A Smartphone-Assisted Device-to-Device Communication for Post-disaster Recovery

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Abstract. Natural disasters like earthquakes often cause partial or complete breakdown of existing telecommunication infrastructure leaving the helpless people in the affected areas without means of exchanging emergency messages. Under such situations, a temporary ad-hoc system to help in exchanging emergency communication messages and post-disaster recovery can be set up utilising the smartphones of affected victims and the IoT devices of the smarthomes in the affected areas and this paper proposes a method to do that. In the proposed method, smarthome IoT devices are set up to act as relay nodes to communicate emergency messages in absence of a fully functioning telecommunication network. A relay node is chosen based on multiple independent parameters like the residual lifetime of an IoT device and its degree of connectivity. MATLAB-based simulations conducted prove the efficiency of the method.

Keywords: Natural disaster · Energy consumption
Relay · IoT · Smartphone

1 Introduction

During disaster incidents like earthquakes, people get trapped under collapsed buildings or debris and they get seriously injured or even die. Failure to quickly locate and rescue the victims trapped under debris is a problem. Communication of post-disaster emergency messages is highly crucial for fast localization and saving the lives of the victims trapped under rubbles and debris immediately aftermath a natural disaster incident.

Most studies performed so far to provide improved communication abilities during and after disaster situations focused on the deployment of additional wired or wireless connection infrastructure. For example, in [1] a geosynchronous

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earth orbit satellite access point (SAP) is deployed in the disaster area to provide connectivity with a cost of time, which is unrealistic in disaster scenarios. A Hybrid Wireless Mesh Network (HWMN) using the free unlicensed spectrum and IEEE 802.11b/a/g off-the-shelf devices is considered in [2]. A combination of the previous concepts proposed in [3] considered a portable transmission tower with two radio interfaces and a Very Small Aperture Terminal transceiver. However, the delay associated with bringing in and deploying a portable communication tower in the disaster area was unrealistic. As an alternative to fixed infrastructure, the authors in [4–6] proposed an on-site network configuration to support disaster recovery based on the concept of wireless Multi-hop communication abstraction. In [6], each smartphone connected to the nearby access point (AP) for communication as well as a virtual AP (VAP) to extend the network. This formed a tree-based multi-hop access network that extended the coverage and provided additional network resources to victims to communicate. Smartphones based disaster recovery methods are also proposed in [7–9] to locate immobilized survivors.

Telecommunication infrastructure during such disaster incidents may partially or completely collapse. In such situations, an ad-hoc communication network may be set using smartphones. A smartphone assisted device-to-device (D2D) victim localisation method (SmartVL) is proposed in [10], where a smartphone self-senses a disaster scenario, self-switches to a pre-set disaster mode and self-connects to nearby available smartphones to create an ad-hoc communication network in order to relay emergency messages containing the tentative location of victims trapped under rubbles. However, SmartVL only considers smartphone-based D2D communication, whereas, currently, there are various other IoT devices that can support communication under such disaster circumstances. So far, only a limited number of efforts [11,12], have focused on the IoT based communication for post-disaster emergency communication and recovery.

In this paper, we propose a smartphone and IoT based D2D ad-hoc networking mechanism to support post-disaster emergency communication and recovery. This research considers that smarthome-based IoT devices can act as relaying devices to relay the emergency messages (data packets) from smartphones belonging to victims in the disaster affected areas to first responders or other rescue people. We consider IoT gateway devices (IoTGD) that can support multiple heterogeneous RATs and normal IoT devices (NIoTD). Such a smartphone and IoT-based multi-hop ad-hoc communication method can be effective post-disaster scenarios with little or no functional telecommunication coverage or internet connectivity. Every IoT device (or node) can choose its immediate relaying device based on the independent parameters like the residual lifetime of the device (depending on the leftover battery energy of the device) and the degree of connectivity of a device enroute the destination. In the remaining paper, the terms ‘device’ and ‘node’ are used interchangeably, where a node implies an IoT device.

The rest of the paper is organized as follows: Sect. 2, presents the proposed method, while Sect. 3 explains the selection of an ideal relay node in the method.

The simulation set up and results are discussed in Sect. 4 and Sect. 5 concludes the paper.

2 The Proposed Method

Immediately aftermath a disaster incident, like earthquake, cellular networks in the affected area may get congested owing to an excessive increase in the network traffic volume or can be completely damaged or collapsed leaving helpless people stranded without means of communication. Under such circumstances, smart homes in the disaster affected areas fitted with the different IoT devices (e.g., smart alarms, smart smoke monitors, smart temperature monitors etc.) can be utilised in the emergency communication and recovery as explained here. The different IoT devices in a smart home communicate to each other and relay messages. For the simplicity of this work, we assume that a small scale heterogeneous network in a disaster affected area consists of few structurally symmetric smart homes fitted with the different IoT devices that are fixed and locations of the devices in the homes are known to each other.

This work considers both smartphones and smart homes IoT devices. We assume that smartphones belonging to victims and other people in the affected areas are able to self-monitor the radio environment and detect the occurrence of a natural disaster. Upon detection, a smartphone can self- switch to a predefined disaster mode in order to communicate emergency HELP messages to other smartphones in the vicinity. The details of this procedure is discussed in [10]. However, in [10], the authors only considered smartphone to smartphone communication. If a victim or affected person's smartphone is unable to find another smartphone operating in the same mode in the proximity, the communication is dropped and emergency messages are terminated, which certainly is not desirable. To address this issue, in this work we have leveraged the concept of D2D communication and considered the IoT devices in the smart homes to relay the emergency messages in absence of fully functioning cellular networks. We assume that an IoT device can sense an event and communicate messages with other devices (a more powerful IoT device has some processing abilities as well). Also, IoT devices are generally battery powered and its functioning consumes battery energy.

An example of the communication scenario mentioned above is presented in Fig. 1, where a smartphone belonging to user A relays emergency messages to another smartphone belonging to user B through the smart home IoT devices. Here, we assume two different types of IoT devices, namely, an IoT gateway device (IoTGD) and a normal IoT device (NIoTD), which is not a gateway. An IoTGD is a multi-RAT device that can communicate both with smartphones and other IoT devices (i.e, with NIoTDs) and each smarthome can have more than one IoTGDs. A NIoTD on the other hand is just a normal single RAT IoT device that can only communicate to other NIoTDs and IoTGDs but not with a smartphone. Both IotGD and NIoTD are capable of relaying messages. In case of a post-disaster scenario, we further assume that an IoT device can relay emergency messages only if it has adequate amount of leftover energy in the battery to support such actions. This is because, aftermath a disaster, power outage is common and devices have to rely on battery backups for functioning. Therefore, appropriately predicting the leftover energy of a device is important to estimate its tentative life time. An IoT device with leftover energy in the battery below a threshold limit is not considered for the relaying purpose.

In the proposed method, a smartphone which is unable to find another nearby smartphone to pass on the emergency message, can instead communicate the message to an IoTGD in a smarthome (in the disaster affected area) having adequate leftover battery energy. The IoTGD then relays the message to another suitable IoTGD or NIoTD, which has the highest leftover battery energy and the largest degree of connectivity. This process continues until the message is forwarded to another smartphone (located outside the smarthomes) by the final IoTGD. The section below explains the proposed method in detail.

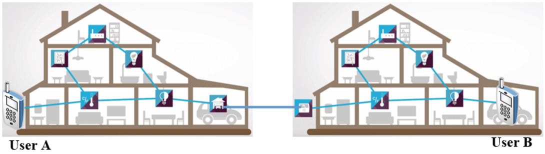

Fig. 1. Considered network scenario

3 Selecting an Ideal IoT Device to Relay Messages

An IoTGD or a NIoTD selects the next IoT device to relay an emergency message based on the following criteria: (a) the lifetime of an IoT device depending on the residual or the leftover energy of the device's battery, and (b) the degree of connectivity of an IoT device.

3.1 Lifetime of an IoT Device

An Iot device can either be in a sleep state or in an active state. While, energy consumption of such a device during sleep state is negligible, it consumes significant energy when operating in an active state. Here we explain the energy consumption of an IoTGD and an IoTD when operating in active state.

Normal IoT Devices: As mentioned above, the cycle of operation of a NIoTD is composed of sleep and active states. The energy consumption while in the sleep state is negligible in comparison to that in the active state and can be written as:

$$E_{sleep} = P_{sleep} \times T_{sleep} \tag{1}$$

On the other hand, a NIoTD performs the following activities when operating in an active state:

- Idle: No event occurred; $E_{idle} = P_i \times T_i$.
- Sensing: A device senses the environment and processes the sensing information; $E_{sense} = P_{se} \times T_{se}$.
- Transmitting: A device transmits the processed sensing information; $E_{transmit} = P_t \times T_t$.

Therefore, the total energy consumption for an NIoTD when in an active state can be calculated as:

$$\begin{aligned} E_{NIoTD} &= E_{idle} + E_{sense} + E_{transmit} \\ &= P_i \times T_i + P_{se} \times T_{se} + P_t \times T_t \end{aligned} \tag{2}$$

IoT Gateway Device: An IoTGD is capable of communicating to smartphones and hence is a multi-RAT device supporting heterogeneous connectivity. An IoTGD has multiple transceivers and hence consumes more energy than a NIoTD. The energy consumption of an IoTGD can be written as:

$$\begin{aligned} E_{IoTGD-hm} &= E_{idle} + E_{sense} + E_{re-hm} + E_{transmit} \\ &= P_i \times T_i + P_{se} \times T_{se} + P_{re-hm} \times T_{re-hm} + P_t \times T_t \end{aligned} \tag{3}$$

Moreover, an IoTGD may require extra energy to convert or process the emergency messages received from or communicated to a smartphone as the message formats may be different. Thus, the energy consumption of an IoTGD including that for the message conversion is:

$$\begin{aligned} E_{IoTGD-ht} &= E_{idle} + E_{sense} + E_{re-ht} + E_{transmit} \\ &= P_i \times T_i + P_{se} \times T_{se} + P_{re-hm} \times T_{re-ht} + P_t \times T_t \end{aligned} \tag{4}$$

It is obvious that $E_{re-ht} > E_{re-hm}$due to additional processing and protocol conversions of different RAT. Now, for a cycle the total energy consumption is the sum of the energy consumption in sleep state and active state which is as follows:

$$\begin{aligned} E_{total} &= E_{sleep} + E_{active} \\ &= \Big(E_{sleep} + E_{idle} + E_{sense}\Big) \times (1 - R) + R \times \Big(E_{transmit} + E_{re-hm} \\ &\quad \times R_{hm} + E_{re-ht} \times (1 - R_{hm})\Big) \end{aligned} \tag{5}$$

Here, the value of R will be 0 for non-relay node and 1 for relay node. Same as if the relay node is homogeneous relay then R_{hm} will be 1 otherwise 0.

Let us consider that E_{thr} is the minimum energy required to maintain the communication with the other IoT devices and relay devices. Hence the lifetime of an IoT device can be defined as a number of cycle periods before the

IoT device reach below the E_{thr}. Hence the lifetime of an IoT device can be written as:

$$K_{life} = max(m) : E_{total} \geq E_{thr} \tag{6}$$

3.2 Neighbour Discovery and Degree of Connectivity

An IoT device needs to discover its neighbour nodes or other available IoT devices to relay messages and also needs to know the degree of connectivity of each of the neighbours. For an IoT device, the degree of connectivity can be defined as the ratio of the number of IoT neighbours it has over a total number of IoT devices [13] in the small network considered. Any IoT device can initiate a neighbour discovery operation by sending a simple HELLO message consisting of the sender's ID, energy level and location coordinate. Upon receiving the HELLO message, the receiver can add the sender as a neighbour and responds back with a HI message with the same. On receiving the reply message, the sender can similarly add the receiver as a neighbour. The neighbour discovery process is presented in Algorithm 1. The degree of connectivity is calculated in line 14 of Algorithm 1.

Algorithm 1. ND Algorithm

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Input:  (i) Transmission flag, $Flag_{Tx}$;
       (ii) Rescan period, $T_{out}$;
      (iii) No of node, $n$
Output: (i) The neighbour of node $X$: $N(X)$;
       (ii) Degree of connectivity, $D$;
Begin
 1: while $mod(t, T_{out}) = 0$ do
 2:     Node $X$: Send HELLO message
 3:     if Message received:Node $Y$ then
 4:         $N(Y) = N(Y) \cup x$
 5:         Node $Y$: Send HI message
 6:         if Message received:Node $X$ then
 7:             $N(X) = N(X) \cup Y$
 8:         else
 9:             Eliminate Y from the list
10:         end if
11:     else
12:         Send HELLO Message
13:     end if
14:     $D = \frac{|N(X)|}{n}$
15: end while
End
```

3.3 Relay Node Selection

As mentioned above, in our proposed method, an ideal relay node is chosen based on the lifetime of a node or device (which is dependent on its leftover battery energy) and the degree of connectivity of an IoT device. So, if the neighbour discovery phase, finds two or mode nodes that are eligible to qualify as relay nodes, then ideally the one with the maximum leftover battery energy (i.e., with maximum lifetime) and the highest degree of connectivity is chosen as the relay node. However, the ideal scenario may not always be the case and there could be a trade off between the above two parameters that we may have to consider in order to priorities one node above the other as explained in (Eq. 7) below.

$$T_{factor} = \left(\frac{k}{n}\right)^{A} + (k_{life})^{B} \tag{7}$$

Equation 7 ensures that, always the ideal node will be selected as the relay node depending on parameters A and B, which provides the flexibility of choice. If the residual lifetime of a device is the main concern in a disaster scenario, then the node with higher lifetime can be selected, but if the priority is to minimise the message transmission time, then the node with higher degree of connectivity needs to be selected as the relay node.

4 Performance Evaluation

We have used a MATLAB-based simulation system to evaluate the performance of the proposed method and have compared the results with existing relay selection methods explained in [14]. In [14], the authors proposed three relay deployment or selection strategies based on degree of connectivity, lifetime and hybrid. In all cases network operation progress in rounds. Higher the number of relay nodes, lesser is the network lifetime as relay nodes consume more battery power. For our simulation, we have considered three performance parameters, namely, the mean residual energy consumption, relay node survival and average success rate. Table 1 lists the simulation parameters.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
Number of nodes	50–100	T_{active}	$d \times T_{Cycle}$
Network range	100 m × 100 m	T_{slp}	$(1-d) \times T_{cycle}$
Data packet size	500 bytes	T_{idle}	$\frac{T_{active}}{2}$ (No event) T_{active} (event)
Control packet size	25 bytes	T_{sense}	1.1 s
T_{cycle}	5 s	$T_{transmit}$	1.4 s
d	[0,1]	$E_{threshold}$	0.5 mJ
$T_{hm} = T_{ht}$	1 s	$E_{initial}$	0.5 J

4.1 Mean Residual Energy Consumption

We explain here the performance of our proposed method in context to the mean residual energy consumption parameter, which provides us with an understanding of the residual lifetime of a device. (Figure 2) shows that the mean residual energy in the case of our proposed method is higher than the other protocols. A significant performance difference can be observed with hybrid scheme, which considers both degree of connectivity and node's residual energy. However, the energy consumption in hybrid model is mainly dominant by the distance between relay nodes and base stations. Interestingly, a significant amount of energy is consumed for sensing and data (message) processing in IoTGDs (supporting heterogeneous RATs), which are introduced in our method. Figure 2 shows that mean residual energy of relay nodes in our proposed method is 14% higher than the hybrid, 37% higher than the lifetime and 58% higher than the other connectivity-based relay selection scheme.

4.2 Relay Node Survival

The number of active relay nodes that survive at each round is an important parameter to study in a disaster scenario. Power failure or outages is common aftermath a disaster incident. In such cases, the in-house IoT devices needs to survive on battery backups as long as possible. More the number of active relay nodes, better is the end-to-end delay performance. Figure 3 depicts that proposed method, in context to this parameter, shows the following improvements: 12% in comparison to the hybrid scheme, 27% in comparison to lifetime and 69% in comparison to connectivity schemes. Such improvement is a result of the fact that in our proposed method an IoTGD or a NIoTD only transmits data to the nearest relay node enroute the destination in the multi-hop communication scenario. As higher the distance between two nodes, more is the energy consumption, in our proposed method energy consumption is always less as there are intermediate nodes available to help relay the emergency messages.

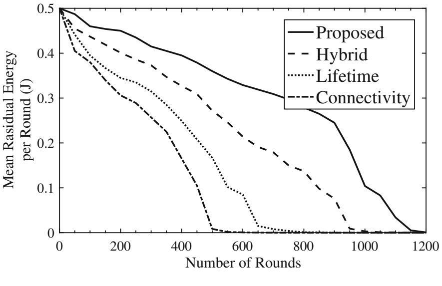

Fig. 2. Mean residual energy with number of rounds

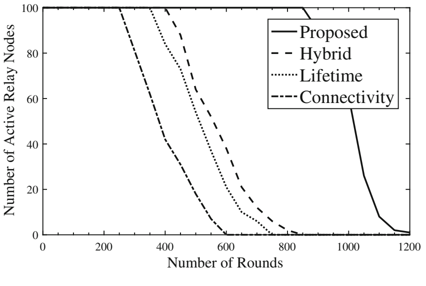

Fig. 3. Relay nodes survival per round

4.3 Average Success Rate

The average success rate (ASR) implies the reliability of the method to successfully transmit packets (messages) to the destination even if intermediate relay nodes fail. ASR is defined as the ratio of the number of transmitted packets from a source to the total number of packets received by the destination from the same source. To study the performance of the proposed method in context to this parameter, the simulation is configured for 1200 rounds. Figure 4 shows that the success rate is increased with the number of relay nodes. In most cases, the proposed scheme has an increased success rate of 10% compared to hybrid, 30% compared to lifetime and 47% compared to connectivity schemes.

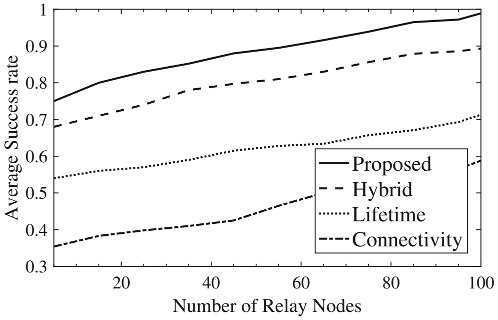

Fig. 4. Average success rate of packet delivery

5 Conclusion

This paper proposes a smartphone and IoT devices-assisted emergency and recovery method in a post-disaster environment, where smartphones can utilise the IoT devices in the smartphones in the disaster affected areas to successfully relay the emergency messages to other smartphones. We considered two different types of IoT devices, namely, the IoTGD and NIoTD, both with relaying capabilities and have proposed methods to select an ideal relaying node based on multiple criteria like, the residual lifetime of an IoT device and the degree of connectivity of each of the devices. Our proposed criterion for relay node selection is appropriate for disaster situations requiring lower energy consumption and end-to-end delay in data transmission. Simulation results have shown better performance of our proposed method in comparison to other such schemes.

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