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D2D-based Survival on Sharing for critical communications

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Abstract Wireless industry, driven by manifold increase in data and devices, is attracting the attention of public safety services for critical communications under disaster scenarios and unpredictable events. In this paper, we present a Device-to-Device (D2D)-based communication mechanism that can serve as an additional alternative to the existing critical communication technologies, used in public safety networks. D2D-based low power transmission and energy saving features make it a perfect candidate for vital communication backup, in a case of a network infrastructure failure or a natural disaster. Our proposed mechanism, referred as Survival on Sharing (SoS), utilizes these D2D features to overcome the mobile devices' power limitation faced during disaster and emergency situations. Our aims are to prolong the battery life and extend the device connectivity in disaster zones. This is achieved by optimizing the amount of valued battery life available in the network. Simulation results show that our proposed mechanism is able to extend devices' usage duration up to 11 hours and reduce the devices' outage probability in comparison to the traditional cellular scheme. Battery lifetime gain ranging from 3.6 to 12% is achieved for varying number of users and coverage areas.

Keywords Device-to-Device communications · Critical communications · Battery lifetime · Battery outage · Disaster management server · Disaster management cache

1 Introduction

Recent unfortunate events, such as floods in Eastern Europe, earthquakes in Italy, bomb attacks in Paris and the illegal human and drugs trafficking across borders, have increased the public awareness of the impact of disasters, natural or man-made. A rising trend in catastrophic occurrences has also been recorded during past decades, as statistically shown in Fig. 1 [1], adding concerns to public safety organizations all over the world. Based on Fig. 1, more than 500 catastrophic events were recorded worldwide in 2014, increasing at an average rate of almost 50% every decade since 1980. The added concerns and the heightened public awareness result in the need for an efficient crisis management, especially in mission critical communications.

Public safety networks use various technologies for their mission critical communications, with the most common being the Terrestrial Trunked Radio (TETRA) and Digital Mobile Radio (DMR). Certain features in today's public safety networks, such as mission critical voice communication, guaranteed access and Quality of Service (QoS), still require additional works, in order to be supported by LTE standards [2]. In the legacy system, for example, in TETRA, though dedicated communication systems for emergency response teams are available, they do not offer functions to actively track down, identify victims or to communicate with them. Detail requirements for the critical communications are described in [3]. Although it might take years for the transition to be accomplished, each and every element listed in [3], has to be addressed, for a network to fully support public safety mission critical communications.

Fortunately, the recent advances related to the Device-to-Device (D2D), being standardized in the 3rd Generation

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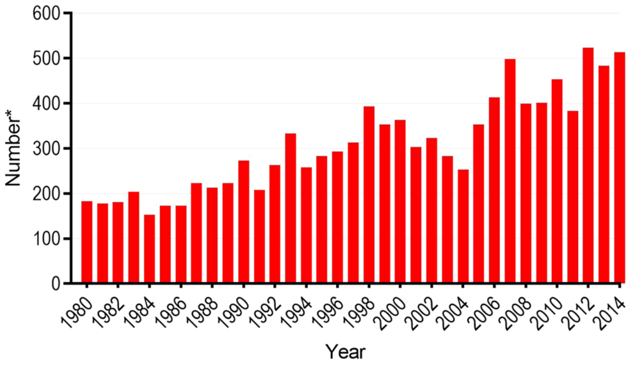


Fig. 1 Natural catastrophic events worldwide 1980–2015 [1]. *Number includes geophysical, meteorological, hydrological and climatological events

Partnership Project (3GPP) Release 12 and beyond, significantly contribute to the transition and development of the critical communications for public safety networks. The D2D communication feature is being worked on in 3GPP under the name of Proximity based Services (ProSe) [4, 5]. In ProSe communications, User Equipments (UEs) that are near or are in proximity of each other, communicate directly bypassing the cellular base stations. However, the interference caused by D2D devices, challenges the performance of D2D underlaying cellular communication significantly [6].

Interference Alignment (IA) is a promising interference management technique for multiuser wireless networks [7, 8]. In IA-based technique, the transmitted signals are constrained towards the unintended receivers by the coordinated-concentrated interference and hence, interference-free subspaces are opened up for the desired signal [7, 8]. IA algorithm along with power allocation for energy efficient networks with guaranteed fairness among users is proposed in [7]. IA-based scheme offers to reduce interference and improve energy efficiency for both D2D and cellular links [6]. Along with network traffic offloading and spectrum utilization improvement, D2D communications allow the UE to operate independently and energy efficiently, especially if the network is down or the UE is located outside the coverage range following a disaster. Efficient, dynamic and decentralized approach to proximity discovery and direct communication between devices makes ProSe a perfect communication solution for evolving public safety networks.

Motivation This motivates us to take advantage of D2D-based ProSe communications to overcome the battery drain issue experienced by the mobile cellular systems under emergency situations. The loss and panic at the time of undesirable event along with difficulty in battery recharging further accentuates the vulnerability of battery life. We believe that prolonged battery life would not only assist in extended communication but would also help in active tracking and location identification of victims.

Contributions We propose D2D-based Survival on Sharing (SoS) mechanism for extended connectivity in disaster zones. The significance and contributions of this paper can be summarized as follows:

1. We present an alternative D2D-based communication option and operation flow that is able to extend devices' usage duration by an average of 12.5% as compared to the standard communication operation.
2. We propose a SoS communication scheme that can prolong connectivity duration for users under distress up to 11 hours.
3. We also provide a simple power control algorithm, based on Lagrange multipliers method, to address the interference management problem caused by the coexistence of D2D and cellular communications in the same spectrum.
4. We validate the benefits of SoS mechanism through experimental as well as simulation based analysis.

The remainder of the paper is organized as follows. Section 2 discusses some related works as well as advances in public safety and critical communications. Our proposed D2D-based SoS mechanism is presented in detail in Sect. 3. Section 4 presents the power control mechanism for mitigating interference in D2D and existing cellular communications. In Sect. 5, performance evaluation and results are presented along with comparisons with the existing scheme. Finally, concluding remarks are presented in Sect. 6.

2 Related works

This section summarizes related works and advances in public safety and critical communications development into two different categories; non-D2D-based approach and D2D communications based approach. Table 1 provides list and work summaries of the related publications in public safety communications (PSC) and critical communications.

Non-D2D-based approach Public safety communications have been through an unprecedented evolution, starting with the use of one-way (receive only) mobile radio in 1928 by the Detroit Police Department in the United States, until the release of Voice over Long Term Evolution (VoLTE) standards in August 2012 [9]. Authors in [9–11] review and compare two major technologies that contribute to the public safety communication advances, the Land Mobile Radio (LMR) systems and LTE-based FirstNet.

Table 1 Related work in public safety communications (PSC) and critical communications

Technology in focus/Approach	Refs.	Work summary	Objective(s)
LMR, LTE (VoLTE, FirstNet)	[9]	Provides overview of LMR and LTE technologies for PSC Presents discussion on VoLTE as an important aspect of PSC	To investigate the feasibility of implementing VoLTE in FirstNet To investigate the LMR and FirstNet interoperability
LMR, LTE (FirstNet)	[10, 11]	Investigates and compares the performance between LMR and LTE-based PSC networks	To investigate LMR and LTE systems capabilities to support PSC services and requirements
LTE	[12]	Proposes BS deployment architecture for public safety broadband network based on different traffic patterns	To improve network coverage To develop a cost efficient system
LTE	[13]	Delineates benefit of deploying unmanned aerial vehicles in the event of damage to the network infrastructure	To improve the throughput coverage To enhance communications during public-safety situations
LTE & D2D	[4]	Proposes comprehensive review of D2D operations as in 3GPP Release 12	To provide insights into D2D system architecture and radio interface To boost the knowledge of D2D communications over cellular networks
D2D	[5]	Proposes clustering-procedure-based approach for integrating cellular and ad hoc operation modes	To improve network coverage
D2D	[15]	Outlines principles and technical challenges for multihop and multi-technology pervasive spectrum sharing for public safety communications	To ensure spectrum access To develop sharing as the norm
D2D	[16]	Proposes D2D-based messaging scheme to overcome UE power limitation problems in disaster and emergency situations	To improve energy efficiency
D2D	[17]	Proposes analytical method (Stochastic geometry) for studying the effect of D2D relays in reducing the damage caused by a natural disaster	To improve network coverage
D2D	[18]	Proposes a D2D discovery mechanism based on proximity area (P-Area) concept. Enables UEs to perform D2D discovery procedures only when there is a high probability to find other UEs	To improve energy efficiency

LMR is a method for transmitting analog voice messages from a fixed amplitude modulation (AM) base station to a mobile receiver and evolves into a two-way frequency modulation (FM) system. Project 25 (P-25) and European TETRA are commonly used standards based on the LMR digital radio communication systems [10, 11]. P25 is responsible for the LMR's transition from wideband analog (25 kHz) to digital narrowband (12.5 KHz) radio channels, that could operate in either the UHF, VHF, 700 MHz, or 800 MHz frequency spectrum [9]. LMR offers some important features that help define the mission critical communications system such as, Direct/Talk Around, Push-to-Talk (PTT) Over Cellular (POC) and group calling modes. However, despite these various features, the LMR's design has been focused on critical voice communications, with limited use for data applications. In terms of power consumption, the mobile unit's transmission power is inflexible as it always transmits at full power, ranging from 1 to 5 W, depending on the frequency being used for transmission [10].

On the other hand, the emerging high speed and low latency transmission advancements, provided by the LTE technology, make LTE a viable solution for public safety communications. The United States has taken the initial step by developing the First Responders Network Authority (FirstNet), an LTE-based broadband technology, dedicated to public safety services. Core features of FirstNet include direct communication mode, push-to-talk, full duplex voice system, group calls, talker identification, emergency alerting and audio quality [11].

The authors in [12] propose a network architecture for the public safety broadband communications, where stationary base station (BS)s are deployed sparsely and a mobile BS is dispatched to the scene when a major incident occurs. The aim of the proposed method is to support different public safety traffic patterns under normal and emergency scenarios. Stationary BSs are deployed to serve light routine traffic such as patrols and surveillance. Meanwhile, mobile BSs are dispatched during the heavy traffic to cater large numbers of public safety personnel at a

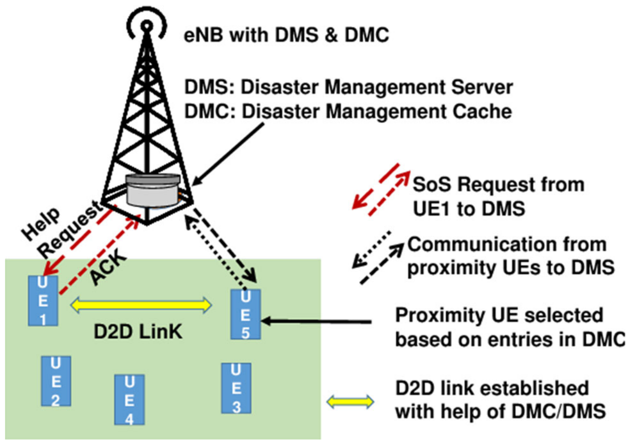


Fig. 2 DMC and DMS at eNB for SoS

major incident scene. A more recent work related to public safety is published in [13]. Unmanned Aerial Vehicles (UAVs) are utilized to reinforce backbone network in the disaster affected areas. The work also proposes relaying and multi-hop communication methods to extend the coverage through UAVs or other UEs [13].

D2D-based approach Ever since D2D communication was first proposed in [14] to enable multihop relays in cellular networks, abundant researches have been carried out by many organizations to further investigate the potential of D2D communications for various applications. Enabling mechanisms for D2D communications over 4G networks (as per 3GPP Release 12) are analyzed in [4]. Work in [4] highlights practical D2D issues, for instance, discovery procedure, mobility and resource management, reference architectures, physical procedures and signals. Few distinctly similar works, which exploit the D2D communications for public safety applications are presented in [5, 15–18]. Authors in [5] take advantage of the network-assisted underlay D2D communications concept to improve network coverage during disasters or emergency situations. Their proposed scheme involves forming dynamic clusters, using ad hoc base stations as well as handheld devices. The clustering-procedure-based approach integrates cellular and ad hoc operation modes, depending on the availability of infrastructure nodes. A multi-hop and multi-technology pervasive spectrum sharing approach is proposed in [15]. Authors believe that spectrum access and infrastructure-less operation are necessary for public safety communications. Moreover, D2D communications over cellular and WiFi bands offer high-speed with ultra reliable wireless data transmissions, suitable for PSCs [15].

Hunukumbure et al. [16] utilize the D2D-based messaging solution to overcome the UE power limitation problems, faced by cellular networks during disaster and emergency situations. The proposed Short Message Service (SMS) mechanism uses D2D communication in the first hop to reach another selected device. The selected device relays the message back to base station in a standard uplink transmission mode. The proposed mechanism in [16], offers to increase the rate of successful transmission over contention based Random Access Channel (RACH) and reduces energy consumption by nearly 90 times, as compared to the default SMS scheme without D2D.

The authors in [17] utilize stochastic geometry approach to analyze the effect of single and multi-hop D2D relays implementation in critical communications. D2D-based chain-relaying communication is adopted to extend the cellular coverage from healthy cells towards damaged cells, caused by defunct base stations due to the disaster event. In [18], the energy consumption aspects are analyzed and focused on the D2D discovery mechanism in 3GPP networks. The proposed discovery scheme uses the concept of Proximity Area (P-Area). It only performs device discovery when there is a high probability of finding other UEs subscribed to the same service. As compared to the conventional aggressive peer discovery method, the proposed mechanism is able to prolong the UEs' battery lifetime by managing discovery cycles efficiently.

Another prominent D2D communication work, though not related to public safety, is published in [19]. Similar to [16], the proposed concept in [19], exploits the D2D links in the first stage and subsequently relies back on the cellular links for further transmission. The authors propose a cooperative system in which users with high battery level help carry the traffic of users with low battery level via D2D link.

Our proposed scheme for critical communications is the extended work based on the protocol introduced in [19]. While many works on D2D for public safety are focused on extending coverage, clustering [5], handling failure of base stations [13], spectrum management or sharing [15], random access and device discovery [16], our proposed SoS scheme offers novel method to mitigate many aforesaid expenses at the UE for an improved battery life. We specifically address ways to shift the D2D overheads at the evolved Node B (eNB). Consequently, in SoS, UEs' battery outage probability in disaster zone is reduced. Depleting battery lifetime and inadequate power saving methods would nullify the advantage of wireless technology in critical communications. Novel SoS protocol enhances battery life in disaster zone, thus improves chances of communication in critical scenarios for survival, security and social purposes.

3 D2D-based Survival on Sharing operation

This section presents the operation of the proposed system. The aim of the proposed SoS mechanism is to extend the device connectivity and usage duration, for as long as possible, during disaster situations. This is achieved by reducing the device's energy consumption and prolonging the device's battery lifetime. We propose the concept of energy redistribution among devices, termed as SoS, as depicted in Fig. 2. In SoS, a device with low energy resource or battery level seeks help from other devices with higher battery levels, in its vicinity, for data transmission to eNB. We refer the device with low battery level as SoS Requester (UE1 in Fig. 2) whereas the devices with high battery levels are considered as potential SoS Rescuers (UE2, UE3, UE4 and UE5 in Fig. 2). The power conservation of low battery device is equivalent to withdrawal from a virtual power bank. Since devices do not follow any uniform usage pattern, their battery values vary at any given point in time [19]. Our protocol benefits from the wide range of battery values created by this usage diversity.

System model The D2D-based ProSe in 3GPP offers two basic functionalities: (1) D2D discovery and (2) D2D communication [18].

Algorithm 1 SoS Algorithm

Assumption: SoS Requester's battery level is below min threshold, τ_{min}. SoS request is sent by SoS Requester.

```
1:  SoS request initialized by SoS Requester to DMS
2:  SoS process at DMS Begin
3:  procedure SoS Rescuer Selection
4:      Send ACK to SoS Requester
5:      Initialize count rescuer = 0
6:      Locate SoS Requester's neighbors (all UEs in
        close proximity to SoS Requester)
7:      Multicast SoS Relay Request to all SoS
        Requester's neighbors
8:      for each neighboring UEs $i \in n$ do
9:          if SoS Replies Received then
10:             if battery level $\geq \tau_{max}$ then
11:                 SoS Rescuer status = true
12:                 increment count rescuer
13:             else
14:                 SoS Rescuer status = false
                end if
15:         else
16:             update count rescuer
            end if
        end for

17:     if count rescuer = 0 then
18:         SoS Rescuer = not assigned
19:     else if count rescuer = 1
20:         SoS Rescuer = selected
21:         else (i.e. count rescuer > 1)
            (SoS Rescuer selection criteria: considering
            fairness)
22:         Selection s.t. fairness elements:
            (i) SoS Requester's target energy usage, $v$
            and
            (ii) SoS Requester's actual energy costs, $E$
        end if
    end procedure
23: DMS sends D2D connection setup to both SoS Requester
    and SoS Rescuer (if assigned)
24: D2D cooperation relay connection established
```

3.1 D2D discovery in SoS

D2D discovery enables a UE to discover the presence of other neighboring D2D-capable UEs, in its vicinity and where permitted, to ascertain certain information about them. Through D2D communication, UE is able to use the LTE radio interface to communicate directly with each other, without routing the traffic through the LTE network. To facilitate both functions, we propose two additional entities implemented at the eNB. A disaster management cache (DMC) and disaster management server (DMS) as shown in Fig. 2.

- DMC serves as a database, that is responsible for maintaining device locations every time a device updates its location coordinates, at Evolved Packet Core (EPC) through the eNB. Unlike conventional network, where the eNB simply forwards the device's location update to EPC, DMC at eNB stores and updates the location coordinates before forwarding the information to the EPC. Thus, under disaster events, the devices in the proximity are already known to the eNB. This saves overheads for the device discovery process under critical conditions.
- DMS is responsible for coordination and formation of the D2D cooperative link. The D2D link is the most critical feature in our proposed protocol, as it consumes significantly less power than a cellular link.

3.2 D2D communication in SoS

D2D communication can be understood by the operational flow of our proposed system as illustrated in Fig. 3 and Algorithm 1.

- In Fig. 3, we assume a UE (referred as SoS Requester), is located in the disaster zone and is running out of battery. When the UE's battery level falls below a predefined threshold τ_{min}, it sends an SoS help request to the DMS (Algorithm 1 line 1).
- SoS process begins at DMS (Algorithm 1 line 2), thus reduces the D2D overheads at UE. DMS verifies the related parameters and acknowledges the request. The probable proximity devices are identified based on location entries stored by DMC.
- DMS multicasts the SoS request message, which includes the scheduled resource for SoS Requester, to all devices in its proximity (Algorithm 1 line 7). 3GPP LTE's evolved Multimedia Broadcast and Multicast Services (eMBMS) are gradually evolving and can efficiently enable multicast communication. The probable SoS Rescuers, with battery level above another threshold τ_{max}, listen to this resource unit. All rescuers

in the proximity of the SoS Requester report about their battery levels to DMS.

- DMS selects the SoS Rescuer from the list of potential rescuers based on battery level and proximity (Algorithm 1 lines 8 to 22). To ensure fairness in terms of equal energy consumption in the overall SoS system, the SoS Rescuer selection is made based upon the overall group's interests rather than the individual devices. Then, the devices with more energy or higher battery level are expected to contribute more, consequently maximizing the lifetime of the group or the overall system.

We adopt the method proposed in [20], for a generic fairness measurement. The objective of this method is to achieve an arbitrary division of energy usage among the connected devices or UEs. Assuming there are n number of connected SoS Requesters, the division of energy usage is defined as a vector $\mathbf{v} = (v_1, v_2, \ldots, v_n)$. Each element $v_i \in (0, 1)$, with $1 \leq i \leq n$, denotes the SoS Requester i's desired fraction out of the total amount of energy, E, and the sum of all v_i's must be 1. Then, $\mathbf{E} = (E_1, E_2, \ldots, E_n)$ is defined as the actual energy costs incurred by each UE, $E = \sum E_i$. The fairness objective is to optimize the E_i's as close as possible to the v_iE's.

To quantitatively measure the fairness of our proposed system, we implement the commonly used fairness index, the Jain's index [21] for energy consumption among n UEs. Based on [21], the Jain's index for the proposed SoS system can be defined as:

$$\jmath(\mathbf{v}, \mathbf{E}) = \frac{\left[\sum_{i=1}^{n} \frac{E_i}{v_i}\right]^2}{n \sum_{i=1}^{n} \left[\frac{E_i}{v_i}\right]^2} \tag{1}$$

where $0 \leq \jmath(\mathbf{v}, \mathbf{E}) \leq 1$. The index measures the deviation of the consumed energy vector $\mathbf{E} = (E_1, E_2, \ldots, E_n)$ from the desired division $\mathbf{v}E = (v_1, v_2, \ldots, v_n)E$. A large value of $\jmath(\mathbf{v}, \mathbf{E})$ represents fairer energy consumption from the system perspective. Table 2 shows the Jain's index values with different number of UEs. In this table, it is observed that the energy consumption is fairly distributed in the proposed system, with all the Jain's indexes being above 0.9.

- By the end of the selection process, an appropriate SoS Rescuer (UE2 in Fig. 3) is chosen to save the SoS Requester. DMS implements the connection establishment procedure (Algorithm 1 lines 23 and 24).
- Data from SoS Requester is then relayed to the Destination UE through SoS Rescuer (UE2 in Fig. 3) throughout the association period.

4 D2D-based Survival on Sharing power control (PC)

The coexistence of D2D and cellular communications in the same spectrum, specifically the underlaid D2D signal, can become a new source of interference to the wireless

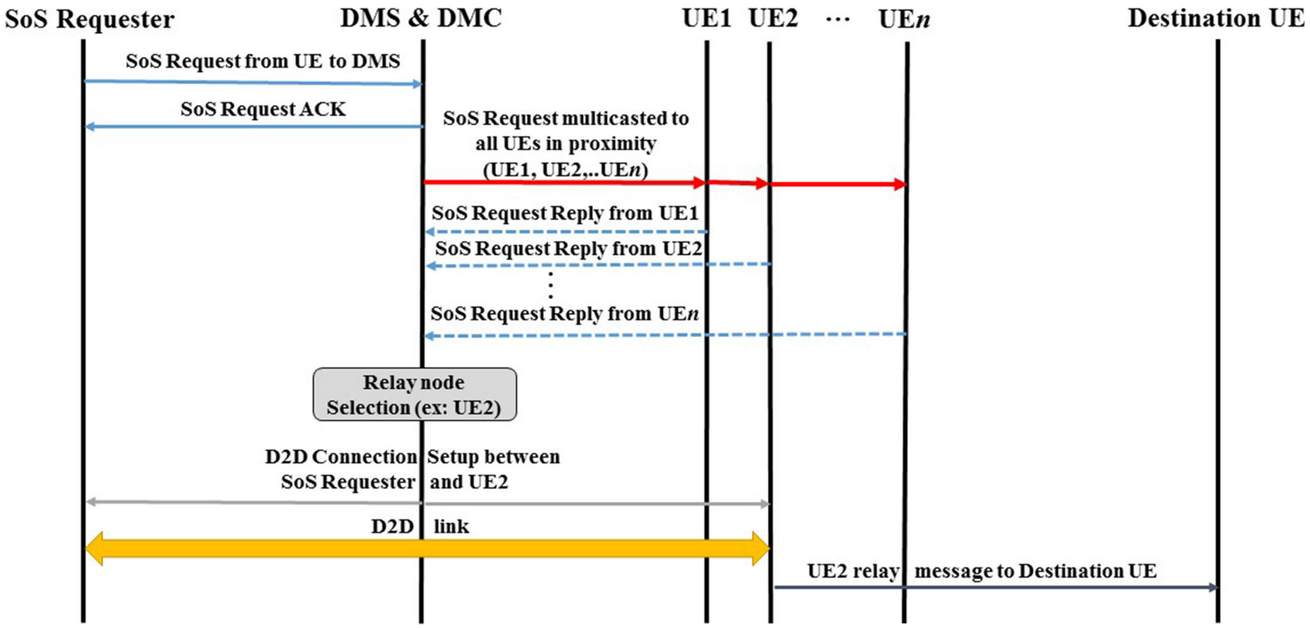


Fig. 3 D2D-based SoS operational flow

network [22]. A PC mechanism is considered as one of the effective solutions to limit the resulting interference in direct communicating devices [23]. In LTE, the fractional PC is defined as [24]:

$$P = min\left\{P_{max}, P_0 + 10\log_{10} M + \alpha L + \Delta_{TF}(i) + f(i)\right\}, \tag{2}$$

where P_{max} is the UE maximum allowable transmit power. In our proposed system, P_{max} are limited to 24 and 20 dBm for normal cellular UE and D2D UE respectively. M is the number of Physical Resource Blocks (PRBs) allocated to a UE. α is the path loss compensation factor. L is the downlink path loss, based on the reference signal at UE and the distance, d, between two UEs in a pair. $\Delta_{TF}(i)$ and $f(i)$ are UE specific closed loop correction value and Modulation and Coding Scheme (MCS) offset, respectively. However, since we focus our analysis based upon LTE uplink open loop fraction power control scheme (OFPC), Eq. (2) can be further reduced by omitting the latter two parameters. The reduced formula is given as in Eq. (3). The OFPC parameters used are provided in Table 3.

$$P = min\{P_{max}, P_0 + 10\log_{10} M + \alpha L\}, \tag{3}$$

In terms of interference mitigation, the PC aims to maintain and limit the transmission power of the newly formed D2D link. However, in terms of quality, the user's QoS demand should also be considered when minimizing the power consumption during transmission. This optimization problem can be solved by setting a specific SINR target, used as a constraint parameter in the PC formula in Eq. (3). It is important to highlight that parameter P_0 in Eq. (3) is used for controlling SINR target [25]. By setting a specific SINR target, γ^t, the overall power used in D2D communication can be minimized without affecting the QoS of the communication link.

Table 2 Jain's index for measuring overall system fairness

Number of UEs	Jain's index
100	0.928
200	0.925
300	0.919
400	0.916
500	0.917

In this paper, we propose to model the power consumption with SINR constraint for D2D link through Lagrange multipliers method [26, 27]. Using the Rayleigh fading model,

$$S_i = G_{ii}p_i,$$

for $i = 1, \ldots, n$ transmitter and receiver pairs and

$$I_i = \sum^{j\neq i} G_{ij}p_j,$$

where the coefficients $G_{ij}, i \geqslant 1, j \leqslant n$ are the path gains from transmitter j to receiver i. Therefore, the SINR function at receiver in terms of the transmit powers $p_1, \ldots, p_n$, is given as:

$$\gamma_i(p) = \frac{S_i}{I_i + \sigma_i} = \frac{G_{ii}p_i}{\sum_{j\neq i} G_{ij}p_j + \sigma_i}, \quad i = 1, \ldots, n, \tag{4}$$

where S_i is a measure of the desired signal power received from the target transmitter. I_i is the total signal power received from all the other receivers and $\sigma_i > 0$ is the measure of receiver noise. The transmit power optimization that minimizes the overall power used for D2D pairs can be formulated as:

$$\begin{aligned} & min\left\{P^D = \sum_{i=1}^{n} p_i^D\right\}, \\ & subject\ to\ \gamma_i^D = \frac{G_{ii}^D p_i^D}{\sum_{j\neq i} G_{ij}^D p_j^D + \sigma_i^D} \geq \gamma^t, \\ & p_i^D \leq P_{max}^D, \quad \forall i, \end{aligned} \tag{5}$$

Using Lagrange multiplier method, the corresponding power for D2D cell is given as:

$$p_i^D = \begin{cases} \gamma^t I_i^D / G_{ii}^D, & P_{max}^D G_{ii}^D \geq \gamma^t I_i^D \\ 0, & P_{max}^D G_{ii}^D < \gamma^t I_i^D \end{cases} \tag{6}$$

Assuming that all normal cellular and D2D users have the same minimum target SINR, denoted as γ^t, we can also obtain the solution to optimize the transmit power for normal cell, as follows:

$$p_i = \begin{cases} \gamma^t I_i / G_{ii}, & P_{max} G_{ii} \geq \gamma^t I_i \\ 0, & P_{max} G_{ii} < \gamma^t I_i \end{cases} \tag{7}$$

Algorithm 2 SoS Power Control (PC) Algorithm

```
Input: $P_{max}$ is the maximum transmit power allowed. $\gamma^t$ is the SINR target. $\Delta p$ is a small increment in transmit power.
Output: $P$ is the total power used.
for $i = 1{:}n$ do
    Increase transmit power by $\Delta p$
    Calculate and update SINR value, $\gamma_i$ by the increment made on the transmit power based on Eq. (4)
    Solve the optimization problem based on Eq. (5)
    Update the current D2D pairs transmit power.
end for
```

The D2D-based SoS PC mechanism is presented in Algorithm 2. In Algorithm 2, the transmit power is increased in steps of Δp and the corresponding SINR value (γ_i) is calculated and updated. Subsequently, overall power

Table 3 OFPC parameters

Parameter	Value	Refs.
LTE UE max. transmit power (P_{max})	24 dBm	[28, 29]
D2D UE max. transmit power (P^{D}_{max})	20 dBm	[19]
Varying transmit power for PC (P_0)	$P_{0_{ini}} = -78$ dBm	[28]
Target SINR threshold	−6 to 21 dB	[19, 22]
Path loss compensation factor (α)	0.8	[28]
Path loss model (L)	$34.5 + 38 \log_{10} d$ dB (cellular) $37 + 30 \log_{10} d$ dB (D2D)	[29]
Number of PRBs allocated to UE (M)	1	[28]
Cell radius	500 m	

used for D2D pairs is evaluated based on the transmit power optimization. The transmit power is bounded by P_{max}, the maximum allowable value.

Figure 4 shows the performance assessment of the SoS PC algorithm with varying minimum target SINR (-6 dB $\leq \gamma^t \leq$ 21 dB) in cellular and D2D communications. As depicted in Fig. 4, the application of the SoS PC algorithm contributes to a better relative performance in terms of power consumption. By slowly incrementing the transmit power (Δp = 1 dB), and using a target SINR to control the maximum power transmitted, the applied PC scheme manages to maintain low transmit powers and protect cellular and D2D communications from mutual interference.

We also compare the performance of our proposed SoS PC method with EPC-assisted D2D discovery methods introduced in [18]. The gain in terms of power consumption and total power savings achieved by applying the SoS PC are illustrated in Fig. 5(a, b). The D2D-based SoS not only reduces the average power consumption by more than 15% but also is able to increase the power savings by more than 45% as compared to the EPC-assisted methods proposed in [18].

Undeniably, there are various existing methods for solving interference issue in heterogeneous wireless networks. For example, Zhao et al. [7] proposed a power allocation scheme designed for managing interference in wireless networks. Through the proposed scheme, selected users are switched into sleep mode to save energy consumption, resulting in significant improvement of the energy efficiency. In comparison to our proposed SoS PC method, though the SoS PC method can effectively reduce the D2D power consumption, it does not guarantee excellent energy efficiency since it only meets the minimum target SINR of all users. This is reasonable in a critical situation where the energy conservation rather than efficiency is more important for the users to extend connection for as long as possible for the search and rescue operations.

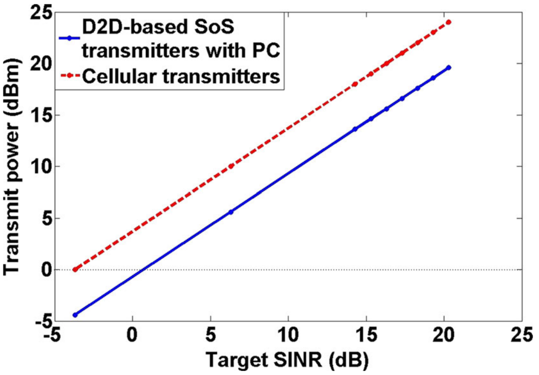


Fig. 4 Comparison of transmit power consumed by cellular transmitters and D2D-based SoS transmitters with PC

5 Performance evaluation

Understanding that the interference in D2D overlaid architecture can be easily mitigated by the power control technique, we explore a more critical element during disaster, the battery's lifetime extension. In this section, we evaluate the proposed D2D-based SoS performance based upon: (1) actual experiments and (2) simulation-based analysis.

5.1 Experimental-based analysis

We conduct experiments to investigate the energy performance of the proposed system, discussed in Sect. 3. We use three mobile devices, termed as SoS Requester, SoS Rescuer and Destination UE. UE1 with low battery level is selected as the SoS Requester, UE2 with high residual battery level is selected as the SoS Rescuer and finally another device, UE3, acts as the Destination UE to receive information sent by UE1. The general device parameters for the experiment are provided in Table 4. We use PowerTutor software [30] application to measure the device power consumption.

The power consumption comparison is presented in Fig. 6. In the figure, *t1*, *t2* and *t3* refer to the time when the SoS Requester sends messages to the Destination UE, with

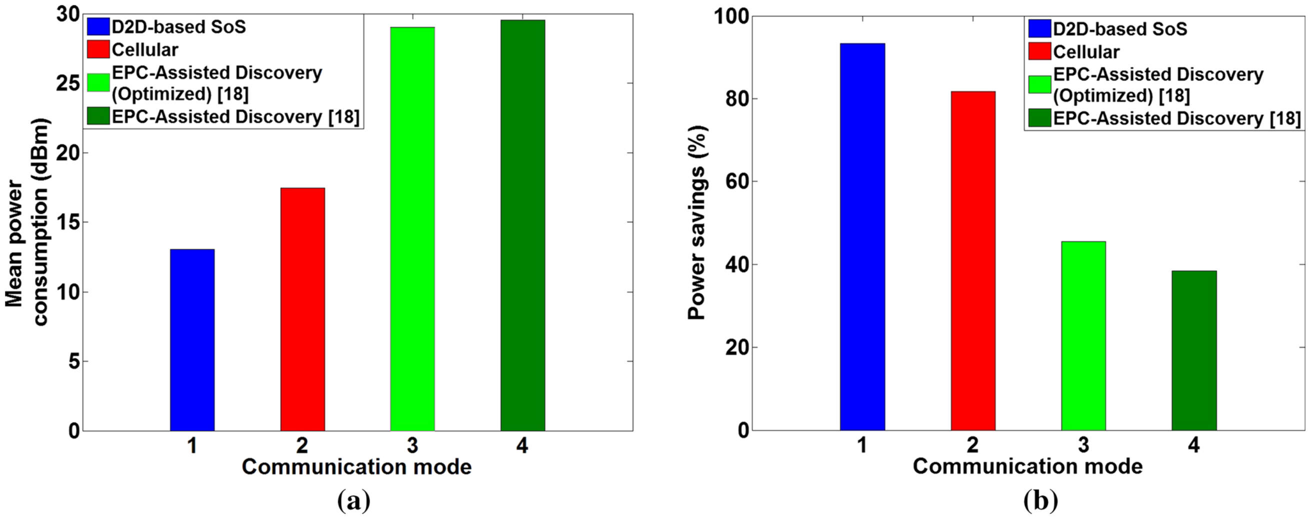


Fig. 5 Performance gain comparison of D2D-based SoS with other communication modes. **a** Mean power consumption, **b** power savings

a random time interval between $0 \leq t \leq 30$ (min). Figure 6 clearly demonstrates that the power consumption in D2D-based link is almost 30% less than in the legacy scenario. This serves as motivation for us to perform detailed evaluation of our SoS mechanism.

5.2 Simulation-based analysis

To validate the SoS performance, a numerical evaluation is simulated using MATLAB. Our simulation scenario is illustrated in Fig. 7. Our analysis is focused on the expected battery lifetime of the device. This parameter is crucial to determine the device connectivity level and to measure the device ability to remain connected during critical situations, even with a limited energy resource.

We consider varying number of devices or UEs between $100 \leq N \leq 500$, in an LTE cell with a maximum radius of $R = 500$ m. The UEs are uniformly distributed at random locations within a cell. Each UE's battery level is initialized randomly to emulate a realistic scenario during a critical event. The main simulation parameters are listed in Table 5.

We use the following Eqs. (8) and (9), based on the formula proposed in [31], to estimate the battery discharge B_{dis}, and the battery life B_{life}, in our simulation.

$$B_{dis}\,[\text{mAh}] = \bar{\varepsilon}/(\psi t), \tag{8}$$

$$B_{life}\,[\text{hour}] = \beta\psi/\bar{P}, \tag{9}$$

where $\bar{\varepsilon}$ is the average energy, ψ = 3.8 V, is the nominal voltage of the mobile device and t is equal to 3600 s. β and $\bar{P}$ represent the residual battery level and the average power consumption respectively.

The benefits of SoS implementation can be observed from the simulation results generated in Figs. 8, 9, 10, 11, 12. The term 'usage duration' refers to the period of continuous battery usage in a UE, until the battery completely runs out. We use the terms 'usage duration' and 'battery lifetime' interchangeably to explain our analysis in this section.

Table 4 Experiment parameters

Parameter	Device		
	UE1	UE2	UE3
Role	SoS Requester	SoS Rescuer/Relay	Receiver (Destination UE)
Model	SAMSUNG S5 (SM-G900F)	SAMSUNG S4 (GT-I9505)	Apple iPhone 5 (A1429)
Nominal battery voltage (V)	3.85	3.8	3.8
Battery capacity (mAh)	2800	2600	1440
Initial residual battery level at time, t1	Low (<30%)	High (>80%)	N/A

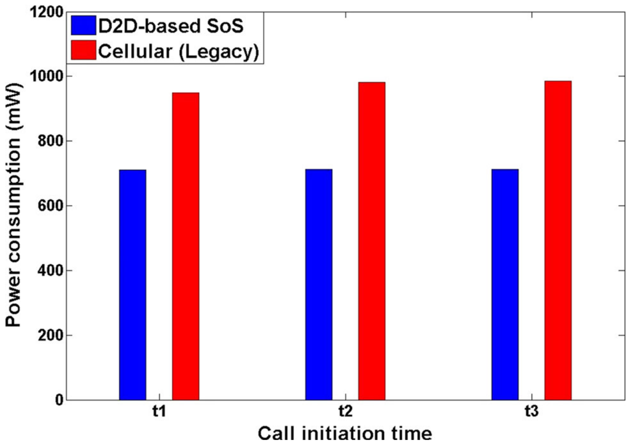


Fig. 6 Power consumption comparison

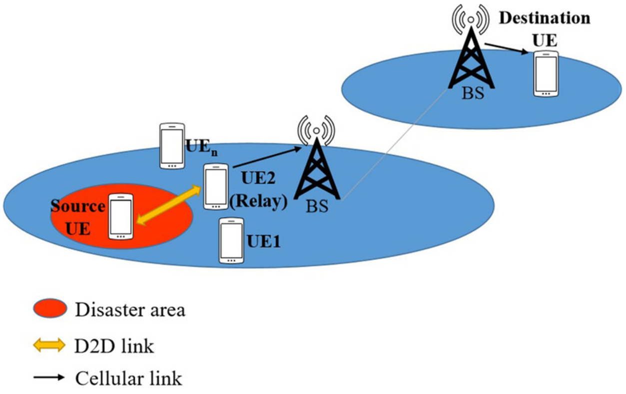


Fig. 7 Simulation scenario

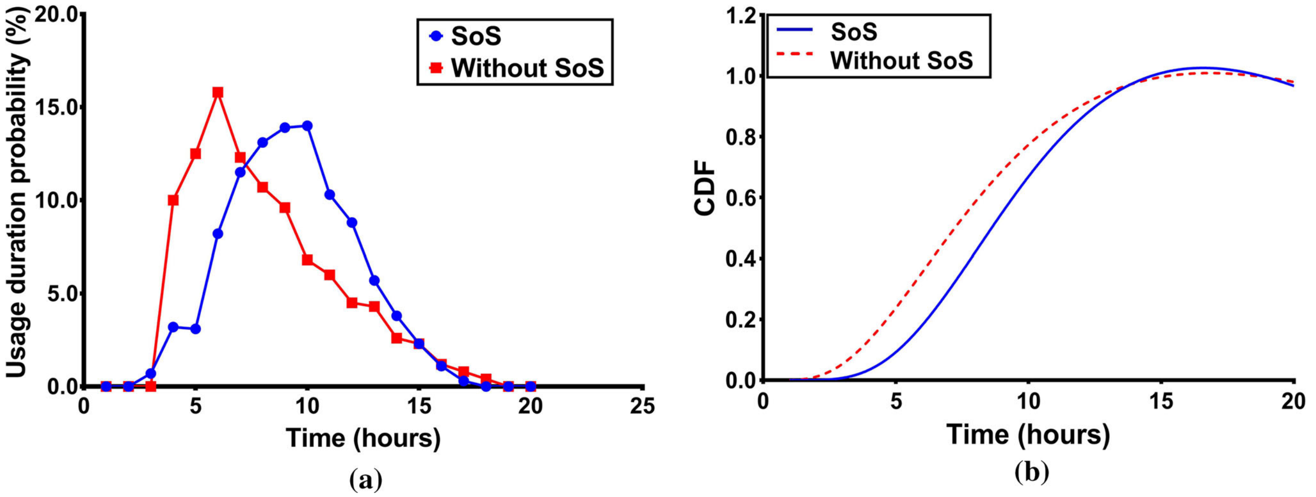
Table 5 Simulation parameters

Parameter	Value
Cell radius (R)	100–500 m
Number of devices (N)	100–500
Max. battery capacity	6.5 J
Battery threshold	$\tau_{min} = 0.3$, $\tau_{max} = 0.7$
SoS cooperation radius	$\leq$ 50 m
Carrier frequency	2.0 GHz
Path loss compensation	0.8
Mobility model	Random walk
Simulation time	20 hours

Figure 8(a) shows that under legacy scenario with continuous usage, 53% of the 500 UEs are able to last around 5–8 hours until they experience battery outage. However, with SoS, around 50% of the UEs remain continuously connected for 8–11 hours. As expected, by redistributing the energy over the network, the proposed scheme offers to extend the usage duration of the devices. This is further supported by the usage duration distribution plot in Fig. 8(b). The figure demonstrates that our proposed SoS scheme performs better than the legacy network for usage duration up to 11 hours. Since the total available energy in the network is constant, the SoS scheme makes the tradeoff of redistributing the available energy fairly to all devices at the cost of shortening the usage time of some devices (i.e. SoS Rescuers). Thus, this limits the devices' usage duration in the network.

Figure 9 delineates fairness distribution as function of number of UEs and battery lifetime. The fairness criteria in selecting SoS Rescuers implemented in SoS algorithm ensures that all participating UEs have equal opportunity to consume available energy in the network. The results are depicted in Fig. 9, in which the UEs are fairly distributed to remain connected in the range between 6 and 12 hours.

In Fig. 10, we evaluate the effect of varying the cell radius on SoS's performance. The result shows the average



(a) (b)

Fig. 8 SoS performance comparison. **a** Probability distribution of usage duration. **b** CDF of usage duration

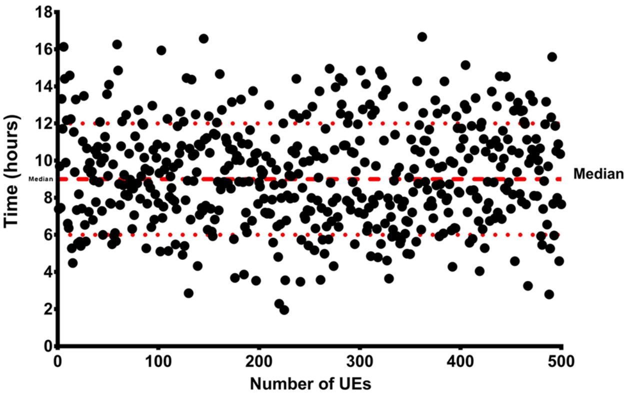


Fig. 9 Fairness distribution

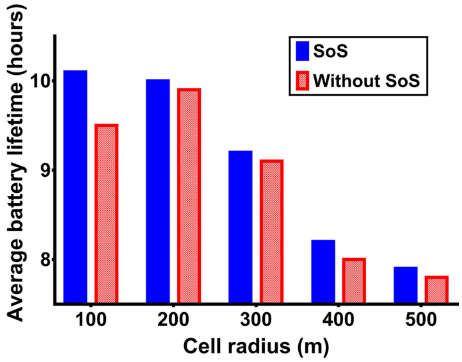


Fig. 10 Average battery lifetime with varying cell radius

battery lifetime for a fixed $N = 100$ number of UEs with respect to the variations in cell radius, R, between 100 and 500 m. From Fig. 10, it is inferred that the average battery lifetime decreases as the cell radius increases. This is expected as the fundamental principal of proposed SoS protocol is based upon proximity between UEs. Hence, as the cell area increases, the distance between UEs also increases, consequently the probability of forming D2D cooperation is reduced. It is to be noted that the SoS scheme performs better and maintains a longer battery lifetime, up to 3.6% more than the traditional scheme even with higher cooperation radius.

The same proximity-based concept can also explain the results presented in Fig. 11. The simulation is executed with a fixed number of UEs ($N = 100$) uniformly distributed within cell radius of $R = 100$ m, with varying cooperation radius between 10 and 50 m. Increasing the SoS cooperation radius, results in the inclusion of more UEs in proximity to participate in the proposed scheme, as potential SoS Rescuers. As a result, the proposed SoS scheme performs better as the cooperation radius threshold is increased. Figure 11 depicts that the SoS scheme achieves an average battery lifetime gain of around 12% with respect to the traditional cellular scheme.

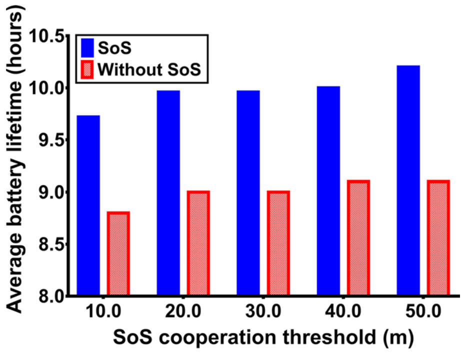


Fig. 11 Average battery lifetime with varying cooperation radius

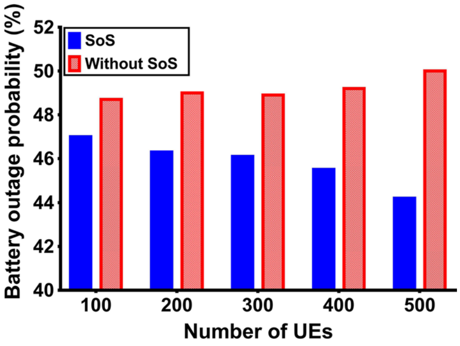


Fig. 12 Battery outage probability

Finally in Fig. 12, the number of UEs is varied from 100 to 500 within a fixed cell radius of $R = 500$ m. In comparison to the traditional cellular scheme, the proposed SoS protocol reduces the probability of battery outage by 7.0% on average.

6 Conclusion

In this paper, we propose a D2D-based cooperative communication mechanism, SoS, as an alternative to the existing critical communication technologies. SoS prolongs battery life and extends the connectivity of devices under disaster scenarios. In our system, devices with low battery levels, stuck in the disaster zone, seek help from neighboring devices with high battery levels. The neighbor selection is assisted by DMS and DMC, new entities at eNB. The selected neighbor, usually with a higher battery level acts as a relay. Thus, the expenses of high power cellular links are borne by the battery rich devices, while devices with critical battery levels communicate over low power short D2D connections. This D2D-based redistribution alleviates the loss of connectivity problem, due to power limitations in disaster and emergency situations. The overall usage duration probability improves for connected devices. Based on the results generated, our SoS protocol along with disaster management server and disaster management cache promise improvement in connectivity, ensure fairness and reduce battery outages in the hour of crisis.

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