SmartDR:A Device-to-Device Communication for Post-Disaster Recovery

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Abstract

Natural disasters, such as earthquakes, can cause severe destruction and create havoc in the society. Buildings and other structures may collapse during disaster incidents causing injuries and deaths to victims trapped under debris and rubble. Immediately after a natural disaster incident, it becomes extremely difficult for first responders and rescuers to find and save trapped victims. Often searches are carried out blindly in random locations, which delay the rescue of the victims. This paper introduces a Smartphone Assisted Disaster Recovery (SmartDR) method for post-disaster communication using Smartphones. SmartDR utilizes the device-to-device (D2D) communication technology in Fifth Generation (5G) networks, which enables direct communication between proximate devices without the need of relaying through a network infrastructure, such as mobile access points or mobile base stations. We examine a scenario of multi-hop D2D communication where smartphones carried by trapped victims and other people in disaster affected areas can self-detect the occurrence of a disaster incident by monitoring the radio environment and then can self-switch to a disaster mode to transmit emergency help messages with their location coordinates to other nearby smartphones. To locate other nearby smartphones also operating in the disaster mode and in the same channel, each smartphone runs a rendezvous process. The emergency messages are thus relayed to the functional base station or rescue centre. To facilitate routing of the emergency messages, we propose a path selection algorithm, which considers both delay and the leftover energy of a device (a smartphone in this case). Thus, the SmartDR method includes: (i) a multi-channel channel hopping rendezvous protocol to improve the victim localization or neighbor discovery, and (ii) an energy-aware multi-path routing (Energy-aware ad-hoc on-demand distance vector or E-AODV) protocol to overcome the higher energy depletion rate at devices associated with single shortest path routing. The SmartDR method can guide search and rescue operations and increase the possibility of saving lives immediately aftermath a disaster incident. A simulation-based performance study is conducted to evaluate the protocol performance in post-disaster scenario. Simulation results show that a significant performance gain is achievable when a device utilises the channel information for the rendezvous process and the leftover energy

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for routing path selection. Our results show that peer discovery in multi-channel D2D environment can be significantly improved when channel quality information is considered in CH sequence design. Moreover, selecting a routing path based on LoE of a device and the standard deviation of residual energy of a path, can not only enhance the network lifetime, but also reduce the chance of network being partitioned.
Keywords: Device-to-Device Communication; Leftover Energy; Disaster Assistance; Emergency; Rendezvous; Channel Hopping; Routing

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1. Introduction

Natural disasters such as earthquakes, typhoons and floods can cause a significant loss to life and property. According to the Centre for Research on the Epidemiology of Disasters, this on an average has affected around 218 million people per annum since 1900 [1]. During such events, it becomes extremely difficult for first responders to locate quickly people trapped inside the debris. Some form of immediate communication between victims and first responders therefore becomes critical in ensuring a successful rescue and saving lives, which may not be possible due to the damaged network infrastructure. Some research efforts have focused on designing disaster management systems to facilitate such communication based on the existing network infrastructure [2]. The existing mobile communication standards for first responders include Project 25 [3], TETRA [4] and TETRAPOL [5], however the performance of these is limited to the devices from same technology and the radio spectrum resources, which might not be available with the users awaiting rescue.

Device-to device (D2D) was a promising technology specified in the 3rd Generation Partnership Project's (3GPP) Release 12 standard. It is also recognized as an important component of the fifth-generation (5G) mobile networks [6]. D2D communication is connection-oriented and requires device discovery to establish communication. The D2D can be single-hop and multi-hop communication which can facilitate a direct communication between the first responders and other rescue teams even if they are out of the coverage areas of the serving BS [7]. Device localization (DL) and leftover energy (LoE) are two critical requirements for employing D2D in disaster recovery, which are further discussed here. Also, in this paper, the term device implies an user's (who is awaiting rescue) mobile device, such as cellular phone (smartphone), and in the remaining write up we have used the terms smartphone and device interchangeably. We also use the term node that implies devices in routing. The paper proposes a smartphone-assisted disaster recovery (SmartDR) method for post-disaster communication by utlizing the D2D communication technology. The method addresses the challenges in D2D enumerated below.

- Finding an Active Device to Transmit Information in Multi-Channel D2D Communication: Most of the existing communication protocols either support single channel or fixed multi-channel communication between devices. In a fixed multi-channel communication, a common set of static channels are used between the devices that are known prior to the communication.

In this work, we consider post disaster as a special case wherein the network becomes open i.e., all the proprietary and non-proprietary channels become available to use; considering that these multiple channels may assist in reducing channel congestion. This will introduce a multi-channel neighbour discovery problem due to the asymmetric channel availability of different users. The channel availability is dynamic in nature and depends on number of users, time and space. This may lead to the two devices communicating on different channels may not able to establish the communication even if they are within the transmission range of each other. This can also lead to an overall increase in the end-to-end communication delay in multi-channel D2D communication.

- Finding an Active Device to Communicate based on its LoE: A device at any time can self-assess the amount of LoE in its battery, and approximately how long it can continue running. Finding another active device within the proximity that has enough LoE to receive and communicate messages can be at times a challenge. If the D2D protocols are able to factor in LoE, this can reduce energy depletion in the devices.

In the proposed SmartDR method, the devices trapped under debris in disaster affected areas can:

1. Self-monitor the radio environment and detect occurrence of a disaster incident (i.e., disaster detection).
2. Self-switch to a disaster mode and perform DL.
3. Relay emergency messages based on the LoE.

The emergency message will have the location coordinates of the devices based on which the rescuers can obtain individual location and to the identity to whom the device belongs to [8]. Rather than blindly searching for trapped victims, rescuers can search in localized areas depending on the location coordinates of the devices. For DL, we propose a modified jump stay channel hopping-based neighbour discovery algorithm, which is able to address the channel asymmetricity between devices. We introduce an energy-aware ad-hoc on-demand distance vector routing protocol (E-AODV) that considers the LoE of devices when routing the packets to an intermediate relay device. The proposed SmartDR method functions with minimal or no human intervention and can enable fast DL to enable rescue of the trapped victims and other people looking for assistance during post disaster recovery and relief.

The remainder of this paper is organized as follows. Section 2 provides a brief review of related work. The proposed SmartDR method is discussed in Section 3. The details of the disaster event detection, and DL are given in Section 4. Section 5 presents the proposed E-AODV routing protocol to relay the emergency message. Simulation results are given in Section 6 followed by conclusions in Section 7.

Table 1: Existing post disaster recovery communication systems

System	Technology	Network Structure	Deployment	Communication
DMM[14]	Satellite Access Point	Fixed and portable	Manual	R-R
HWMN[17]	IEEE 802.11 b/a/g	Hybrid Wireless Mesh	Manual	R-R, R-V
RDCN[9]	GPRS/GSM BTS & 802.11 WLAN	Portable Transmission Tower	Manual	R-R, R-V
AnonNet[18]	WSN 802.15.4	Ad-Hoc DTN	Hybid	R-R, R-V
Rescue[19]	IEEE 802.11b + 3G Cellular	Testbed	Manual	R-R,R-V
DistressNet[20]	WSN 802.15.4 and 802.11	Ad-Hoc	Manual	R-R, R-V
WIISARD[21]	IEEE 802.11	Ad-Hoc	Manual	Medical Response System
TDRAN[2]	WMCA+ Smartphone	Ad-Hoc	Manual	R-R, R-V, V-V
RDSP[22]	Smartphone+relay nodes	Ad-Hoc & server-client	Manual	R-R, R-V
[23]	IoT & wireless device	Ad-Hoc	Manual	R-R, R-V
Router Fusion[12]	Smartphone WiFi, LTE, WiGig	D2D	Self Configurable	R-R, R-V, V-V
TeamPhone[13]	Smartphone	Hybrid	Auto Configurable	R-R, R-V, V-V

2. Related Works

Deployment of additional wired or wireless infrastructure or combination of both is the most common strategy to support the communication during and after the disaster. For instance, a portable transmission tower equipped with multiple radio interfaces can be rapidly deployed in a disaster area to facilitates the communication between rescue team members and victims [9]. However, this deployment may not be very realistic or can be too time-consuming in real-life situations. A wireless multi-hop communication mechanism where the device can act as a relay or virtual access point to extend the network coverage is proposed in [2]. Similarly, the IEEE 802.11S mesh networks can be a viable solution in post disaster scenario where the victims wireless devices can self-configure the transmission parameter and work cooperatively to support post-disaster communication [10]. All these methods, however, are heavily dependent on fixed spectrum allocation such as licensed or unlicensed spectrum. Recently, cognitive radio (CR) based network deployment have attracted significant research attention owing to its intelligence in opportunistic spectrum usage [11]. Device intelligence and its application in post-disaster communication and recovery are also investigated in [12, 13]. Besides the ground-based communication system, airborne communication systems, like the satellite [14], unmanned aerial vehicle (UAV) [15], wireless balloon [16] are also investigated in the literature. The effectivity of airborne communication systems, however, suffers from high latency, cost of deployment, and battery life, which are most critical factors in the post disaster recovery. Table 1 summarises these post disaster communication systems where "R" and "V" represent rescue and victim respectively.

In situations where network infrastructure is crippled fully or partially, D2D is a promising technology that can employed. However, D2D has its own challenges. The authors in [24] have analysed such technology challenges in D2D for disaster recovery and have proposed a clustering procedure that integrates cellular and ad-hoc communication. The method introduces unwanted and extra communication messages in order to maintain and form the cluster, which in turn increases the energy consumption. In order to minimise energy consumption authors in [25] have proposed a D2D based messaging scheme using cellular technology in the licensed bands. However, this has a high dependency on BS, which is not ideal in a post disaster scenario. The messaging service is limited in range as is designed for single-hop communication. To extend the range of communication, a mobile station in a non-disaster are can act as a relay node to the ones in disaster area [26]. A multi-hop D2D communication is proposed in [27], where the devices can relay the emergency messages even outside the coverage of the BS. The authors in [28] proposed a smartphone based D2D communication using WiFi tethering to extent the connection in the disaster area. Unfortunately, all these suffer from network congestion due to single channel assignment policy. A key challenge is to establish multi-hop D2D communication for a multichannel multi-hop mobile ad-hoc network (MANET). Routing is crucial in MANET and although a number of standard routing protocols are available, most of these are for single channel operation [29].

The IEEE 802.11 standard provides an access to multiple non-overlapping channels. Although, using multiple channels provides the advantage of two transmissions occurring simultaneously without interfering with each other, most of the devices due to limitation in hardware can only transmit or receive on one channel at a time. Devices need to agree on a common channel and switch to that channel in order to communicate. Accordingly, some routing schemes in multi-channel networks topology discovery, traffic profiling, and routing are performed along with channel assignment [30]. This scheme requires a high degree of time synchronization and effective node scheduling in order to minimize overhead and ensure a consistent switching to the same channels at the same time. In [20] a combination of wireless ad-hoc and sensor network architecture is proposed that supports end-to-end routes in multi-channel radio environment. It utilizes both on demand and delay tolerant routing to address connected and disconnected networks respectively. A rapidly deployable wireless ad-hoc system (RDSP) is considered in [22] which combines the dynamic ID assignment and minimum maximum algorithms to facilitate the packet routing between victim smartphone and rapidly deployed relay nodes. Typically, these protocols deal with a single quality of service (QoS) metric such as throughput, delay, or round-trip time. Besides the above mentioned quality metrics, the network lifetime is one most critical parameter to consider when design a system to support post disaster network. To increase the network lifetime, the power consumption of a node should be optimized. An extension of [20] is proposed in [23] which overcome the problem of higher energy depletion rate at nodes in single shortest path routing by introducing an energy aware multi-path routing. Some multiple multi-channel multi-interface routing protocols have been proposed, which can select routes in a way that not only enhance bandwidth utilization, but also maximize energy efficiency and minimize end-to-end delay depending on the single or multiple radio transceivers in the devices [31]. In some cases like single path situation, energy harvesting can be an alternative option to enhance the network lifetime where device can harvest the energy from radio frequency or non-RF signal such as wind, vibration, etc. In a disaster scenario, a device with lower energy can harvest energy from the preceding device to forward a packet in successive device [32]. A routing protocol for utilizing multiple channels in multi-hop wireless networks is proposed in [33]. It assumes that radio environment map is available to allocate the best spectrum at each hop. As the receiver switches channels during the route discovery process it increases the possibility of failure of the route discovery. Therefore, it is essential to propose a robust neighbour and route discovery process for dynamic radio environments.

This research work focuses on the dynamic radio environment that may vary in time and space and is built upon our preliminary work in [8]. It is assumed that there is a partial or complete outage of network infrastructure immediately aftermath a disaster incident, and D2D communication can be employed track devices under debris and communicate emergency messages in such situations. This corresponds to ad-hoc communication with the additional complexity of dynamic multi-channel hopping. To address this, an efficient rendezvous (abbreviate as RDV, which means to meet each other on same channel at the same time) or neighbour discovery protocol in conjunction to multi-hop routing is detailed in Section 3 of the paper. Because of the dynamic nature of the environment, two devices may observe different channel information and owing to such asymmetric channel information it may result in higher RDV delay. In our proposal, we have introduced a channel ranking based multi-channel RDV process, which can result in a faster neighbour device discovery. For routing the proposal links the LoE of a device, which are critical for the devices to establish the routing path to forward the emergency messages to another device in the path. This is because even if the transmitting device locates a potential receiver device operating in the same channel, the receiver device may not be ideal to further relay the message due to limited LoE, which may result in disruption of the communication.

3. SmartDR Method

Radio environment monitoring, disaster event detection and DL are the major capabilities of the SmartDR method and it can function with minimal or no human intervention. In SmartDR, a device self-monitors the radio environment to self-detect the occurrence of a natural disaster incident termed as event in this paper and then immediately self-switch to a pre-defined disaster mode. In this mode, the device sends out help messages to other devices belonging to first responders' device operating in the disaster mode. These help messages contain the current location coordinates of the transmitting devices. The search area for the device can be localized reducing the rescue time.

We consider an urban environment as the earthquake-affected area. We assume that the area has network coverage (e.g., Long Term Evolution (LTE)) and user devices are connected to the LTE base station (BS). Immediately after the occurrence the event, networks in the affected areas are either fully/partially damaged or become heavily congested owing to a sudden increase in the network traffic resulting from an increase in the volume of calls made/received by people in those areas. Figure 1 depicts the telecommunication network scenario in an affected area. The solid and dotted

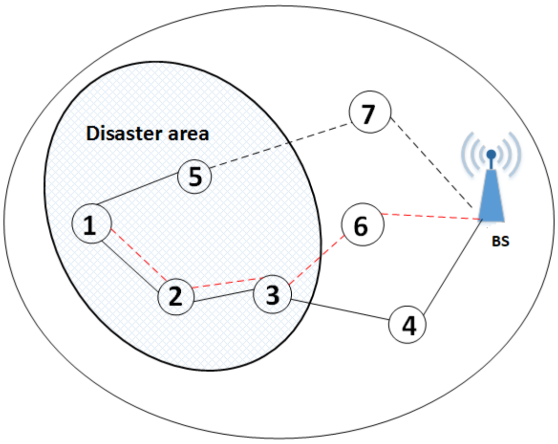


Figure 1: Post disaster Network scenario

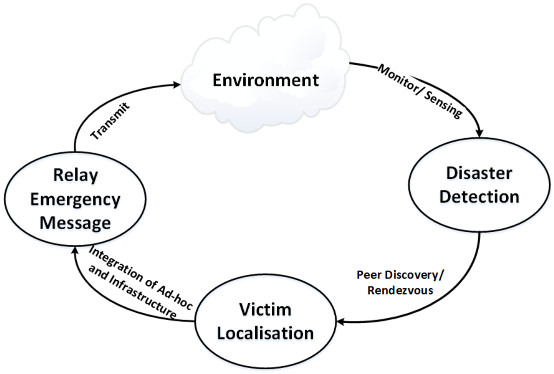


Figure 2: SmartDR Cycle

lines between BS and devices, respectively, shows active and failed (or blocked/heavily congested) communication links. The outer circle depicts the cellular coverage of the serving BS during normal operation (i.e., before the disaster) and the inner circle represents the area of the trapped devices. According to the proposed SmartDR method, the trapped devices can self-monitor the environment, self-detect the occurrence of the disaster incident and can self-switch to a predefined disaster mode to send out emergency HELP messages with the devices current location coordinates to a group of other devices (smartphones) belonging to rescuers and survivors nearby by using ad-hoc communications. Figure 2 illustrates the SmartDR cycle. To detect a disaster, a device continuously scans the LTE radio environment and monitors several parameters, such as control message interval, any sudden change in the volume of network traffic, and direct communications from serving BS in regards to the occurrence of a disaster. Based on such self-monitoring of the radio environment, the device can tentatively self-detect the occurrence of an unnatural incident primarily from the sudden change in the volume of network traffic in the serving BS. Section 4 explains the disaster event detection in detail. Once detected, the device goes into disaster mode, and perform RDV to locate other devices nearby.

In a normal situation (let's say, non-disaster situation), a mobile device (a smartphone in this case) can locate another mobile device nearby through the serving BS both are connected to. However, in a disaster situation like the one discussed in this work, if the serving BS is either congested or damaged, finding another neighbouring device to communicate the HELP message as well as localizing the trapped devices become challenging. In such instances, these trapped devices operating in the disaster mode will run a neighbour discovery or RDV process to identify the members of the ad-hoc communication group in order to send emergency HELP messages. In this work, we consider the neighbour discovery as a multi channel RDV problem. The ultimate goal of such neighbour discovery is to route and forward the emergency HELP message to another nearby device (operating in disaster mode). In this paper we use the words relay and forward interchangeably. Here, we have proposed the E-AODV routing protocol to communicate the HELP message to other devices. The existing

AODV protocol are not applicable to multi-channel route discovery and does not consider LoE. The E-AODV considers both delay and LoE of a device for route discovery and maintenance, details of which are described in Section 5.

4. Disaster Event Detection and Device Localisation

This section describes in detail how the device in SmartDR self-detects the occurrence of an event by monitoring the LTE radio environment and how it assists the DL process after self-switching to a disaster mode. As already mentioned earlier in this paper minimum or no human intervention happens in this entire process.

4.1. Radio Environment Monitoring and Event Detection

There is no straight forward way for a device to understand the occurrence of the event unless it is notified by the BS or manual trigger. During or immediately after the event there is a significant change in network traffic or load which can be a very good indication of occurrences of an event. This event can be natural or man made disaster which is out of scope of our work. During an event network load changes dramatically due to high number of devices initiate the communication of high number of calls being transferred in the current BS as some of the serving BS either becomes non-functional or over loaded. This change can be identified by a device by monitoring the physical resource block (PRB) in LTE network. In allocation of PRB is advertised by the BS in physical download control channel (PDCCH). The load of the cell is defined as a ratio of the number of allocated PRBs over the total number of PRBs in a cell.

The allocation of PRB is specific to a user which may not be decodeable by other devices. Alternatively, the total received signal strength indicator (RSSI) can be measured per PRB to understand the allocation of PRB. The RSSI is the linear average of the total received power observed only in OFDM symbols carrying reference symbols by devices from all sources, including co-channel non-serving and serving cells, adjacent channel interference, and thermal noise. If the measured RSSI is higher than a certain threshold value, the PRB is considered allocated otherwise it is considered empty. Thus a device performs such measure for all PRBs and may be able to determine the current load of the serving cell.

$$RSSI_x(t)) = 2\left(RSRP_{x\_c}(t) + \sum_{l=1}^{L} RSRP_{N_L}(t)\right) \tag{1}$$

$$+10\alpha\left(RSRP_{x\_c}(t) + \sum_{l=1}^{L} RSRP_{N_L}(t)RB_{x\_N_L} + N_n(t)\right)$$

$$RSSI = \sum_{x=1}^{X} RSSI(t)) \tag{2}$$

$$RB_{X_c}(t)) = \begin{cases} Allocated & if 10\alpha RSRP_{x\_c}(t) + 10\alpha\sum_{l=1}^{L} RSRP_{N_L}(t)RB_{x\_N_L} \\ & +N_n(t) > \lambda \\ Empty & otherwise. \end{cases} \tag{3}$$

Here the Reference Signal Received Power (RSRP) is measured by the device over the cell-specific Reference Signals (RSs) within the measurement bandwidth over a measurement period. x_c is current serving cell and $N_n(t)$ represents the noise from the neighbouring cells. λ is used as threshold. At this point, we may assume that the estimation is always done every T_s seconds (in practice, T_s can be around a minute), to generate the sequence of connection count samples $L_m(t)$, $L_m(t+T_S)$, $L_m(t+2T_S)$, $L_m(t+3T_S)$, ..., up to a certain limit (let's say M samples). Hence the value of the accumulated count of samples M at the time $(t+pT_S)$ may be given by the summation of the samples. When the accumulated count of samples M will exceed an appropriately chosen threshold value, the desired event will be considered to have occurred.

4.2. Device Localization

The current practice of device (i.e. victim carries or nearby the device) localization issue is mostly depends on manual search by civil defence authorities and assisted technologies. In our research we proposed a device initiated peer discovery methods to identify the victim or victim devices. This is known as rendezvous (RDV) in D2D communication. In normal operation, the RDV process is facilitated by the serving BS which may not available at the aftermath of disaster. This results an uncoordinated RDV process where two devices will try to discover and establish communication. It is assumed that after the disaster the radio environment becomes open means all the licensed and unlicensed radio frequency will become available for communication. This refers to multi-channel environment.

There are two possible ways to achieve RDV in multi-channel environment: common control channel (CCC) and channel hoping (CH).In CCC, it is considered that there is a common channel in the network which can be used to exchanged the control information. Due to single point of failure, security, and congestion issues, CCC is not a viable option in disaster scenario. In contrast to CCC, CH based RDV is a distributed approach where each device has a hopping sequence to visit the channel and send a control signal to discover the intended peers. In this research we considered CH based RDV protocol. Minimizing the time to achieve RDV and guaranteed RDV on all available channels are the main design constraints of a CH based RDV protocol. To achieve RDV, each device will generate a CH sequence based pre-defined procedure and hop accordingly. The CH sequence can be described as a tuple of two elements which includes the timestamp and channel index. For instance, CH sequence for device X is $X = (t_0, CH_0), (t_1, CH_1), \cdots, (t_n, CH_n)$. Hence to achieve RDV, there should be at least one common tuple between the sequences generated by the peers. Mathematically, it can be written as $\forall X, Y \in U; \mid X \bigcap Y \mid \neq 0$ where X and Y are the CH sequence generated by device X and Y from the network available channel set U.

Here we discuss in detail the peer discovery process in multi-channel environment. We consider a channel quality-based device discovery process where a device gathers channel availability information through sensing and design a CH sequence in order to minimize the time it takes to RDV with the device. This information is used to rank the channel and narrow down the search region i.e number of channels. The size of the search region depends on the number of channel. The channel ranking can be formulated as a convex combination of linear optimization problems[34]. The objective function is to maximise a weighted sum of the channel average availability. The weight is used to rank the channels and the channel with the maximum weight will be considered the best channel to communicate with the peer device. Consider that w_m is a weight associated with channel $f_m, m \in \{1, ..., L\}$. The weight is used to rank the channel such that the channel with the highest weight will be considered the best channel. The objective function of the linear optimisation problem can be written as (4)[35]:

$$w = \underset{(w_1, w_2, \ldots, w_L)}{\text{maximise}} \{\mathbf{C(w)} \overset{\text{def}}{=} \sum_{m=1}^{L} \pi^{(m)} w_m\} \tag{4}$$

$$\text{subject to} \big[1 - \prod_{i=1}^{h} \big(1 - p^{(m)}(1, s)\big) < \lambda_s^{(m)} col(n)$$

$$\forall s\{K, P\}, \forall m \in \{1, 2, ..., L\}, K \in \{1, 2, 3, ..., N\} \tag{5}$$

$$\sum_{m=1}^{L} w_m = 1; 0 \leq w_m \leq 1, \forall m \in \{1, 2, ..., L\} \tag{6}$$

Here, π^m is the steady state distribution of channel m and λ_s represents the service request by other devices. The probability of collision with other device transmission is considered to be the constraints in the optimization problem. Eqn. 5 describes the constraints of the optimization problem. $p(1, s)$ is the probability that the channel will move from the idle state (i.e., state 1) to state occupied in CH slot u. $1 - p(1, s)$ is the probability that the channel state will not change during slot u. $\prod(1 - p_u(1, s))$ is the probability that the channel state will not change during any of the CH slots of a particular sequence. $1 - \prod(1 - p(1, s))$ is the probability that the channel state will change (i.e., will no longer stay idle) during at least one of the slots that belong to a particular sequence. Here n is the length of the RDV cycle or number of time slots, which depends on the number of available channels. In an asymmetric channel scenario, a node experiences a different number of channels and has a different cycle length. Hence, channel sorting will also be different due to collision probability.

4.2.1. Channel Hopping Sequence Design

In the previous section, we have presented the channel selection and ranking procedure and output of this is going to use to design the channel hopping sequence. The channel with highest rank will appear more compare to others to identify or localize the device. The basic concept of device localization or neighbor discovery is inspired by the concept of clique. In mathematics, Clique is used to identify the adjacent vertices. In this work, we use clique to generate the channel hopping sequence so that two users jump over the channel to achieve RDV. Here, we first provide a brief introduction of clique followed by CH sequence generation using clique.

Definition 1: Clique: A clique C is defined as a collection of non-empty subset of a finite universal set which satisfies the intersection property. Mathematically, $\forall X, Y \in U : X \bigcap Y \neq 0$ Where X and Y are two non-empty subset of Universal set U. For instance, $C = \{\{1,2\},\{1,3\},\{2,3\}\}$ is a clique under the set $U = 1, 2, 3$. The same principal is used to design a CH sequence so that two devices can have a subset of channels from the available channel list and hop at each time based on the channel subset.

Definition 2: x-Clique: A x-clique is a subset of a finite universal set U can be defined as:

$$\begin{gathered} x(p,q) = \left\{ \left(\left\lfloor \frac{\sqrt{n}}{q} i \right\rfloor \sqrt{n} + p + j \right) (mod \quad n), \\ i = 0, ..., p-1; j = 0, ..., \sqrt{n} - 1 \\ 0 \leq p \leq \sqrt{n} \quad \& \quad 1 \leq q \leq \sqrt{n} \end{gathered} \tag{7}$$

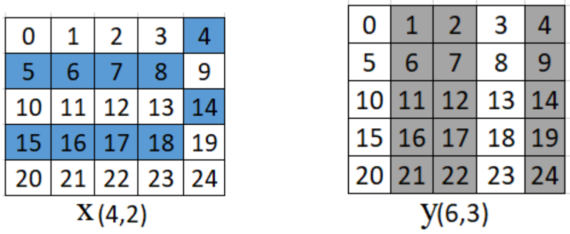
For instance, when $n = 25$, for $p = 4$ and $q = 2$, the $x(4, 2) = \{4, 5, 6, 7, 8, 14, 15, 16, 17, 18\}$. Here p defines the starting position of the sequence such as $p = 4$ and q is used to determine the size of the sequence which is $q\sqrt{n}$. An example of x-clique x(4,2) shows in Figure 3(a).

Definition 3: y-Clique: A y-clique is a subset of a finite universal set U can be defined as:

$$\begin{gathered} y(r,q) = \left\{ \left(\left\lfloor \frac{\sqrt{n}}{q} i \right\rfloor + r + j\sqrt{n} \right) (mod \quad n), \\ i = 0, ..., r-1; j = 0, ..., \sqrt{n} - 1 \\ 0 \leq r \leq n-1 \quad \& \quad \leq q \leq \sqrt{n} \end{gathered} \tag{8}$$

For example, $n = 25$, for $r = 6$ and $q = 3$, the $y(6, 3) = \{1, 2, 4, 6, 7, 9, 11, 12, 14, 16, 17, 19, 21, 22, 24\}$. Same as previous p is for the starting portion of the element modulus n, such as $r = 6(mod \quad n) = 1$ and q is for the number of columns as shown in Figure 3(b).

During the post disaster in order to save energy, a device will perform periodic sensing to identify the available channels. Using the Eq. 4 it will rank the observe channels. If the device has data to queue it will construct a x-clique. The size of the x-clique depends on the number of available channels. The channel with higher rank will allocate more timeslots.The algorithm 1 describe the timeslot assignment for each channel. The duration of each timeslot is considered long enough to exchange the control information. At the receiver side, the receiver visits the channel based on y-clique.



(a) x-clique of x(4,2) (b) y-clique of y(6,3)

Figure 3: CH sequence is generated by (a) x-clique and (b)y-clique for n =25.

Algorithm 1 DL Algorithm

Input:
(i) Number of available channels, p;
(ii) Rescan period, T_{out};

Output:
(i) Channel map CH_{map};
(ii) Channel timeslots CH_{slots};

Begin

while $mod(t, T_{out}) = 0$ **do**
  $[Avail_{CH}]$; {Available channel set}
  Rank($[Avail_{CH}]$) = $[CH_{List}]$
  $n =\mid Avail_{CH} \mid$
  $CH_{slots} = n \times n$n{Grid formation}
end while
while packets arrive **do**
  $k \leftarrow k + 1$
  for $i = 1 : n$ **do**
    p = randperm[0,n-1]
    construct x-clique $x(p(i), q_1)$ {Sender CH sequence generation}
    $CH_{slots}\big(x(p(i), q_1) = CH_{list}(i)$
    $D = setdiff(T_{slots}, x(p, q_1))$
    $CH_{new\_slots} = (n - 1) \times (n - 1)$
    if $CH_{new\_slots} < D$ **then**
      $CH_{new\_slots} = [D, d]$ {d is dummy variable to construct the grid}
    else
      $CH_{new\_slots} = D$
    end if
  end for
end while
for $j = 1 : n$ **do**
  r = randperm[0,n-1]
  construct $y(r(j), q_2)$ {Receiver CH sequence generation}
  $CH_{slots}\big(y(r(j), q_2\big) = CH_{list}(:, i)$
end for

End

A CH sequence in a time slotted architecture indicates the timeslots on which a device transmit or receive data to or from neighboring devices. Two CH sequence is called time synchronised if they start channel hopping at the same time. The performance of CH sequence depends on time synchronisation. Consequently delay to achieve RDV will also fluctuate due to the same. Hence, CH sequence that designed for time synchronize environment may not suit for time asynchronise environment.

Definition 4: (Rotate) For a clique x under $U = \{0, ..., n - 1\}$ and a non-negative integer $i \in \{1, 2, ..., n - 1\}$, we define $x' = rotate(x, i)$ or $R(X, i) = \{(j + i) \ mod \ n \mid j \in x\}$ to be a new clique x'.

Definition 5: (Rotation Closure Property) A clique $x' = rotate(x, i)$ is said to satisfy the rotation closure property if $\forall X, X' \in C, i \in \{1, 2, ...n - 1\} : X \bigcap X' \neq 0$.

For instance, $C = \{(0,1,2,4),(1,2,3,5),(0,2,3,4),(1,3,4,5),(0,2,4,5),(0,1,3,5)\}$ is a clique under $U = \{0,1,2,3,4,5\}$ which satisfies rotation closure property. The rotation closure property guarantee the RDV between devices even they start hopping at different time.

Theorem 1: A clique with rotation closure property can guarantee RDV for two devices.

Proof: Let us consider that, $a_i fori = 0, 1, \cdot, -1$ be $\sqrt{n}$ elements of R(y), then we can write $a_{i-1} \leq a_i \leq a_{i-1} + \sqrt{n} + 1$ as the distance between two successive elements of $R(a)$ is $\sqrt{n}$. Now to proof the theorem we need to show that a_i is an element of $R(x)$. It is consider that the smallest element in $R(x)$ is a b which is larger than $a_{i+1} \leq b \leq a_i + n - \sqrt{n} + 2$ as any two elements in $R(x)$ must have distance less than or equal to $n - \sqrt{n} + 1$. This implies that $a_i \in R(y), b \leq a_i \leq b + \sqrt{n} - 1$ is also contained $R(x)$.

Moreover, according t0 definition 1 and 2, $x(p,1)$ clique can generate a sequence of $\sqrt{n}$ successive elements and has at least one intersection with $y(r,1)$. Now, with $x(p,q_1)$ we will have q_1 intersections with $y(r,1)$. Similarly $y(r,q_2)$ will have q_2 intersections with $x(p,1)$. Hence the number if RDV that can be achieved with $x(p,q_1)$ and $y(r,q_2)$ is $q_1 \times q_2$. Figure 4 shows the graphical illustration of the same. The first and second block of the Figure. 4, show the the selection of timeslots according to $h(4,2)$, and $v(6,3)$, where $l_1 = 2$ and $l_2 = 3$. The third block of the Figure. 4 represents the timeslots where RDV is achieved. The no. of RDV is $l_1 \times l_2 = 2 \times 3 = 6$.

0	1	2	3	4
5	6	7	8	9
10	11	12	13	14
15	16	17	18	19
20	21	22	23	24
No. of RDV = 6				

Figure 4: Illustration of degree of overlap using clique channel hopping sequence.

5. E-AODV Routing

After the successful establishment of an RDV, it is considered that neighbour devices in the disaster area are able to communicate. To be considered as neighbours, two or more devices need to operate within the transmission range of each other. However, data communication is not possible between a pair of devices unless they are on the same channel within the transmission range. Let us consider the scenario depicted in Figure 1 where device 1 wants to transmit an emergency message to the nearby BS. As the disaster affected currently serving BS for device 1 is unavailable, device 1 has to depend on other intermediate devices to relay its packets to the another nearby functioning BS. Moreover, it is assumed that a device can access several proprietary and non-proprietary channels when the formal networks fail due to the event. Hence, it is necessary to design a routing protocol in multi-channel multi-hop wireless networks that targets the creation and the maintenance of wireless multi-hop paths among devices by deciding both the relay devices and the spectrum to be used on each link of the path. Such problem exhibits similarities with routing in multi-channel, multi-hop ad-hoc networks and mesh networks, but with the additional challenge of having to deal with the dynamically changing spectrum availability and LoE.

In an emergency scenario, it is crucial to take into consideration the following: the importance of establishing a routing path based on the energy consumption and the LoE of the devices as well as the delay it takes to relay a packet from source to destination. We propose here a reactive routing protocol which constructs the routing path based on leftover battery energy of each intermediate devices and the delay associated with the path. In the following subsection, we discuss the different delay components that have been considered.

5.1. Delay Component

End-to-end delay along a route is a traditional metric for any routing protocol. In traditional fixed multi-channel scenarios, delay components are as follows:

Switching Delay: Time required to switch from the current channel to another channel. The delay associated with this type of switching is generally 10ms for each 10MHz step in the spectrum range of 20MHz 3GHz [36], which can be written as $D_{i,j} = \sum_{j=1}^{H} C \mid Band_i - Band_j \mid$. Here C is 10ms per 10MHz and H is the number of hops from source to destination. Hence the switching delay in multi-flow interference and active frequency switching becomes [36]:

$$D_s = 2C \cdot \mid Band_M - band_1 \mid \tag{9}$$

Backoff Delay: As the wireless medium is shared by multiple users and no simultaneous transmission is possible on the same channel unless they are physically far apart. Hence, the time required for the successful transmission of a packet is known as backoff delay. The backoff delay on a channel (i) can be written as [37]:

$$D_B(n_i) = \frac{1}{(1-p_c)\big(1-(1-p_c)^{\frac{1}{n_i-1}}\big)} \times W_0 \tag{10}$$

where p_c is the collision probability, n is the total number of contending devices and W_0 is the minimum value of the contention window size.

Queuing Delay: It is the time difference the packets is assigned to a queue for transmission and the time it starts transmission. The queuing delay on $Band_i$ before it starts transmission can be written as follows [36]:

$$D_Q(BAND_i) = \sum_{n=1}^{n_i-1} \frac{P_n}{B_i} \tag{11}$$

where P_n is the packet size of flow n and B_i is the bandwidth of $Band_i$.

However, there is another delay that has to be considered in the dynamic multi-channel environment, as channel availability information among devices is not considered fixed. In order to established a communication, the communicating parties need to find each other one the same channel at the same time which is know as RDV. The Time required to achieve RDV is called the RDV delay.

Rendezvous Delay: Time required to find a neighbour on the same channel at a particular instant. It is also known as time to RDV (TTR). RDV delay indicates the number of time slots that a device takes for RDV, which depends on the underlying RDV scheme being utilised. Moreover, symmetricity of channel information, number of hops and number of common channels between peers play an important role on TTR calculations. In this paper, we have applied the DL RDV scheme as described in section 4. Let us consider that a CH sequence is generated using x-clique with a length of $q_1 \times \sqrt{n}$ elements where the maximum distance between two successive elements can be written as $\sqrt{n}\left(\left\lceil \frac{\sqrt{n}}{q_1} \right\rceil - 1\right) + 1$. And a CH sequence based on y-clique with $q_2 \times \sqrt{n}$ elements. The maximum distance between two CH sequences is the sum of the distance of x-clique and y-clique elements. Given two integers q_1 and q_2, $1 \leq (q_1, q_2) \leq \sqrt{n}$ and two random numbers p and r, $0 \leq (p, r) \leq n - 1$. Hence, the two users can achieve RDV or time to RDV (TTR) can be expressed as follows:

$$D_R = \sqrt{n}\left(\left\lceil \frac{\sqrt{n}}{q_1} \right\rceil - 1\right) + \left\lceil \frac{\sqrt{n}}{q_2} \right\rceil \tag{12}$$

Hence the total delay becomes: $D = D_S + D_B + D_Q + D_R$.

5.2. Energy Component

Our proposed protocol also considers the energy consumption and LoE of a device in the route selection procedure. Instead of choosing a path with minimum energy consumption, here we consider the path in which the intermediate devices have the maximum LoE. The rationale behind this is as follows:

- The path with the minimum energy consumption may attract more traffic flows but consequently may also suffer from faster battery exhaustion.
- If an intermediate node, in the minimum energy consumption path, fails owing to battery exhaustion, it will leave the path broken and may also disjoint the network.

An ad-hoc network shown in Figure 1 can be represented by an undirected directional graph, $G = (V, E)$ where V is the set of network devices or smartphones and E represents the set of bidirectional links. Let us consider that E_R represents the energy required to transmit a packet from X to Y, and $LoE(X)$ is the leftover energy of device X. $LoE(X)$ of can be calculated by subtracting the consumed energy from initial energy, which is:

$$LoE(x) = X_{E_{initial}} - X_{E_{consumed}} \tag{13}$$

Let us assume that, there is more than one path to reach from source to destination. The sum of a path can be written as the summation of the LoE of individual devices in the path, i.e. $LoE_{path}(X, Y) = \sum_{i=X}^{Y} LoE(i)$. The idea is to find the path with maximum LoE and avoid the path which may create disjoint networks. Figure 5 illustrates a routing selection scenario where X, the source device has a data packet to send to the destination Y. The number inside the circle represents the LoE of an intermediate device.

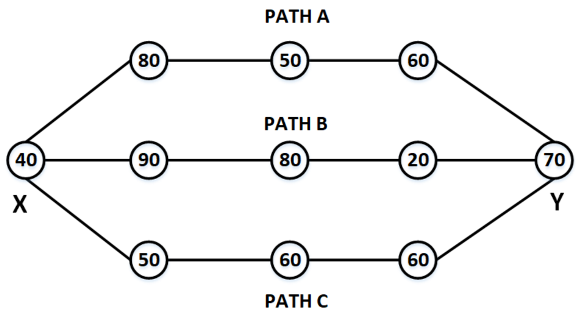


Figure 5: Routing paths from X to Y

Here the summation of LoEs of Path A (Upper line), path B (middle line) and path C (lower line) is 300, 300, and 290 respectively. Hence path C is discarded as it has lower LoE compared to path A and B. Now, it is required to find the path with maximum lowest LoE and discard that path. To do this we take the standard deviation of both path A and B. The path with the lower standard deviation is going to be selected as the routing path. In this example $\sigma_{pathA} = 14.14$ and $\sigma_{pathB} = 24.49$. Therefore path A is selected. This helps to prevent the network disjoint effect. In the next section, we will discuss the procedure of routing establishment and maintenance.

5.3. Routing Establishment Procedure

For route establishment, we adopt the same procedure as described in ad-hoc on-demand distance vector (AODV) [38] with some modifications and called it energy aware ad-hoc on-demand distance vector (E-AODV). When a source wants to send a packet to its destination, a route discovery procedure is performed. As a part of route discovery, the source broadcasts a route request (RREQ) to its surrounding neighbours. A device that receives an RREQ but not the destination of the RREQ packet, will rebroadcast the RREQ. Before rebroadcast, the RREQ will be updated by adding its identifier, energy status and its available channel list.

Upon successful reception of the RREQ, a unicast route reply (RREP) message will be generated by the destination with encapsulate channel information to be used by the peer device. The detailed procedures of RREQ and RREP are shown in the algorithm below.

5.4. Route Maintenance

In order to update the route information, it is necessary to do route maintenance. Route information needs to be updated as some of the routing paths may not be available any longer or may get very congested with traffic from other users. Moreover, due to mobility or failure of intermediate devices, the existing route may break while in use. The procedure of the proposed algorithm is illustrated in figure 5. There are three disjoint paths A, B, and C to reach the destination Y from Source X. All these paths will be ranked based on the LoE and standard deviation of residual energy. The path with highest rank will be selected as the best routing path. If, however, the selected path is not available or if the path fails, then the second best path will be selected. Moreover, in order to update

Algorithm 2 E-AODV Route Establishment

Input:

(i) Available channel $Avail_{Ch}$;

(ii) Left over Energy LoE;

(iii) Left over Energy Threshold, $LoE_{threshold}$;

(iv) Route Request $RREQ$

(v) Route Reply $RREP$

Output:

(i) Route List R_{list};

Begin

while Packet Arrives **do**
    Broadcast RREQ
    Cheque SEQ
    Cheque LoE
end while
if $SEQ_i^d < SEQ_j^d \wedge LoE_{path}(i) > LoE_{threshold}$ **then**
    if Node is destination **then**
        Find $max(LoE_{path})$
        if $\mid max(LoE_{path}) \mid > 1$ **then**
            for $n = 1 :\mid max(LoE_{path}) \mid$ **do**
                Calculate $\sigma(LoE_{path}(n))$
            end for
            Select $R_{list} = min(\sigma)$
        else
            $R_{list} = max(LoE_{path}(i))$
        end if
    else
        Node is an intermediate node
        Update $RREQ$
        Rebroadcast $RREQ$
    end if
end if
while $RREQ$ received **do**
    Generate $RREP$
    Unicast $RREP$
    if Node is Source node **then**
        Packet Transmission
    else
        Node is Intermediate node
        Assign Channel
        Forward $RREP$
    end if
end while

End

the routing information, we consider that there is a timer set up for each route. If the route remains unused for a certain period and the timer expires, it will be considered that the route is no longer available and this path information will be removed from the routing table. This information will then be sent to other devices as a route error (RERR) message. On receiving the RERR message, the source may use an alternate route from the routing list to continue delivering data packets. If none of the route paths are available, the source will initiate a new route discovery process.

6. Performance Analysis and Validation

A MATLAB-based simulation is used to evaluate the performance of the proposed SmartDR in post-disaster scenario. Here we assume that devices switch to the disaster mode after detecting the occurrence of the disaster event and performance of post-disaster recovery is studied through the simulation. We first evaluate the performance of peer discovery DL protocol and compare it with the existing non-channel ranking-based hopping protocol such as JS [39], disjoint relaxed difference set (DRDS)[40] and channel ranking-based protocols such as Basic and Enhanced adaptive multiple rendezvous control channel (AMRCC)[41]. While, the Basic AMRCC and Enhance AMRCC [41] protocols use channel ranking information to construct the CH sequence, all others use random channel selection to map the channels in hopping sequence. Secondly, the proposed E-AODV routing protocol is evaluated and compared with AODV[38], AOMDV[42], Improved AOMDV[43], Switch-Aware [30], RSDP [22],PDC [23], and k-hop [44] routing protocols.

For the simulation, a network with varying number of devices is considered with the number of available channels ranging from 2 to 40 spanned across of $1500m \times 1500m$ with each device having a consistent transmission radius of $100m$. This work considered both licensed and unlicensed channels with equal priority. It is also considered that devices were asynchronous at the beginning of the network initialization and they synchronized themselves after achieving RDV. During simulation, each device trapped initiated the spectrum sensing, which lasted for approximately 25ms per channel and $\leq$ 1ms/channel, respectively, for fine and fast sensing processes [45]. Fast sensing is performed by selecting the samples of the Poisson traffic within its sensing period and create a list of available channels. Thereafter each of the devices performed fine sensing on a channel from the list before jumping into it. The ranking table of devices is based on channel availability and channel activity observed locally by a victim user. It is assumed that if a packet has arrived during the spectrum sensing or hand-shaking process, it is queued and it remained in the queue till RDV is achieved. In this research, collision among control or handshake packets is not considered.

Table 2: Simulation Parameters

Parameter	**Value**
Simulator	MATLAB and ***OPNET***
Area	$1500m \times 1500m$
Number of Devices	100
Channel Type	Wireless Channel
Number of Channel	2 to 40
Initial Energy of Device	100J
Simulation time	5 mins
Traffic	CBR
Packet Size	512 bytes

All simulation results presented in this paper are based on an average of 1000 simulation runs. The simulation covered both symmetric and asymmetric channels with rankings from 0 to 1, where $\alpha \in [0, 1]$. While, 0 implies that the channels between devices A and B are in different order in terms of channel ranking, 1 implies that devices A and B have the same channel ranking list which is called channel ranking similarity factor.

6.1. Performance Analysis of DL protocol

The proposed DL protocol is compared with different channel rank and non-channel rank-based CH protocols under varied channel orders and number of channels.

6.1.1. Channel Order/Rank

Figure 6 shows the time to RDV (TTR) or peer discovery delay with respect to channel rank or channel order similarity. Here channel order α refers to degree of channel ranking observed by both sender and receiver. We considered 40 channels were available in the system. It is expected that the higher the value of α the better the delay performance. Figure 6 exhibits the same. In comparison to other CH protocols, DL outperformed as the value of α increased. A similar delay trend can be observed for both JS and DRDS CH protocols. A significant performance gap can be observed in comparison to DL specially for lower value of α. For instance, When $\alpha = 0.2$, the peer discovery delay is almost three times higher for JS and two times for DRDS with respect to DL. This is because in DL more number of time slots are assigned to the channel with higher rank. The JS and DRDS did not consider the channel ranking in the CH protocol design, rather have assigned the channel in random fashion but still show better performance than basic and enhance AMRCC. The exponential growth of the length of CH sequence is the main issue which seize the performance of AMRCC protocols, nevertheless more number of time slots have been allocated for higher rank channel. This is the fundamental difference in design with our proposed DL CH protocol. Most of the protocols perform almost same when devices observe channel with similar rank.

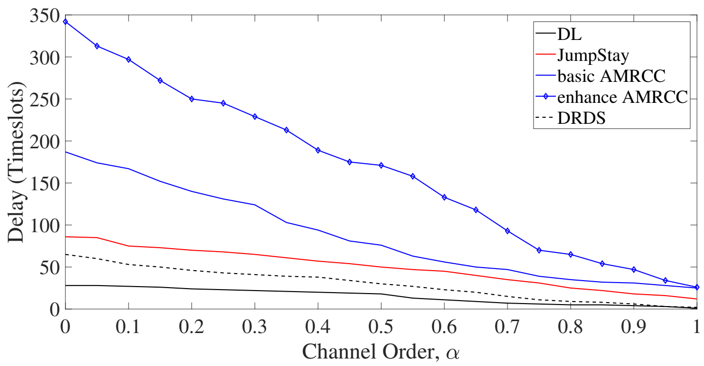


Figure 6: Illustration of Rendezvous performance enhancement in terms of delay with channel ranking

Figure 7 shows the number of achieved RDV or the number of times the devices meet each other using the considered protocols. It is also called degree of overlap of the channel and the timeslot. We have normalized the degree of overlap as the CH cycle length is not same for all CH protocols. Our proposed DL protocol achieve better performance as more RDV can be achieved when integrating the channel quality information in the CH sequence design. The higher the degree of overlap the lower the RDV delay which have been presented in Figure 6 and 7. DL, JS, and DRDS exhibit guaranteed RDV even when there is no match in the channel ranking of the participating devices. Hence, degree of RDV is 1 for α=0. None of the two AMRCC protocols can guarantee the RDV if the devices experience completely different channel order. As channel order increases, the degree of overlap also increases for all the CH protocols. A significant performance gap can still be observed.

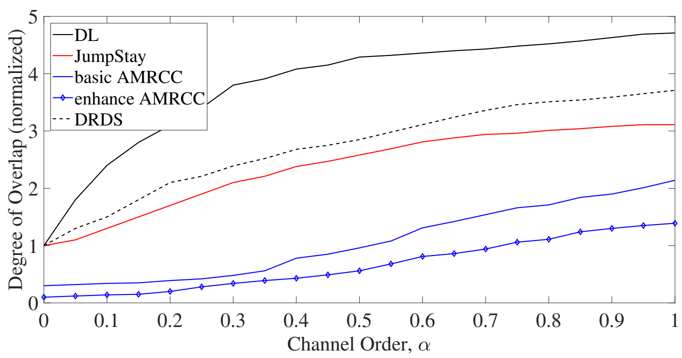


Figure 7: Illustration of Rendezvous performance enhancement in terms of degree of overlap with channel ranking

6.1.2. Number of Channels

The length of CH cycle strongly depends on the number of available channels observed by a device. For DL, JS, DRDS, and basic AMRCC the length of CH sequence increased mostly linearly with the number of channel but there is an exponential increment in CH sequence length for enhanced AMRCC. Figure 8 and 9 show the performance differences in terms of delay and degree of overlap respectively for the considered CH protocols. In both cases, our proposed DL protocol outperformed in comparison with others. For instance, the DL protocol experiences 45 timeslots delay with 35 channels where as 55, 69, 109, and 309 timeslots delay for DRDS, JS, basic AMRCC, and enhanced AMRCC respectively. DRDS and JS guarantee rendezvous in $\mathcal{O}(N^2)$ and $\mathcal{O}(N^3)$ time slots where N represents the number of channels. Using DL CH sequence RDV can be achieved in $\mathcal{O}(N)$ time slots. The observation of degree of overlap with the number of channel is presented in Figure 9. The degree of overlap decreased rapidly as we increase the number of channels. Here we consider fixed value of $\alpha = 0.5$. The degree of overlap decreased as the CH sequence length increased with the number of channels. The rate of decrease depends on underlying mathematical construction of the sequence. Using the clique and map the timeslots with channel rank enhanced the performance.

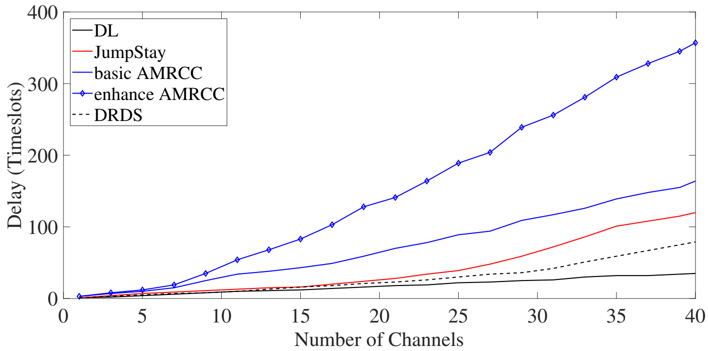


Figure 8: Impact of number of channels on delay performance

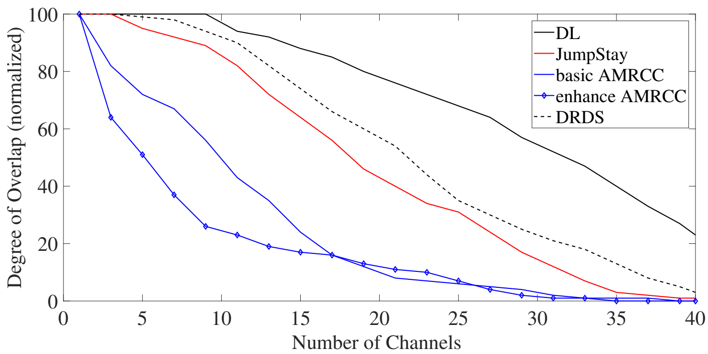


Figure 9: Impact of number of channels on degree of overlap performance

6.2. Performance Analysis of E-AODV Routing Protocol

6.2.1. End-to-End Analysis

- *Impact of Number of Devices*: In this subsection, we evaluate the performance of the E-AODV routing protocol by measuring average end-to-end delay with respect to the number of devices and the number of active flows. The performance is compared with the AODV [38], RSDP [22], and PDC [23] protocols. We choose RSDP and PDC, as these protocols were developed to address the post-disaster communication. Figure 10 shows average end-to-end delays with number of devices. The results show that for AODV and RSDP, the end-to-end delay increases very significantly with the number of devices. This is because route selection in AODV does not consider the delay associated in the path. In RSDP, a reliable coordination between server, client, and relay devices is necessary to establish the end-to-end route. To achieve the coordination it utilizes dynamic ID assignment and minimum-maximum neighbour algorithms, which exchange multiple control messages. In contrast, the E-AODV and PDC protocols embed the delay component in each hop and select the path with the minimum delay unless the selected path consists of a device with very low LoE. This is because the path with critical LoE is discarded from the routing list even though it shows minimum delay. The PDC protocol only considers the device with better lifetime. The ratio of residual energy and the energy consumption is considered to the lifetime of a device. Additionally, E-AODV experiences overall lower end-to-end delay by 209%, 164%, and 51% when compared with RSDP, AODV, and PDC, respectively.

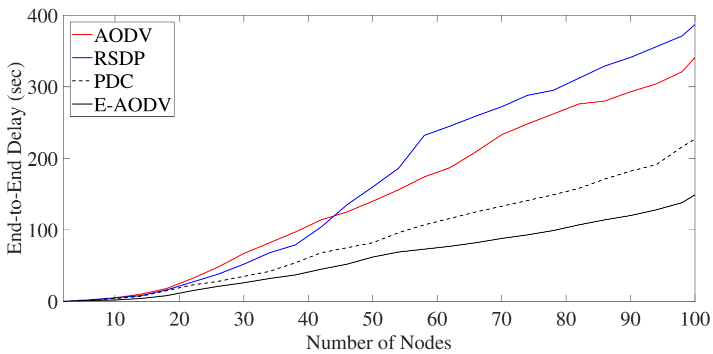


Figure 10: Average End-to-End delay with number of devices

- *Impact of Number of Flows*: We measured how our proposed approaches selected the path/route with the lowest possible delay. It is clear that when routing incorporates the delay and energy of a device, the routing path is selected in a way that can increase the network lifetime and maintain network connectivity. As traditional AODV cannot handle multi-flow operations, we considered the Switch-Aware [30] and K-hop distance [44] protocols in addition to RSDP and PDC routing protocols to compare the performance. Switch-Aware [30] and K-hop distance [44] are multi-channel multi-hop routing protocols using a single transceiver, in which two consecutive devices in a path cannot switch channel and if they do, they notify the neighbour whenever channel switching happens. However, Switch-Aware protocol still faces increasing backoff delays with the number of flows and continuously switches channels to find the best route. K-hop and PDC utilize a common control channel to exchange the multi-channel peer discovery process, which requires $\mathcal{O}(N^2)$ timeslots. Moreover, the control channel suffers from congestion with the increase of number of flows. As a result there is a rise in end-to-end performance as shown in Figure. 11. E-AODV also exhibits similar behavior but better performance in terms of delay. In E-AODV, routing discovery is embedded with a rendezvous process, which enables peer devices to exchange the available channel list information. Moreover, E-AODV takes into account channel switching, backoff, queuing and rendezvous delays when selecting the routing path.

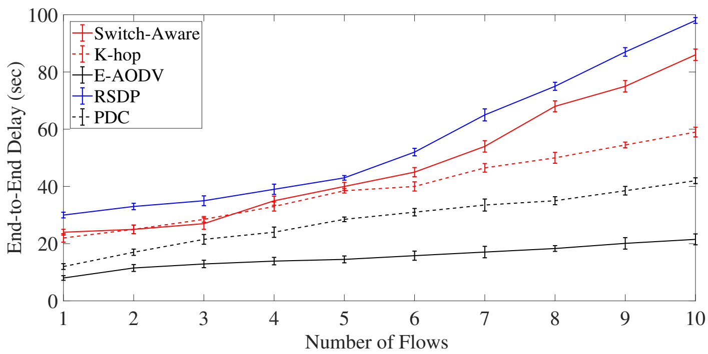


Figure 11: Average End-to-End delay with number of nodes

6.2.2. *Average Throughput*

To compare the performance gain, we considered the aggregate throughput with the increasing of flows even though throughput may not be a very important performance parameter for disaster recovery protocol. However, for any routing protocol, throughput is considered one of the key parameters to understand the protocol performance. We exclude the AODV here as it is originally designed for single channel and cannot handle multi-flow operations. Here we consider that each flow generates traffic at 2 Mbps. With the increase in the number of flows, the channel bandwidth becomes saturated and that has resulted in the degradation of performance. A nonlinear performance behavior is observed in Figure 12 owing to unfair handling of flows with different number of hops under increased network congestion. With the increase in the number of flows from 7 to 10, the total throughput has decreased since higher network congestion has resulted to queue buildups and high drop rates. E-AODV outperformed the other protocols because of the inclusion of the RDV delay in the path selection. In an open radio environment, the rendezvous delay is very significant. The probability of packet drops increased with route discovery delays and that has caused significant throughput degradation. The PDC and K-hop still shows better performance compared to Switch-aware and RSDP protocols. In switch-aware, a device in multi-flow scenario needs to switch the channel very frequently, which introduces an additional switching delay and results in lower throughput. A very poor performance can be observed for RSDP owing to the network overhead as different types of devices are required to constitute the network topology.

6.2.3. *Energy Performance*

Figure13 and 14 show the performance of E-AODV protocol in terms of the number of energy exhausted nodes and residual energy with the increase in simulation time. The E-AODV performs better in comparison to other protocols as shown in Figure 13. This superior performance is achieved by considering the energy consumption and LoE of the device in the route path. E-AODV calculates the standard deviation of LoE of all the paths and chooses the path with lowest standard deviation.

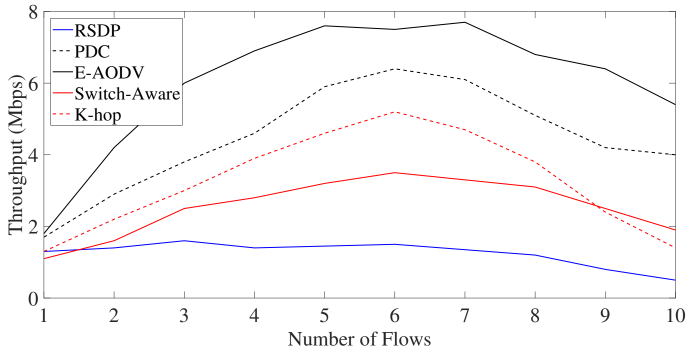


Figure 12: Average End-to-End delay with number of nodes

Considering the standard deviation in routing path selection reduces the probability of failure of intermediate nodes as well as network partition being happened. Figure 14 shows the residual energy of the network. The initial energy of a device is 100 J and there are 100 devices considered in this scenario. Hence the overall network energy is 10000 J. As the Switch-Aware protocol does not consider the energy issue, we have selected the AOMDV[42] and improved AOMDV[43] protocols, in addition to RSDP and PDC protocols to compare the performance. AOMDV is an extension of AODV which facilitates multi-path routing but hop count is the metric for path selection. Performance of Improved AOMDV protocol is enhanced because it select the nodes with higher residual energy. It is natural that residual energy of a device drops with time. The rate of drop depends on the how often the node has been selected to forward the packet. In our proposed protocol we consider the path not only having higher LoE, but also having lower standard deviation of LoE, which means that we can use the path for a longer duration compared to the one having a higher standard deviation. Moreover, unlike other protocols, E-AODV does not select the path with minimum energy consumption because that path may have nodes with lower average residual energy, which might lead to faster battery depletion. The result for residual energy in figure 14 shows that nodes with AODV and RSDP protocols have run out of all residual energy at the end of the simulation time (i.e., 500 sec), whereas a device with E-AODV has one third of energy still left to carry on.

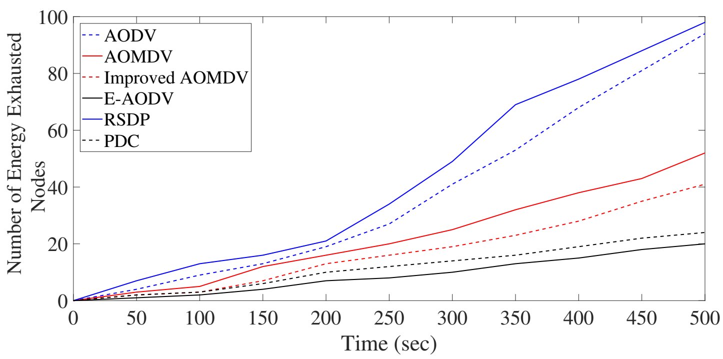


Figure 13: Energy exhausted nodes

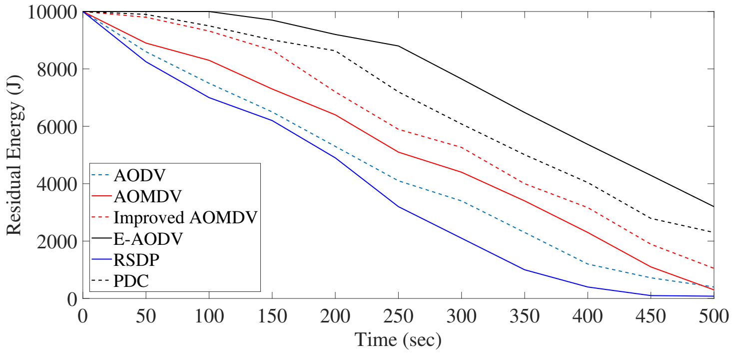


Figure 14: Residual energy

7. Conclusion

Immediately aftermath a disaster incident, like earthquake, the network in the affected areas can suffer from significant performance degradation due to power outages, congestion and the physical break-down of the communication infrastructure. In such situations, it is paramount to quickly locate and save the victims trapped under rubble. The SmartDR method based on the 5G D2D communication technology is proposed in this paper as an effective method of communication in such situation. In SmartDR, devices sharing the same channel communicate to each other without using any infrastructure. The proposed method integrates both device discovery and route establishment. The E-AODV routing protocol, as discussed in the paper, considered both delay and energy metrics during the routing establishment. Instead of always considering the shortest path or the path with the minimum energy consumption, we have designed the routing protocol based on the LoE of a node as this is critical in an emergency communication. Simulation results indicate that considering energy consumption and LoE of a device to select a routing path can significantly improve the network performance, especially in post-disaster scenario. As part of our future work, we plan to integrate the disaster detection (pre-disaster scenario) part with the post-disaster recovery methods in order to design a complete end-to-end system for disaster detection and recovery.

8. References

[1] C. for Research on the Epidemiology of Disasters, The human cost of natural disasters: A global perspective (2015).

[2] Q. T. Minh, Y. Shibata, C. Borcea, S. Yamada, On-site configuration of disaster recovery access networks made easy, Ad Hoc Networks 40 (2016) 46–60.

[3] D. Hawkins, Project 25: The quest for interoperable radios, in: Cops Interoperable Communications Technology Program, Vol. 6, 2007.

[4] Federal Communications Commission, Report and order-amendment of part 90 of the commissions rules to permit terrestrial trunked radio (TETRA) technology, Tech. rep. (sep 2012).

[5] Tetrapol Specifications, Part 1: general network design, part 2: voice and data services in network and direct mode, Tech. rep. (Jan 2015).

[6] G. R. A. N. W. Group, et al., Study on channel model for frequencies from 0.5 to 100 ghz (release 15), Tech. rep., 3GPP TR 38.901 (2018).

[7] K. Ali, H. X. Nguyen, P. Shah, Q.-T. Vien, N. Bhuvanasundaram, Architecture for public safety network using D2D communication, in: Wireless Communications and Networking Conference (WCNC), IEEE, 2016, pp. 1–6.

[8] A. Hossain, S. K. Ray, R. Sinha, A smartphone-assisted post-disaster victim localization method, in: IEEE 18th International Conference on High Performance Computing and Communications, IEEE, 2016, pp. 1173–1179.

[9] S. Mathur, A rapidly deployable communications network architecture for disaster management, Tech. rep., Citeseer (2009).

[10] M. A. Ertürk, M. A. Aydin, L. Vollero, R. Setola, IEEE 802.11 s mesh network analysis for post disaster communication, in: International Telecommunications Conference, Springer, 2019, pp. 53–59.

[11] S. Ghafoor, P. D. Sutton, C. J. Sreenan, K. N. Brown, Cognitive radio for disaster response networks: survey, potential, and challenges, IEEE Wireless Communications 21 (5) (2014) 70–80.

[12] H. Nishiyama, M. Ito, N. Kato, Relay-by-smartphone: realizing multihop device-to-device communications, IEEE Communications Magazine 52 (4) (2014) 56–65.

[13] Z. Lu, G. Cao, T. La Porta, Networking smartphones for disaster recovery, in: IEEE International Conference on Pervasive Computing and Communications (PerCom), IEEE, 2016, pp. 1–9.

[14] F. Patricelli, J. E. Beakley, A. Carnevale, M. Tarabochia, D. K. Von Lubitz, Disaster management and mitigation: the telecommunications infrastructure, Disasters 33 (1) (2009) 23–37.

[15] K. G. Panda, S. Das, D. Sen, W. Arif, Design and deployment of UAV-aided post-disaster emergency network, IEEE Access 7 (2019) 102985–102999.

[16] I. D. Wahyono, I. Fadlika, A. Afandi, M. R. Faiz, Preliminary study of wireless balloon network using adaptive position tracking technology for post disaster event., Telkomnika 17 (4).

[17] R. B. Dilmaghani, R. R. Rao, A wireless mesh infrastructure deployment with application for emergency scenarios, in: 5th International ISCRAM Conference, Citeseer, 2008.

[18] H. Chenji, A. Hassanzadeh, M. Won, Y. Li, W. Zhang, X. Yang, R. Stoleru, G. Zhou, A wireless sensor, adhoc and delay tolerant network system for disaster response (2011).

[19] S. Mehrotra, C. Butts, D. Kalashnikov, N. Venkatasubramanian, R. R. Rao, G. Chockalingam, R. Eguchi, B. Adams, C. Huyck, Project RESCUE: challenges in responding to the unexpected, in: Electronic Imaging 2004, International Society for Optics and Photonics, 2003, pp. 179–192.

[20] S. M. George, W. Zhou, H. Chenji, M. Won, Y. O. Lee, A. Pazarloglou, R. Stoleru, P. Barooah, DistressNet: a wireless ad hoc and sensor network architecture for situation management in disaster response, IEEE Communications Magazine 48 (3) (2010) 128–136.

[21] O. Chipara, W. G. Griswold, A. N. Plymoth, R. Huang, F. Liu, P. Johansson, R. Rao, T. Chan, C. Buono, WIISARD: a measurement study of network properties and protocol reliability during an emergency response, in: Proceedings of the 10th international conference on Mobile systems, applications, and services, ACM, 2012, pp. 407–420.

[22] A. Khan, A. Munir, Z. Kaleem, F. Ullah, M. Bilal, L. Nkenyereye, S. Shah, L. D. Nguyen, S. Islam, K.-S. Kwak, RDSP: Rapidly deployable wireless ad hoc system for post-disaster management, Sensors 20 (2) (2020) 548.

[23] N. K. Ray, A. K. Turuk, A framework for post-disaster communication using wireless ad hoc networks, Integration 58 (2017) 274–285.

[24] D. Velev, P. Zlateva, X. Zong, Challenges of 5G usability in disaster management, in: Proceedings of the 2018 International Conference on Computing and Artificial Intelligence, ACM, 2018, pp. 71–75.

[25] M. Hunukumbure, T. Moulsley, A. Oyawoye, S. Vadgama, M. Wilson, D2D for energy efficient communications in disaster and emergency situations, in: Software, Telecommunications and Computer Networks (SoftCOM), 2013 21st International Conference on, IEEE, 2013, pp. 1–5.

[26] E. Ever, E. Gemikonakli, H. X. Nguyen, F. Al-Turjman, A. Yazici, Performance evaluation of hybrid disaster recovery framework with D2D communications, Computer Communications 152 (2020) 81–92.

[27] G. Deepak, A. Ladas, C. Politis, Robust Device-to-Device 5G cellular communication in the post-disaster scenario, in: 2019 16th IEEE Annual Consumer Communications & Networking Conference (CCNC), IEEE, 2019, pp. 1–6.

[28] A. Pal, M. Raj, K. Kant, S. K. Das, A smartphone-based network architecture for post-disaster operations using wifi tethering, ACM Transactions on Internet Technology (TOIT) 20 (1) (2020) 1–27.

[29] J. Macker, S. Corson, Mobile ad hoc networks (MANET) (1997).

[30] P. Kyasanur, N. Vaidya, A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver, in: International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QSHINE), 2005.

[31] G.-X. Kok, C.-O. Chow, Y.-H. Xu, H. Ishii, EAOMDV-MIMC: A multipath routing protocol for multi-interface multi-channel mobile ad-hoc networks, Wireless personal communications 73 (3) (2013) 477–504.

[32] S. Ghosh, S. Mondal, S. D. Roy, S. Kundu, D2D communication with energy harvesting relays for disaster management, International Journal of Electronics (2020) 1–19.

[33] S. Debroy, P. Samanta, A. Bashir, M. Chatterjee, SPEED-IoT: spectrum aware energy efficient routing for device-to-device iot communication, Future Generation Computer Systems 93 (2019) 833–848.

[34] M. J. A. Rahman, H. Rahbari, M. Krunz, Adaptive frequency hopping algorithms for multicast rendezvous in dsa networks, in: IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN), IEEE, 2012, pp. 517–528.

[35] M. A. Hossain, N. I. Sarkar, Rendezvous in cognitive radio ad-hoc networks with channel ranking, in: Proceedings of the 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, ACM, 2015, pp. 55–63.

[36] T. 8067, Spectrum processor data specification (2000).
URL `http://www.tcibr.com/PDFs/8067webs.pdf`

[37] M. A. Hossain, N. I. Sarkar, A distributed multichannel MAC protocol for rendezvous establishment in cognitive radio ad hoc networks, Ad Hoc Networks 70 (2018) 44–60.

[38] C. E. Perkins, E. M. Royer, Ad-hoc on-demand distance vector routing, in: Proceedings of the Second IEEE Workshop on Mobile Computer Systems and Applications, IEEE Computer Society, 1999, p. 90.

[39] H. Liu, Z. Lin, X. Chu, Y.-W. Leung, Jump-Stay rendezvous algorithm for cognitive radio networks, IEEE Transactions on Parallel and Distributed Systems 23 (10) (2012) 1867–1881.

[40] Z. Gu, T. Shen, Y. Wang, F. C. M. Lau, Efficient rendezvous for heterogeneous interference in cognitive radio networks, IEEE Transactions on Wireless Communications 19 (1) (2020) 91–105.

[41] C. Cormio, K. R. Chowdhury, Common control channel design for cognitive radio wireless ad hoc networks using adaptive frequency hopping, Ad Hoc Networks 8 (4) (2010) 430–438.

[42] M. K. Marina, S. R. Das, On-demand multipath distance vector routing in ad hoc networks, in: Proceedings Ninth International Conference on Network Protocols. ICNP 2001, IEEE, 2001, pp. 14–23.

[43] L. Guo, P. Li, A improved AOMDV routing protocol based on load balancing with energy constraining for ad hoc network, in: International Conference on Green Communications and Networking, Springer, 2019, pp. 114–119.

[44] S. Krishnamurthy, M. Thoppian, S. Venkatesan, R. Prakash, Control channel based MAC-layer configuration, routing and situation awareness for cognitive radio networks, in: MILCOM 2005-2005 IEEE Military Communications Conference, IEEE, 2005, pp. 455–460.

[45] C. Cordeiro, K. Challapali, D. Birru, S. Shankar, IEEE 802.22: the first worldwide wireless standard based on cognitive radios, in: First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, IEEE, 2005, pp. 328–337.