicate the classical communication between gNB and UE.

A. *Informational model*

Each device $m \in M$ is characterized by the following data:

- current battery level (residual energy), $\mathrm{SoC}_m \in [0, 100]$
- coverage status by at least one gNB, $\mathrm{Ic}_m \in \{0, 1\}$:
  The coverage status indicates if the UE has at least one direct communication link with a station $n \in N$, allowing it to communicate directly with the core network. When a UE is out of coverage, it no longer has a direct connection link with the gNBs.
- GPS localization accuracy, $\mathrm{LocAcc}_m \in [0.001, 1]$:
  Location information is obtained using the GPS measurement. It is assumed that the error in such GPS measurement is represented by the distance between the actual position and the estimated position of m, $\delta_m \in [0..\infty]$ measured in meters. Hence, LocAcc_m is modelled as,

$$\mathrm{LocAcc}_m = \frac{1}{\delta_m + 1} m^{-1}. \tag{1}$$

  where LocAcc_m can take a value between 0.001 and 1.
- RSSI signal power that is detected, RSSI_m:
  The broadcast physical layer synchronization signals (PBCH) periodically transmitted by the operational gNBs enable the UEs to establish quality indicators, including RSSI, RSRP, RSRQ, SINR and CQI up to 75 km from the gNB [36], [37]. These measured indicators are useful in the selection of the best paths toward the nearest operational gNB.
  The RSSI indicator [38] is measured by each UE to estimate the strongest signal received from the surrounding operational stations $g \in N$ as shown in (2). The RSSI value depends on device location and more specifically on the signal path loss [38] between the gNBs and the device. Signals' path loss, namely $P_l(d, f)$, is varied due to the propagation parameters such as the distance between gNB and receiver UEs, height and location of UEs, transmission frequencies, terrain contours, environment.

$$\mathrm{RSSI} = \max_{n \in N} \left(\mathbb{E} \left(\sum_{rb \in RB} P_t(n) - P_l(d, f) \right) \right), \tag{2}$$

  where $P_t(n)$ is the power of the transmitted signal by a given station n. RB represents the set of radio resource blocks used to transmit the PBCH signals. RB corresponds to the set of OFDM symbols and sub-carriers on which the PBCH is transmitted. For each operational station, the user equipment (UE) computes the average received signal power [39] over all the symbols and sub-carriers, f, of RB. Finally, the UE only considers the highest computed average.

B. System model

The emergency call procedure can be triggered either by human intervention or automatically (e.g., after a car accident detection). Once the call is triggered, the emergency application starts incorporating the data related to the victim, i.e., voice, text, video message, the UE id emergency call id, indicators about the emergency degree (level), RSSI indicator and device position. If the emergency caller is within the coverage of a network gNB, then the call is directly sent to the gNB using the classical communication mode. However, if the caller is out of coverage, the call is locally diffused using out of coverage D2D procedure.

Once a relay receives an emergency call and decides to relay it, the relay adds its identifier, position, and RSSI value to the relayed message. Then the relayed message is sent using either the traditional mode if the relay is covered by a gNB or the D2D communication if the device is out of coverage. The emergency source position and relay's positions help the public safety center to localize precisely the source of the emergency call.

Once an emergency call is received by a given gNB, a notification is diffused to all the UEs under coverage, indicating the successful transmission of that emergency call with its specific ID. That way, redundant uplink transmissions of the same emergency call are reduced.

C. Out of coverage D2D procedure

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 UEs to send the sidelink control information (SCI) that informs the receivers about the data transmission parameters used during the next sidelink period: subframes and radio resource blocks [40]. 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. ADAPTIVE MULTI-HOP EMERGENCY CALL PROTOCOL (5G-SOS)

5G-SOS protocol is conceived with the main objective of alleviation of problems associated with lack of adaptability of M-HELP protocol [35]. Indeed, initial M-HELP protocol behavior depends on many constant parameters mainly used by the UEs to decide either to relay or not, the received emergency calls.

The 5G-SOS protocol aims to maximize the probability that the emergency call reaches at least one gNB with a minimum delay and with a reasonable number of exchanged messages. 5G-SOS procedures used by an emergency device and relay device are summarized in Algorithm 1, Algorithm 2, and Algorithm 3.

As detailed in Algorithm 1, when an emergency UE, E, generates an emergency call, *DATA*, the application layer constructs a data message including the emergency data (rescue video, voice, or text), GPS localization, observed RSSI and a couple of value $DATA.srcID$ and $DATA.callID$. *DATA.srcID* corresponds to the identifier of the source of the emergency call, E. $Data.callID$ is the internal identifier given

Algorithm 1: On emergency call generation

```
Input data: my srcID, emergency data, GPS localization, RSSI, $T_0$, $RS_{\text{threshold}}$, $I_{\text{TRP}}$, RIV, MCS, $n_0$
DATA.content $\in$ {emergency data, localization, RSSI}
Generation
DATA.srcID = my srcID, DATA.callID = callIDGenerator()
if I am out of coverage then
    nbAttempts=0
    repeat
        send PSCCH with $I_{\text{TRP}}$, 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.srcID == my srcID then
                    $N_{RS}++$
                end if
            end if
        end while
        if $N_{RS} \geq RS_{\text{th}}$ then
            EXIT
        end if
        nbAttempts++
        DATA.callID = callIDGenerator()
    until nbAttempts > $n_0$
else
    send DATA using ordinary link (RACH + PUSCH)
end if
```

Algorithm 2: On receiving an emergency call, DATA

```
if (!$\chi$.contains(DATA.srcID, DATA.callID)) then
    $\chi$.Push(DATA)
    if $\eta$.size() $< 3$ then
        Compute $T_r$
        DATA.deadline = $T_r$ + now ()
        DATA.$N_{RS} = 0$
        $\eta$.Push(DATA)
    end if
else if $\exists$ waitingCall $\in \eta$ such as (DATA.srcID,DATA.callID) = (waitingCall.srcID,waitingCall.callID) then
    waitingCall.$N_{RS}++$
    if waitingCall.$N_{RS} \geq RS_{\text{th}}$ then
        $\eta$.Remove(waitingCall)
    end if
end if
```

Table II
NOTATIONS USED IN ALGORITHMS 1,2,3

Notation	Description
η	FIFO list of calls in the buffer to be relayed
χ	List of calls already received and processed in the past
DATA	Emergency call
srcID	Identifier of the source device
callID	Identifier of the emergency call
callIDGenerator	Function used by each UE to generate unique call IDs
waitingCall	A call stored in η
deadline	latest time by which a waitingCall is transmitted
nbAttempts	Count that *DATA* was trasnmitted or relayed
relay	relay device information content in DATA

Algorithm 3: Every one second

```
Input data: my srcID, GPS localization, RSSI
for all waitingCall $\in \eta$ do
    if now () >= waitingCall.deadline and my State is "idle" then
        my State ="busy"
        if I am out of coverage then
            DATA.content = waitingCall.DATA.content
            DATA.relay.add (GPS Localization, RSSI,my srcID)
            DATA.srcID = waitingCall.DATA.srcID
            send PSCCH with $I_{\text{TRP}}$, RIV, MCS
            send DATA on PSSCH channel
        else
            send DATA using ordinary link (RACH + PUSCH)
        end if
        $\eta$.Remove(waitingCall)
        myState = idle
    end if
end for
```

by E to the emergency call using the function *callIDGenerator*. $callIDGenerator$ makes that whatever two different emergency calls initiated by E are, they have different $callID$.

If the emergency phone, E, is under the coverage of a given gNB, then the emergency call is sent using the traditional 4G/5G uplink communication (PRACH and PUSCH channels). Otherwise, a D2D communication procedure is opted. First, a PSCCH message is sent announcing that emergency data will be sent during the next sidelink radio frame 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 destination group ID of the PSSCH is set to "ANY" since it concerns all neighboring UEs.

Next, the emergency phone E counts the number of times its own call is relayed by the neighbors (see lines 10-17 of algorithm 1). To do so, each *DATA* is identified by the exclusive couple of values (*DATA.srcID,DATA.callID*). If the received message by the R is its own message (the same couple *(srcID, callID)*), then the number of relay neighbors, N_{RS}, is incremented. If after a period of $T_0, N_{RS} \leq RS_{\text{threshold}}$, the *DATA* is resent until the maximum number of re-transmissions, n_0, is reached. Every attempt is considered as new emergency call by changing the *DATA.callID* identifier of the message.

As described in Algorithm 2, once an emergency call is received, the relay device, r, studies the opportunity of forwarding it. First, r checks if the (*DATA.srcID, DATA.callID*) of the received *DATA* is in the already received calls list, χ. If it is new emergency call, r stores the received message $DATA$ in the list of being considered calls, η. η allows to manage up to 3 emergency calls simultaneously. Each emergency call in η is associated with two new fields: N_{RS} and $deadline$. N_{RS} is initialized to 0 and stores the number of times that the message *DATA* is relayed by other neighbors. $deadline$ gives the limit date of the call in η. $deadline$ is computed using the maximum waiting duration, T_r, as it is shown in line 5 of Algorithm 2. If the received message is already received (line 9 of Algorithm 2), r checks if the message belongs to the being considered messages η. If so, the number of times the waiting call is relayed $waitingCall.N_{RS}$ is incremented and the call is removed from η if this number reaches the number of relays threshold RS_{th}.

Every second, the relay phone r checks its η list as explained in Algorithm 3. If the *waitingCall.deadline* of a being considered call, $waitingCall$, is reached then the call is relayed after including, in the $DATA.relay$ field, the relay's data, such as the RSSI, GPS location and srcID and in $DATA.content$ the content of the received call $waitingCall$. According to whether r is in-coverage or not, the *DATA* is transmitted using the classic or D2D mode.

Moreover, only one emergency call is transmitted at a time and each device is associated with a state variable (my State) initialized to "idle". When the device starts to transmit an emergency call, the state is turned to "busy". During the busy state, the device continues to receive and queue emergency call requests.

A. *Waiting time, T_r*

The role of the waiting time T_r is to define an order between the relay devices in a fully distributed way. A short T_r means that the relay device is suitable for relaying the emergency call. When the T_r is long, the device relays the call only if necessary, i.e., the neighbor relaying is not sufficient. In other words, UEs with a low SoC, out of coverage, low RSSI signal, or with poor localization accuracy wait longer before deciding to relay the received emergency call. Therefore, longer T_r allows the UE to wait for the decisions of more suitable devices. To prevent a very long waiting time, a maximum waiting time $T_{\max}$ is introduced. In M-HELP [35], the waiting time is computed as follows:

$$T_r^{M-HELP} = \min\left(T_{\max}, \frac{1}{\text{LocAcc}_r + \delta} \times \frac{1}{\text{Ic}_r + \delta} \times \frac{\text{SoC}_{\max}}{\min\left(\text{SoC}_r, \text{SoC}_{\max}\right)}\right), \tag{3}$$

where the coverage state, localization accuracy and residual energy of r is given respectively by Ic_r, LocAcc_r and SoC_r. In the M-HELP protocol, $T_{\max}$ was fixed to a specific value. However, it is clear that the value of $T_{\max}$ should be adapted according to many factors such as the observed emergency calls rate and the UEs density. That is why the computation of T_r value is adjusted as follows:

$${T_r}^{5G-SOS} = \min\left(T_{\max}(n_k, n_c), \frac{\text{RSSI}_{\text{tx}}}{\text{RSSI}_{\text{r}}} \times \frac{1}{\text{LocAcc}_r + \delta} \times \frac{1}{\text{Ic}_r + \delta} \times \frac{\text{SoC}_{\max}}{\min\left(\text{SoC}_r, \text{SoC}_{\max}\right)}\right). \tag{4}$$

The parameter $T_{\max}$ is now expressed by a modified Rosenbrock [41], [42] function [1]. The Rosenbrock function given in (5) is modelled to increase the sensitivity of protocol to the real-time local factors such as the amount of emergency requests and neighborhood congestion detected in the previous minute.

$$T_{\max}(n_c, n_k) = \min(\max((a - n_c)^2 + b \times (n_k - {n_c}^2)^2, 0), u_b), \tag{5}$$

where n_c represents the total number of received emergency requests including multiple receptions during the last minute. n_c is used to measure the level of congestion in the neighboring environment in the past minute. Further, n_k measures the total number of different emergency call requests received in the previous minute. In addition, a and b are two parameters that govern the shape of the Rosenbrock $T_{\max}$ function in (5).

A low number of distinct emergency calls n_k with a high congestion level n_c expresses a low emergency load but with many relaying opportunities for each emergency request due to the network density. In this case, a high $T_{\max}$ value allows to better select the relevant relays. However, if both n_k and n_c are low, the $T_{\max}$ value is decreased since there are not enough relay alternatives, i.e., weakly dense network. Finally, when n_k is high, a lower $T_{\max}$ is preferable in order to quickly handle the newly received emergency requests. Further, if the number of neighboring relaying devices is less and such devices have a low battery level, they will be assigned a relatively shorter $T_{\max}(n_c, n_k)$ by 5G-SOS based on the low neighborhood congestion.

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[1] Rosenbrock is used often as a test problem for optimization algorithms. Rosenbrock is used in this work seeing that it has a slope with the same behavior to $T_{\max}(n_c, n_k)$ given in Table. III

Table III
EXPECTED BEHAVIOR OF T_{MAX} WITH n_c AND n_k

n_k	n_c	$T_{\max}$
↓	↓	↓
↓	↑	↑
↑	↑	↓

The expected adaptive behavior of $T_{\max}$ according to n_c and n_k value is summarized in Table. III. The curve of the original Rosenbrock function, f is given in Figure 4. When x increases while y is fixed, $f(x,y)$ increases. However, when y is increased, while keeping x fixed, $f(x,y)$ decreases gradually.

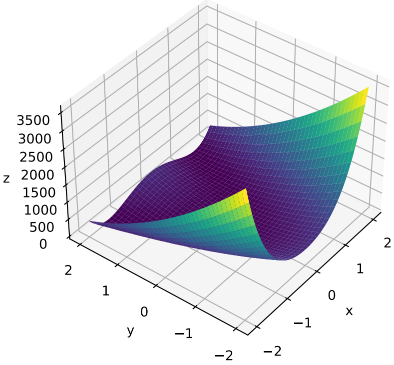

Figure 4. Illustration of the standard Rosenbrock function defined by two variables and given by $f(x,y) = (a-x)^2 + b(y-x^2)^2$. Here we assume a = 1, b = 100 and the minimum value of zero is at (1,1). Adaptive $T_{\max}$ given in (5) is based on the Rosenbrock function.

B. RSSI ratio

To compute the waiting time T_r, r uses its coverage state Ic$_r$, its localization accuracy LocAcc$_r$, and its residual energy SoC_r. However, (3) and (4) show that the protocol 5G-SOS introduces the use of RSSI in the computation of the waiting time parameter.

The ratio between the $RSSI_{\text{tx}}$ of the transmitter device that sent the call request, and the $RSSI_r$ of the r itself is computed. This ratio is higher than 1 when the transmitter of the emergency call is in better radio conditions than the receiver (farther from the gNBs). In this case, the ratio contributes to increasing the value of T_r^{AM-HLP} in order to penalize the receiver in its selection for relaying the emergency call. Otherwise, when the ratio is less than 1 the receiver is in better radio conditions (closer to the gNB), and the waiting time is decreased to give priority to the receiver.

The RSSI ratio is used to improve the latency fairness between UEs. Indeed, a relay device waits less time when the request is sent by a farther device than when the request is sent by a closer device as depicted in Figure. 5. Therefore, when two requests are received at the same time, the request of the farthest device from the gNB is transmitted first, which contributes to balance the emergency calls transfer delays.

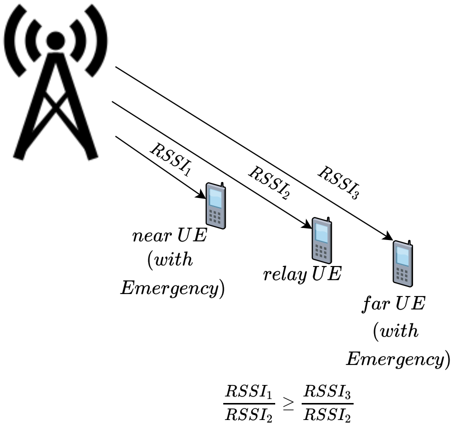

Figure 5. A relay UE gives higher priority for a far emergency UE than a near UE using the RSSI ratio. RSSI ratio in (4) is lower for a far UE than near UE. The relay UE waits a lesser time, hence relays faster, the transmissions of the far UE emergency call in the direction of a functioning gNB

C. Emergency call buffering

The 5G-SOS protocol enabled device uses two kinds of lists to store the history of received emergency calls. In the χ list, the device stores the identifiers of received calls represented by the couple $(srcID, callID)$, while the data of the emergency are not stored. To prevent the excessive increase of this list, the emergency calls are removed from the list after a given period (30 minutes). In the second list η, the device stores the pending received emergency calls. A call is removed from η when the T_r expires and the call is relayed by the device, or when the call is sufficiently relayed by neighboring devices. The size of η is limited to 3 calls. If the limit size is reached, new emergency calls are ignored as presented in Algorithm 2. The use of η is a new feature of the 5G-SOS protocol. In M-HELP protocol, only one emergency call is processed by the device at a given time. All emergency calls, received during the transmission of a previous emergency request or during the pending period before relaying a previous emergency call, are ignored.

D. Relaying threshold, RS_{th}

The parameter RS_{th} is a critical parameter that determines the balance between the reliability of the communication and the fairness in transmitting distinct emergency calls. If the RS_{th} of an emergency call is high, the probability that the call reaches a gNB becomes higher. However, under a dense network and/or a high number of emergency calls, increasing the number of relays threshold may lead to the saturation of network devices in the busy state, and many interference. Besides, late emergency requests are penalized or rejected since the first emergency requests remain longer in the pending requests list η. In 5G-SOS protocol, a device adjusts the value of its RS_{th} according to the real-time conditions following the expression:

$$RS_{\text{th}} = RS_{\text{th}}^{\text{max}} - |\eta|. \tag{6}$$

In the next section, the performance of 5G-SOS is discussed and compared to the M-HELP and FINDER protocols.

V. SIMULATION RESULTS

A. Test environment

1) Propagation pathloss model and RSSI: In 4G/5G networks, operational gNBs periodically broadcast control signals, PBCH, over predefined resource blocks. The RSSI of such signals was computed using (2), where $P_l(d,f)$ represents the path loss of the signal due to environmental factors, i.e, buildings, mountains, etc.

To compute the $P_l(d,f)$ in (2), the Cost231 propagation model for semi-urban areas, given in [43], was used. $P_l(d,f)$ of a signal transmitted by a working gNB varies according to the signal transmission frequency of the working gNB, f, and the distance between the working gNB and receiver UE, d, as given in (7). Further, h_g and h_m represent respectively the height of the gNB and receiver UE. C_m is a correction offset associated with the semi-urban environment. For the simulations, f was set to 885 MHz. $P_l(d,f)$ varies according to the used frequency, f, and the distance between a functioning gNB and a receiver UE, d, as given in (7). Further, the measured values of RSSI were handled in Watts.

$$\begin{aligned} P_l(d,f) = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_g) - a(h_m) \\ + (44.9 - 6.55\log_{10}(h_m)) \times \log_{10}(d) + C_m, \end{aligned} \tag{7}$$

with:

$$a(h_m) = 3.2 \times log(11.75h_m)^2 - 4.97. \tag{8}$$

2) RS_{th}: The maximum threshold for neighbor relaying, $RS_{\text{th}}^{\text{max}}$, was set to a constant and $|\eta|$ denoted the number of pending call requests in the UE buffer. The latter was used to estimate the number of different emergency calls being relayed in the neighboring area.

Further, the maximum limit for $|\eta|$ was assumed to be a constant. Hence, when the value of $|\eta|$ changes from a minimum to maximum, the RS_{th} adapts its value according to (6). In comparison, the value of RS_{th} was fixed in the M-HELP protocol.

3) Rosenbrock parameters: The values of a, b parameters in Rosenbrock function were empirically fixed for the three ranges of n_c as shown in Table IV. Figure 6, Figure 7 and Figure 8 show the impact of the n_c and n_k factors on the value of T_{max}.

Table IV
ADAPTIVE T_{MAX} MODEL PARAMETERS

n_c limits	a	b
$0 \leq n_c \leq 10$	1	0.5
$10 \leq n_c \leq 200$	1	0.2
$200 \leq n_c$	1	0.1

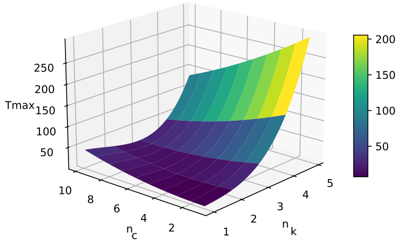

Figure 6. Variation of T_{max} against the total number of the received emergency requests including copies, n_c, and the total number of different emergency call requests excluding copies, n_k, received by a relay UE in the previous minute when the n_c observed in the neighborhood is between 0 and 10

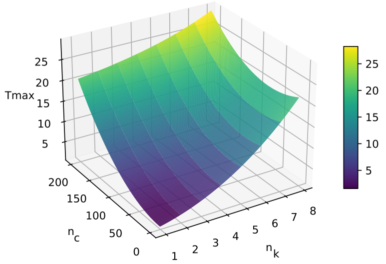

Figure 7. Variation of T_{max} against n_k and n_c when the n_c observed in the neighborhood is between 10 and 200

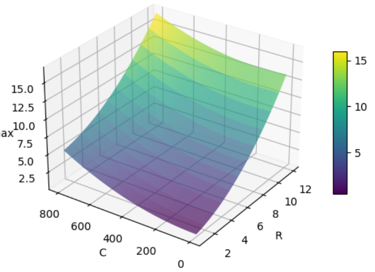

Figure 8. Variation of T_{max} against n_k and n_c when the n_c observed in the neighborhood is above 200

$$T_0 = T_{\text{max}}(n_k, n_c). \tag{9}$$

- Limits of n_c: was determined by applying M-HELP in each individual device in the network devices and n_c observed under 10 random replications were collected. The minimum and maximum limits of n_c for different device density values such as 100, 1000 and 4000 were gathered and were used as n_c limits possible to be observed by an UE given in Table IV.

4) Scenarios and tests: The performance of the proposed 5G-SOS, was assessed in AnyLogic® software. An emergency scenario in the Transverse city in Michigan USA with a number of devices varying between 5,000 to 15,000 and 7 working gNBs covering an area of 16.2 × 21 km^2 was considered. Further, such performance was assessed for a scenario where all nodes were stationary. In all the network protocols considered in this work, if the network nodes do not form a connected graph, emergency calls cannot reach the gNBs during a single emergency call initiation. Hence, the D2D link connection range was set in order to maintain such a connected network and NoU was set satisfying the condition, NEC<NoU. Other features of the mid-sized city scenario are given in Table V The provided results were all averaged over 10 random executions with the same input parameters. The random executions differ by the sources of the emergency calls and the events' arrival times. Table V summarizes the parameters used in the simulation scenarios. The emergency data transfer takes T_{d2d} seconds. During the emergency call transmission (D2D transmission or ordinary transmission) the UE cannot transmit other emergency requests.

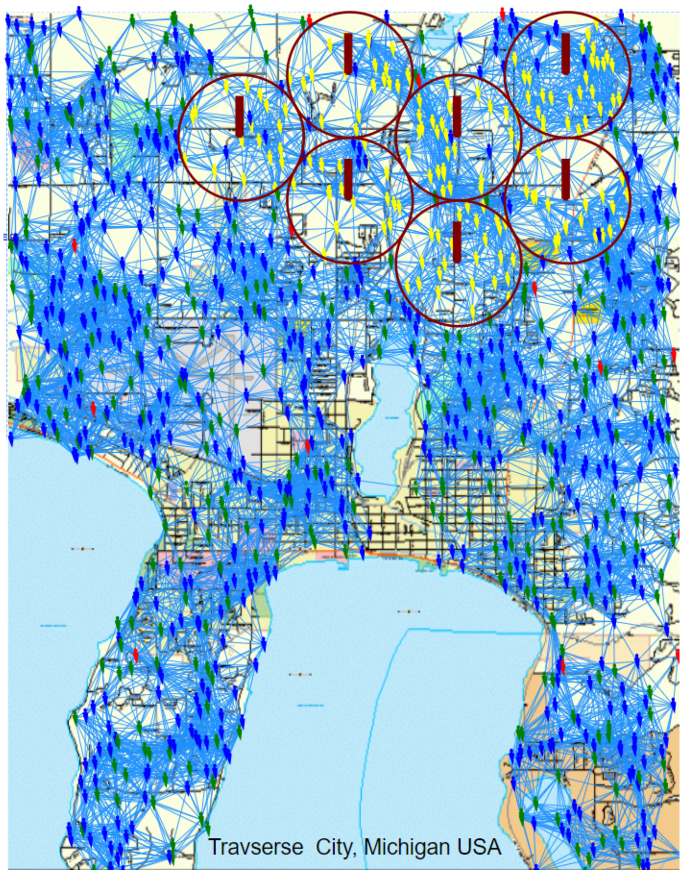

Figure 9. Studied scenario of the Traverse city in Michigan USA with 7 gNBs and 15000 randomly distributed UEs in the AnyLogic® software. Linked UEs (resp. UE-to-gNB links) represent D2D (resp. traditional) communication possibilities. Dark Red circles represent the gNBs' covering areas in which the gNBs are at the center. Victim (emergency) devices, relay devices, in-coverage devices and idle devices are represented respectively by the colors, red, green, yellow and blue.

5) *Evaluation criteria:* The following metrics were considered to assess the protocol efficiency.

- **success rate** represents the ratio between the number of emergency calls received successfully by at least one gNB/eNB and the total number of emergency calls.

$$\text{success rate} = \frac{\text{\#of successfully received emergency calls}}{\text{\#of emergency calls}} \quad (10)$$

- **end-end latency (EEL)** is the average delay between emergency call generation and its first successful reception by a gNB. EEL is measured in seconds and includes all the delays caused by processing, buffering, temporizing, and transmission times.

$$EEL = t_{\text{call}_{\text{reception}}} - t_{\text{call}_{\text{generation}}} \quad (11)$$

- **number of messages per node** represents the average number of relayed emergency calls per device.
- **energy consumption per node** measures the average energy consumption per device. This includes the energy consumed for the transmission and reception of emergency calls.

Table V
TRAVERSE CITY AREA EMERGENCY SIMULATION PARAMETERS

Parameter	Value
Total network area	16.2×21 km^2
Amount of working gNBs	7
Total UE spread	RAND(16.2,21)
Initial $T_{\max}$	120 sec (2 min)
Initial T_0	120 sec
UE's localization accuracy	RAND (0.001,1)
Initial UE's SoC	RAND(0,100) J
BS/gNB Link distance (d)	1.5 km
D2D link connection range	1.5 km
Data transfer delay by D2D mode, T_{d2d}	10 sec
Data transfer delay by classical PUSCH mode	1 sec
Maximum limit for RS_{th}, $RS_{\text{th}}^{\max}$	5
Upper bound of waiting time, u_b	120 sec
Upper limit of re-transmissions, n_0	4
Maximum number of messages in a UE buffer	3
Transmit power of gNB, (P_g)	300.0 dBm
Signal transmission frequency of gNBs (f)	885 MHz
BS/gNB antenna effective height (h_g)	100 m
UE antenna effective height (h_m)	1.5 m
Constant offset of Cost231 Hata model (C_m)	0 dB
Number of UEs, NoU	variable
Number of emergency calls, NEC	variable
Emergency calls occurring interval, ETI	variable
Energy to transmit	0.08 mJ [34]
Energy to receive	0.05 mJ [34]
Total Simulation running time	30 minutes

B. *Performance analysis*

In this section, the performance of 5G-SOS is studied and compared with M-HELP [35] and FINDER [34] under multiple disaster configurations while 75% of the gNBs in the network area are out of operation. The emergency calls were randomly generated in a uniform distribution, over a time interval (ETI) of 30 minutes. The displayed results represent the average over three random replications of different UEs positions and emergency calls. The performance difference in 5G-SOS protocol comparing to M-HELP is mainly due to: the addition of RSSI ratio in the computation of T_r, and the adaptive computation of RS_{th} and $T_{\max}$ according to the congestion level. Meanwhile, in contrast to 5G-SOS which forwards data towards destination nodes (gNBs) using multiple possible paths, FINDER is a routing protocol that determines the shortest route to the destination node [34].

1) Impact of emergency calls occurring time interval: The impact of emergency occurring time interval (ETI) or duration on success rate and *EEL* can be observed in Figures 10 and 11. It was observed that when the emergency calls arrivals were spread over a longer ETI, the amount of successful transmissions increased. Once the relay nodes become overcharged due to a shorter ETI value, the probability that a node ignores an incoming request, due to the buffer saturation, increases. In contrast, when the ETI is longer, the number of idle relay nodes available to cater to each relay request is higher.

Further, it was seen that with the increment in ETI, the success rate and *EEL* of 5G-SOS was significantly improved compared to M-HELP and FINDER. The adaptive parameters in 5G-SOS has enhanced the responsiveness to large number of emergency calls occurring in a shorter ETI. The parameters, RS_{th} and $T_{\max}$, are adaptive in 5G-SOS compared to M-HELP, where such parameters are fixed to a specific value. The reason for success rate being lower in FINDER protocol was due to devices relaying the data only to the cluster head (CH). The CH aggregates the received data and sends them to nearby CHs. Such an aggregation results in a high traffic concentration on CHs and reduced the success rate.

Moreover, under each protocol, the *EEL* increased against the duration of ETI. When the emergency calls occur over a shorter ETI, the amount of idle relay nodes is low. Further, since relay nodes do not buffer the simultaneously received calls in M-HELP, only a few calls are successfully transferred to the gNB. Hence, initially the corresponding latency in M-HELP is low. The *EEL* in 5G-SOS was initially higher than M-HELP since the success rate of calls was higher and hence the corresponding latency increased. However, since the adaptive parameters in 5G-SOS allow the quick transferring of calls, the amount of waiting at the relays has decreased and hence resulting in a lower *EEL* compared to both M-HELP and FINDER. In FINDER, the delay in allocating a cluster head and communicating calls via multiple cluster heads caused the increment in *EEL*, when the amount of successful calls increased.

2) Impact of device density: In Figures. 12 and 13, we study the impact of the network density on the emergency call transfer under a fixed number of emergency calls and fixed emergency time interval. As observed in Figure. 12, the success rate increased with the increment in the number of UEs since it increased the availability of more idle nodes, under all the protocols considered. Higher number of idle nodes increased the probability of serving a large number of emergency calls compared to a low device density network.

As in the previous section, initially the *EEL* in 5G-SOS incremented compared to M-HELP, since a higher latency is consumed to achieve a higher success rate under the constraints of increasing local congestion. It is reflected in the Figure 11 where the *EEL* increased against the number of UEs due to the increment in the local congestion and thus the waiting times T_r in 5G-SOS. The increment in local congestion increases $T_{\max}$ and causes a saturation in buffers which result in lower relaying efficiency. However, the adaptive nature in 5G-SOS parameters allow faster relaying of calls compared to M-HELP and FINDER.

It was observed that increasing the number of devices plays a positive role in the improvement of the success rate of 5G-SOS, M-HELP and FINDER. The use of 5G-SOS has significantly reduced the *EEL* compared to M-HELP and FINDER, since 5G-SOS uses the local congestion data, RSSI, and buffering to increase the relaying efficiency in an adaptive manner.

3) Impact of emergency data size: The emergency data size depends on the type of the data such as text, audio, video. The emergency data size increases respectively with text, audio and video data types. Moreover, the emergency call data size is completely correlated with the transmission duration of the emergency call (D2D or classic mode).

Hence, the impact of emergency data size on the performance of 5G-SOS was observed in Figures 14 and 15 where emergency calls occurring within a fixed ETI.

As shown in Section V-B3, when the data quality was low, the success rate was higher compared to transferring high quality data. Hence, it was noted that the proposed 5G-SOS is mostly suitable for low quality data transfer which would be convenient during disaster situations.

When the duration for emergency call transfer increases, the number of busy nodes, processing other emergency calls, increases. This lead to a lower relaying efficiency and thus a drop in the overall number of successful transmissions. As expected, the latency increased in 5G-SOS. M-HELP and FINDER with the increase of the data transfer time, since the data type directly impacts the delay at each relay. Further, only one emergency request could be transmitted at a time which correspond to the delay before relaying.

4) Impact of the percentage of the number of emergency calls (NEC) over the total number of UEs (NoU): First, it was observed, in Figure. 16, that the success rate of 5G-SOS was nearly 100% when the number of emergency calls were less than 5% of the total devices. Further, when the percentage of NEC over NoU approached 80%, i.e. almost all nodes generated an emergency call, around 37.4% of calls were relayed successfully against only 29.5% in M-HELP and 8.7% in FINDER. remained acceptable even under extreme situations. Moreover, when 5000 emergency calls occurred within ETI of 600 seconds (10 minutes) more than 50% of calls reached the core network as was observed in Figure. 10.

Figure 17 presents the *EEL* under varying NEC over NoU ratios. It was noted that 5G-SOS adapted the $T_{\max}$ parameter according to the n_k and n_c factors, as discussed in the Section IV. Hence, when the ratio between the number NEC and NoU reached 80%, the *EEL* was further reduced by adapting parameters such as $T_{\max}$, RS_{th}, to serve large amounts of emergency calls. Overall, we observe that the 5G-SOS protocol presents a reduced latency than M-HELP and FINDER.

Additionally, as seen in Figure. 18, 5G-SOS provided a slightly higher average number of messages per node than M-HELP. The amount of emergency call requests served by 5G-SOS was higher than M-HELP due to buffering multiple calls. Hence, the average number of messages per node has

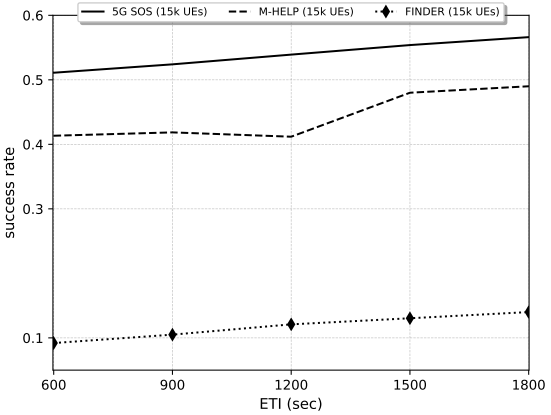

Figure 10. Comparison of successful rate against emergency time interval (ETI) under 5G-SOS, M-HELP and FINDER. Parameters: ETI: 600 - 1800 seconds, NoU: 15000, NEC: 5000

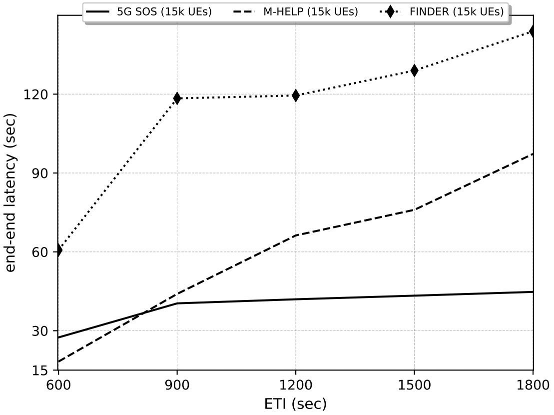

Figure 11. Comparison of end-end latency against ETI under 5G-SOS, M-HELP and FINDER. Parameters: ETI: 600 - 1800 seconds, NoU: 15000, NEC: 5000

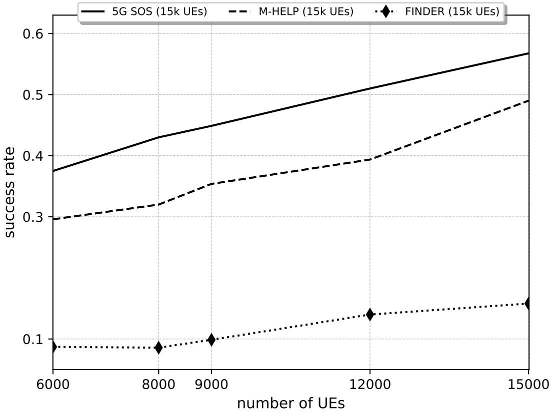

Figure 12. Comparison of successful rate against number of UEs (NoU) under 5G-SOS, M-HELP and FINDER. Parameters: NoU: 6000 to 15000, NEC: 5000, ETI: 1800 seconds (30 minutes)

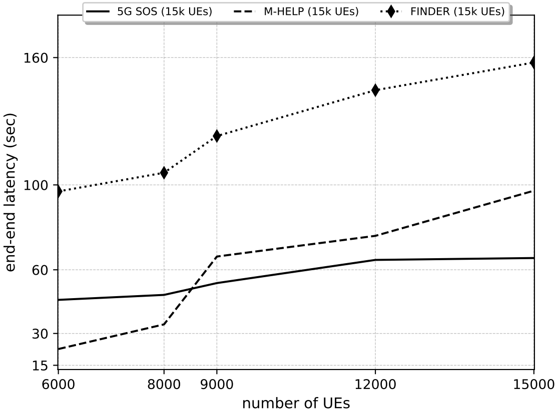

Figure 13. Comparison of end-end latency against NoU under 5G-SOS, M-HELP and FINDER. Parameters: NoU: 6000 to 15000, NEC: 5000, ETI: 1800 seconds (30 minutes)

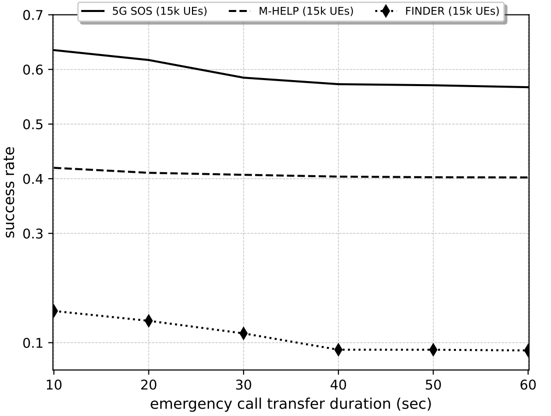

Figure 14. Comparison of successful rate against emergency call transfer duration under 5G-SOS, M-HELP and FINDER. Parameters: NoU: 15000, NEC: 5000, ETI: 1800 seconds (30 minutes)

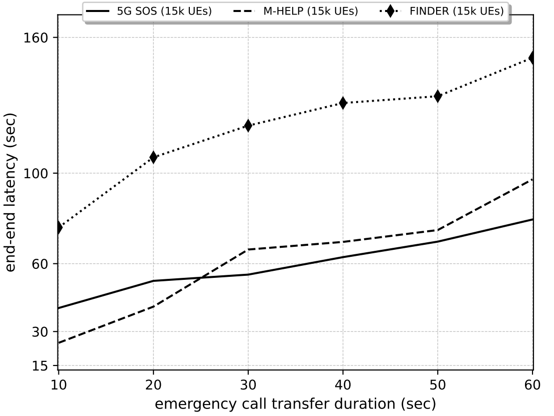

Figure 15. Comparison of end-end latency against emergency call transfer duration under 5G-SOS, M-HELP and FINDER. Parameters: NoU: 15000, NEC: 5000, ETI: 1800 seconds (30 minutes)

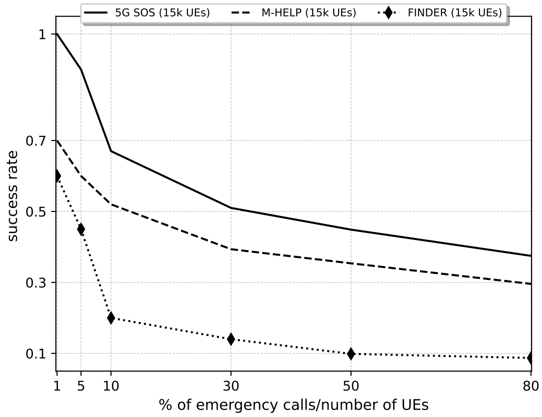

Figure 16. Comparison of the success rate against the ratio of the number of emergency calls (NEC) to the number of UEs (NoU). Parameters: NoU: NEC: 1% of NoU to 80% of NoU, NoU: 15000 UEs, ETI: 1800 seconds (30 minutes).

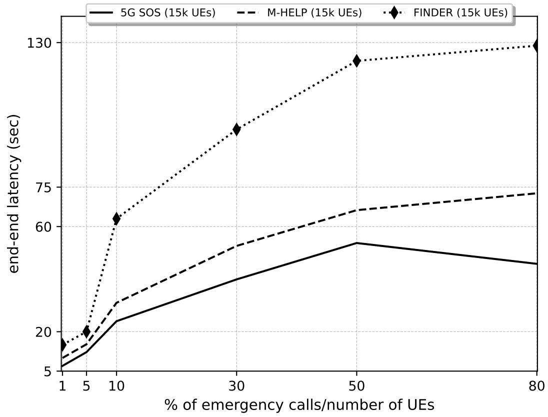

Figure 17. Comparison of end-end latency against the ratio of the number of emergency calls (NEC) to the number of UEs (NoU) under 5G-SOS, M-HELP and FINDER. Parameters: NEC: 1% of NoU to 80% of NoU, NoU: 15000 UEs, ETI: 1800 seconds (30 minutes).

an increase against M-HELP. Also, compared to FINDER, 5G-SOS and M-HELP adopt 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 the emergency data on their own, less traffic is generated in the network. Furthermore, the stronger relay devices transfer the message before any other relay device in the neighborhood.

In terms of residual energy, FINDER has a higher energy consumption compared to 5G-SOS and M-HELP. Furthermore, CHs in FINDER consume higher energy than its cluster member devices. Moreover, 5G-SOS consumes a higher energy compared to M-HELP. 5G-SOS buffer the multiple simultaneous calls received while M-HELP ignore such calls. The computation of the waiting time T_r in (4) offers a dynamic and distributed way to select the stronger relay devices and limit the maximum T_r based on congestion detected in the local neighborhood; this avoids high data congestion at a particular relay device, disperses the traffic among the network devices and conserve the energy of the intermediate relay devices. Furthermore, the use of the RS_{th} parameter prevents overloading the network with multiple copies of the same requests in a dense environment. Moreover, the lightness of the protocol adding less weight on the relay devices and utilizing the stronger devices to transmit emergency data are the major contributions of 5G-SOS and M-HELP compared to FINDER. All in all, 5G-SOS and M-HELP has an improved performance compared to FINDER in terms of transmission success rate, *EEL*, energy consumption and network congestion control.

All in all, the average improvement by 5G-SOS over all the scenarios considered was approximately, 24.9% than M-HELP and 73.9% than FINDER in terms of success rate. Further, the reduction in average end-end latency was 20.8% compared to M-HELP and 61.7% compared to FINDER. Moreover, 5G-SOS enabled reduction in the average energy consumption by 79.2% compared to FINDER. However, 5G-SOS has a higher energy consumption than M-HELP by around 29.1%. On top of that, the average messages per node in 5G-SOS is lower than FINDER by around 81.3%, but higher than M-HELP by 6.2%.

VI. CONCLUSION

Simulation results using 5G-SOS, over Traverse city of Michigan, USA, with a 15000 population, demonstrated that 5G-SOS succeeds to transfer more than 80% of the emergency calls when the victims represent <5% of the devices. Further, it was observed that 5G-SOS provided a higher success rate, higher average residual energy per node, and lower average number of sent messages per node than FINDER. Moreover, 5G-SOS enhanced M-HELP performance in terms of success rate and end-end latency. In addition, 5G-SOS provided satisfactory performance (success rate of 50%) even when the number of simultaneous emergency calls became very high (5000 calls over 10 mins). On average, 5G-SOS performed 24.9% better than M-HELP and 73.9% than FINDER in terms of success rate. Additionally, 5G-SOS has reduced the average end-end latency of the emergency calls transfer by 20.8% compared to M-HELP and 61.7% compared to FINDER. The 5G-SOS protocol is characterized by adaptive behavior that uses locally available data provided by sidelink (from neighbors) and downlink (from gNBs) signals. This adaptation allows adjusting the expected performance of the service (latency and success rate) to the current charge of the network.

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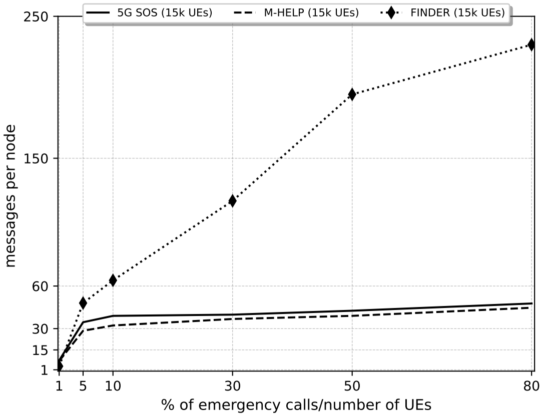

Figure 18. Comparison of the number of messages per node against the ratio of the number of emergency calls (NEC) to the number of UEs (NoU). Parameters: NoU: NEC: 1% of NoU to 80% of NoU, NoU: 15000 UEs, ETI: 1800 seconds (30 minutes)

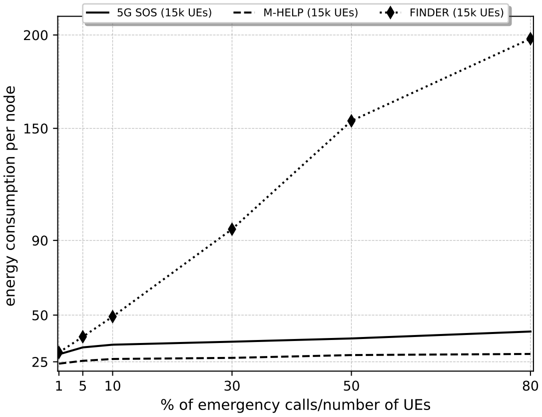

Figure 19. Comparison of the energy consumption per node against the ratio of the number of emergency calls (NEC) to the number of UEs (NoU). Parameters: NoU: NEC: 1% of NoU to 80% of NoU, NoU: 15000 UEs, ETI: 1800 seconds (30 minutes)

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