Architecture for Public Safety Network Using D2D Communication

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***Abstract*—Device to Device (D2D) communication has been proposed as an underlay to Long-Term evolution (LTE) network as a means of harvesting the proximity, reuse and hop gains. However, D2D communication can also serve as a technology for providing public safety and disaster relief services. In this article, the basic concepts of D2D communications are first introduced and then existing fundamental works on disaster communication are discussed. We focus on the performance of the network architecture by utilizing the relay assisted transmission which can effectively enhance the capacity and power saving of the network. We also propose the distance based strategy to reduce the computational complexity and power transmission. Finally, simulation results are provided to verify the proposed architecture.**

I. Introduction and Motivation

Information and communication technologies (ICT) provide vital services and systems for our daily lives as well as in emergency and disaster situations. Natural disasters like earthquakes, floods and tsunamis are occurring from time to time in many places around the world. The need for communication and other types of ICT services is very high after such events. The communication infrastructure is often damaged to large extents, making services unavailable or at least heavily congested. Therefore, a number of activities, research efforts and standardisation activities have been started quite recently in the area of disaster-resilient communication. For example, standardisation activities such as ITU-T Focus Group on Disaster Relief System [1] and ETSI TETRA [2] have already occurred and currently are being developed further. Meanwhile 3GPP also started work on critical communication to launch Proximity Services (ProSE) and Group calls [3].

Cellular data traffic has grown explosively in recent past due to the quick popularity of devices like smart phones, tablets with powerful multimedia capabilities and applications. The Wireless World Research Forum envision in 2020 seven trillion wireless devices are serving seven billion people [4]. According to Cisco predictions [5], the global mobile data traffic will outgrow the global fixed data traffic by three times, reaching 10.8 exabytes per month. Therefore, the reasons have been raised to find methods in order to increase the network capacity to accommodate these bandwidth consuming applications and services. The number of mobile subscribers grows along with an explosive increase in the mobile data traffic demand. While enhancing the capacity of the network by allocating more spectrum or the most straight forward solution is to improve the capacity of cellular networks by adding new base stations but they are inherently expensive for the operators. In order to address this problem it is important to raise the network capacity at a low additional cost.

Recently, there has been a surge of interest in supporting device to device (D2D) communication. The Third Generation Partnership Project (3GPP) Release 12 [6] has introduced a D2D communication feature for LTE. The D2D communication based new mobile proximity services targets the potential requirement for an operator to integrate D2D communication in their network. It is capable to creating new mobile service opportunities and reducing traffic load on the networks. The idea behind D2D communication is an underlay direct communication among user equipments (UEs) that use the same licensed radio resource can establish a direct local link and bypass the base station or access point, but after coordinating with the core network via the evolved Node B (eNB).

The topic of D2D communication is not mature yet [7] as few works have been done to propose network architecture level in order to incorporate D2D communication. Our main contribution in this paper explicit the concept of D2D technology application and proposing a disaster communication network architecture for public safety network. The architecture allows sufficient and resourceful connectivity between functional and non-functional area in which victims, rescue teams and other services can carry on communication in the affected locations. The overall system would provide reliability, availability and reduce the complexity by using modern technology of D2D and relay assisted network. Relay assisted concept of transmission in disaster can effectively enhance the capacity of D2D system. Further, power efficiency for D2D system increases as the number of hops increases as shown in our proposed architecture.

The remainder of this paper is organized as follows, Section 2 provides an overview to other related work, while Sections 3 and 4 explain the system model (Design Question) and proposed architecture, respectively. Section 5 provides simulation results and Section 6 concludes the paper.

II. Related work

As we know that Public Safety (PS) networks ought to be reliable, resilient and secure while meeting other stringent functionality requirements in terms of service accessibility, end to end performance and devices characteristics with radio coverage. Network recovery/restores, network infrastructure to their original status or else to a certain level of the availability even temporarily to provide the users with basic communication services after disaster. Keeping the above facts in mind, the research community proposed disaster resilient networks on the basis of earlier disasters experiences and related projects around the world. The common goal of the all efforts is to design network architectures and provide solutions that are resilient to disaster. Network resiliency and recovery against disasters can be tackled with multiple approaches like:

Nippon Telegraph and Telephone Corporation (NTT) [8] proposed a disaster-resilient network architecture using specially designed movable and deployable resource units (MDRUs) being a transportable container that accommodates modularized equipment for networking, information processing and storage. The architecture is based on layers: network facility, network and platform layers. Each MDRU forms a wireless access network around it to reach customer premises equipment. Existing optical fibers can be used for connecting the MDRU to nationwide networks if it found not damaged in disaster area. In [9] described how vehicles could be used as network nodes in temporary disaster information networks. The basic observation behind the ideas presented is the fact of Dedicated Short Range Communication (DSRC) systems gradually coming into practical use in some countries. Both mobile roadside units (RSUs) and vehicular on-board units (OBUs) are used as network nodes in a multi-hop network, while end-users are using regular smart phones. The system is designed to use a variety of protocols for vehicular applications. The authors of [10] presented how to use white space (WS) which is geographically or temporally unused licensed frequency. In that paper the author discussed the competence of IEEE standard 802.22 based wireless regional area network (WRAN) using television TVWS and proposed a prototype. The basic components of the prototype are: a MAC control unit, a transceiver (TRX) unit, a radio frequency (RF) controller and global positioning system (GPS) receiver. The system can use as alternative line or backhaul line of cellular system. The features of the system are flexible channel usage and long range wireless communication availability as they employ DSA under TVWS channel and QoS management. D2D communications have been proposed as an underlay to LTE networks as a means of harvesting the proximity, reuse and hop gains. Authors in [11] shown the growing interest in the broadband telecommunication services in national security and public safety situations. The article reviewed some of the key requirement technology challenges and also solution approaches that must be placed in order to enable LTE networks and D2D communication to meet public protection and disaster relief (PPDR) related situations. However, they proposed a clustering procedure based approach to the design of a system that integrates cellular and ad-hoc operation modes depending on the availability of infrastructure nodes. Moreover, authors in [12] described concepts, necessities and challenges for the recovery of base stations backhaul connectivity under disaster circumstances. The basic idea presented is to use neighbour regional wireless access networks connecting base stations to backhaul, perhaps by using wireless LAN relay nodes to overcome long distances. Deployments of such relay nodes are discussed. Also, the authors point out that the connection between the base station and the aggregator must implement the public LAN mobile networks (PLMN) specific protocol normally used for that link.

III. System Model/Design Question

The idea of D2D transmissions underlying LTE-Advanced network contains signals transmitted from one cellular UE to another cellular UE without passing through cellular infrastructural nodes. Direct D2D technologies have already been developed in several wireless standards, targeting to meet the need of efficient local data transmission required by different services in personal, public and industrial areas. The D2D acceptance in the cellular communication system is becoming more vital because D2D technology aims to, reduce cost of infrastructures, improve transmission speed for cell edge users and secure solution for proximity discovery communication. In conventional cellular communication, UEs communicate via radio area network links and core network (for uplink/downlink). D2D handles connection and data traffic without the core network, however, D2D enabled UE can communicate directly with other D2D-enabled UEs using the D2D link. Figure 1 shows the D2D communication concept.

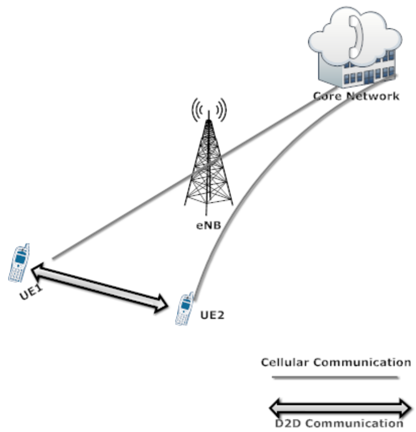

Fig. 1. D2D communication concept.

LTE D2D could provide a decentralised approach to proximity discovery and device to device communication, which is efficient, flexible, dynamic and secure to enable proximity-based service to flourish. The US government has already expressed a desire to move to LTE for future public safety communication. However, strong dependence between access and core networks limits the flexibility, manageability and resilience of 4G-LTE system [13]. In fact, physical destruction of network components has been identified as the most common cause of telecommunication failures in disaster that occurred in past years. Thus, problems caused by the physical destruction are likely to last longer than problems by the network congestion. For instance, the other limiting factor in 4G-LTE network is the strong dependence between UE and access network. The UE not only needs to communicate in a traditional cellular fashion, but also need to communicate directly if the network infrastructure is temporarily unavailable or operation conditions to check reliable communication links. Disaster scenarios are often characterized by damaged network elements or severely impaired communication links between network nodes and entities. But cellular networks that we see today, such as GSM, CDMA, 3G, 4G, etc. all have a similar architecture. Mobile Switching Centre (MSC), Base Station Controller (BSC), Base Transceiver Station (BTS) and cell phones are the main blocks of the architecture. Since all the key components, such as MSCs, BSCs or BTSs function hierarchically, and together they have a single point of failure.

Relaying Node Selection: In order to enhance the quality of communication link, the source*(S)* intends to transmit signal to destination*(D)* with the help of selected relay*(Ri)*. The selection of relay is based on RTS (Ready-to-Send) and CTS (Clear-to-Send) messages which identify the channel quality between *S* and *D*. It is assumed that BTS knows every channel in the field, so it can easily determine which node can perform best. Further to the reduction of the computational complexity of the BTS we can adjust threshold for D2D communication as shown in work [14] that the system can achieve a good performance.

IV. Proposed Architecture/Protocols

We outline two possible scenarios for setting up emergency communication networks, partially damaged BTS and fully damaged BTS. Figure 2 is the schematic of Scenario 1, in which BTS is partially damaged because of disaster so it has only limited accesses and processing ability. Therefore, mobile phones and internet access will be congested in affected areas and difficulties with regular communications are observed as shown in Figure 2.

Fig. 2. Reduced Processing Ability of BTS.

Due to the reduced processing ability, call dropping problem intensifies. Call dropping is caused by lack of available radio channels and also available network capacity which varies unpredictably. Services stupendously increase just after the event when people from the affected zones desperately seek to communicate with both inside and outside of the disaster stricken zones. These states instigate serious traffic congestion. So, keeping in mind channels and call traffic congestion, we perform an experiment on the basis of some assumptions to see how it affects the transmission. It is particularly important to understand the traffic volume at peak times [15]:

$$B = \frac{A^N/N!}{\sum_{k=0}^{N} A^k/k!} \quad (1)$$

where B = loss probability, A = offered traffic intensity in Erlang and N = available number of channels. By using the above equation help us to measure traffic volume and network design for better understanding of traffic patterns. The results show that situation like disaster, if traffic intensity increases the call drop probability rises as well. But if we increase the number of channels drop call probability decreases and vice versa. Figure 3 shows the results.

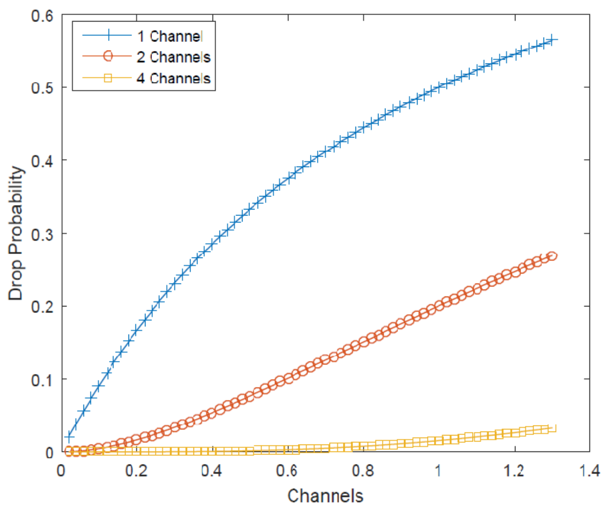

Fig. 3. Variation of Drop-Call Probability and Traffic Intensity with Channels.

In situation such as communication in disaster, reliability and robust architectures are vital in order to keep the network services running because connectivity is more important and bandwidth requirements are not too stringent.

In this paper, we propose public safety network architecture using D2D communication system. The aim is to provide D2D services over ranges of up to 500m to 1km (dependent on propagation condition and network loading) and further extendible in the required area. For general public services, D2D will be available only when a mobile device is within the coverage of the mobile network, which will permit the network to retain ultimate control over radio resources and

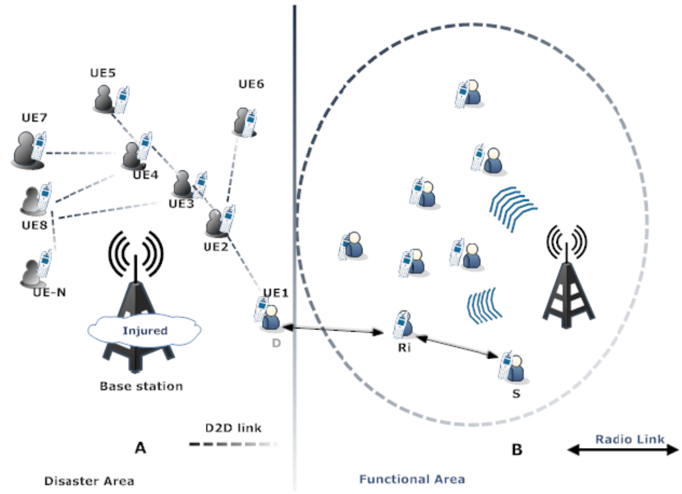

Fig. 4. D2D communication concept with relay node.

security. Further for public safety network only, basic D2D capabilities will also be available in the absence of a network.

Now considering Scenario 2 in Figure 4 where BTS is fully injured and UEs have no radio resource, but utilizing the relaying concept here UE needs to be selected from functional area to perform like a mobile relay (by assuming the best determined relaying node). In Figure 4A, all the UE devices are located in non-functional BTS area and have no radio signals but they have the capacity to communicate with each other through one-hop or multi-hop routes. Once we confirm the relay node (Ri) the system can be able to transmit radio signal (RS) into non-functional area. UE1 receiving RS can now be connected with BTS of functional area and start transmitting signals to its neighbours UEs. This relaying node can not only increase the system capacity, but also reduce the transmission power for mobile host and extend the system coverage area. Here, D2D users must ensure their transmission do not cause a level of interference that leads to failure of cellular link. For instance, interference is caused by spectrum sharing between cellular and D2D system in Figure 4, the signal to interference-plus-noise ratio (SINR) at a receiver in system k becomes:

$$SINR_k = \frac{P_k \delta_{k0} R_k^{-\alpha}}{\sum_{j \neq k} \sum_{X_{ji} \in \prod_j} P_j \delta_{ji} |X_{ji}|^{-\alpha} + N_0} \tag{2}$$

where P_k is transmission power, δ_{k0} fading factor link between desired transmitter and receiver of system k, N_o is the thermal noise power and R_k is the distance between the transmitter and the receiver node (BTS,D2D or relay node) of system k

We consider that the successful transmission of system k can be possible when $SINR_k \geq \upsilon_k$, where υ_k is the target $SINR$ for system k. The probability of successful transmission is represented as [16]:

$$P(SINR_k \geq_{V_k}) = exp\{-\zeta_k \sum_{j \in \Phi} \gamma_{kj} \lambda_j\} \tag{3}$$

where $\gamma_{kj} = (P_j/P_k)^{2/\alpha}$, $C_\alpha = (2\pi/\alpha)\,\Gamma(2/\alpha)\Gamma(1-2/\alpha)$ with Gamma function $\Gamma(x) = \int_0^\infty y^{x-1} e^{-y} dy$ and $\zeta_k = C_\alpha R_k^2 V_k^{2/\alpha}$. Therefore, the outage probability of cellular system can be expressed as,

$$P_c^0(\lambda_c, \lambda_d) = 1 - [exp\{-\zeta_c(\lambda_c + \gamma_{dc}^{-1}\lambda_d)\}] \tag{4}$$

where $\zeta_c = C_\alpha R_c^2 V_c^{2\alpha}$. Equation 4 becomes

$$P_c^0(\lambda_c, \lambda_d) = 1 - \left[exp\left\{C_\alpha R_c^2 V_c^{2/\alpha}(\lambda_c + \gamma_{dc}^{-1}\lambda_d)\right\}\right] \tag{5}$$

$$= 1 - [exp\{(2\pi/\alpha)\,\Gamma(2/\alpha)\Gamma(1-2/\alpha) R_c^2 V_c^{2/\alpha}(\lambda_c + \gamma_{dc}^{-1}\lambda_d)\}].$$

Finally, after putting the values of $\Gamma(x)$ in the above equation, the probability is:

$$P_c^0(\lambda_{c,\lambda_d}) = 1 - [exp\{(2\pi/\alpha)\,(\int_0^\infty y^{2\pi/\alpha-1} e^{-y} dy) \\ (\int_0^\infty y^{2\pi/\alpha-1} e^{-y} dy) R_c^2 V_c^{2/\alpha}(\lambda_c + \gamma_{dc}^{-1}\lambda_d\}] \tag{6}$$

The outage probability of end to end transmission [17] can be expressed as below:

$$P_d^0(\lambda_c, \lambda_d) = 1 - [exp\{-\zeta_{dr}(\lambda_d + \gamma_{dc}\lambda_c)\}]^N \tag{7}$$

where P_c and P_d are the power of cellular and D2D users, $\zeta_{dr} = C_\alpha (R_d/N)^2 V_d^{2/\alpha}$ and $\gamma_d = (P_c/P_d)^{2/\alpha}$. V_d and R_d are the target SINR and the end-to-end distance of D2D.

Since the relay system operates in time division duplex (TDD) mode, only one node can work at the same time. The relay n can decode the codeword transmitted from the relay $n-1$. Therefore, from [17] the capacity of D2D relay system is defined as:

$$C_{D2D} = \lambda_d . \frac{1}{N} \int_0^\infty \frac{1}{1+v} e^{-\zeta_{dr}(\lambda_d + \gamma_{dc}\lambda_c)} dv \tag{8}$$

where λ_d and λ_c is the spatial density of D2D and cellular system and $\zeta_{dr} = C_\alpha R_r^2 V_d^{2/\alpha}$. We consider that in non-functional areas (in Fig.4(A)), the relay distance $R_r = R_d/N$ decreases as the rate the number of hops N increases. The power ratio of cellular and D2D system $\gamma_{dc} = (P_c/P_d)^{2/\alpha}$ has an significant effect on interference level and system capacity. In order to achieve the transmission capacity for the N-hop relay system, the transmit power and spatial density of the D2D system should be designed for the users in D2D transmission. Based on the combined outage probability constraints the spatial density of D2D system is given as:

$$C1 : \lambda_d \leq min(\gamma_{dc}\xi_c, \xi_d) - \gamma_{dc}\lambda_c \tag{9}$$

where $\xi_c = -\frac{ln(1-\theta_c)}{\zeta_c}$ and $\xi_d = -\frac{ln(1-\theta_d)}{N\zeta_{dr}}$. When λ_d satisfies C1, the D2D (C_{D2D}) system capacity increases with increasing λ_d and the increasing rate decreasing when λ_d increases.

The optimal spatial density is affected by the power ratio of cellular and D2D system. As imperviously mentioned in [17] when λ_d increases, γ_{dc} increases and also leading the capacity of D2D system (C_{D2D}) to increase. When λ_d decreases γ_{dc} increases, leading the capacity of D2D system (C_{D2D}) to decrease. Therefore the optimal transmit power and spatial density of the D2D system as derived in [17] is given as:

$$P_d = (\gamma_{dc})^{-\frac{\alpha}{2}} P_c = (\xi_c/\xi_d)^{\frac{\alpha}{2}} P_c \tag{10}$$

$$\lambda_d = \xi_d(1 - \lambda_c/\xi_c) \tag{11}$$

where $\xi_c = \frac{ln(1-\theta_c)}{\zeta_c}$ and $\xi_d = \frac{ln(1-\theta_c)}{N\zeta_{dr}}$. Therefore, relay assisted D2D transmission can benefit from better coverage and high power efficiency. Substitute Eq. (10) and (11) into (8), we obtain the achievable transmission capacity of D2D relay system as:

$$C_{D2D} = (1-\frac{\lambda_c}{\xi_c}).\frac{-ln(1-\theta_d)}{C_\alpha R_d^2 V_d^{2/\alpha}} \int_0^\infty \frac{1}{1+v}(1-\theta_d)^{\frac{(v/v_d)^{2/\alpha}}{N}} dv \tag{12}$$

The Eq. (12) represents the achievable transmission capacity increases slowly as the number of relay hops N increases.

TABLE I
SYSTEM PARAMETERS

Parameters	Explanations	Settings
λ_c	Cellular spatial density	1×10^{-5}
λ_d	D2D spatial density	3.3×10^{-4}
R_c	Cellular transmit disntance	10m
R_d	D2D transmit disntance	10m
v_c	Cellular target SINR	3
v_d	D2D target SINR	3
α	pathloss exponent	4

V. SIMULATION RESULTS

From Fig. 5 we can see the trend of capacity with the number of relay hops. We provide numerical results to analyse the multi-hop system performance in non-functional area of Fig.4(disaster area) When the number of relay hops is small ($N \leq 3$), D2D system capacity increases quickly as N increases. This has been observed because increase of relay hops shortens the transmit signals distance in large scale, which brings high multi-cast diversity gain. However, when the number of relay hops becomes large ($N \geq 5$), the decrease in relay distance is not noticeable, but the risk of transmission failure increases and transmission efficiency decrease in relay mode. Consequently, the achievable transmission capacity increase slowly. Further, from the results, we analyse that for high cellular spatial density, there needs more relay hops to achieve the same system capacity. This is because increasing relay hops can effectively reduce the transmit power of each node, which also reduces the interference between D2D and cellular users of functional and non-functional area of Fig.4. Hence, the multi-hop D2D system can support high D2D spatial density and results in high transmission capacity.

In Fig.6 we investigate the effect of cellular spatial density λ_d on both cellular and D2D system. Increasing the λ_d has stronger effect on D2D system compared to that of the cellular system. In Fig. 6, the outage probability of both systems is plotted against the cellular spatial density λ_d. It can also

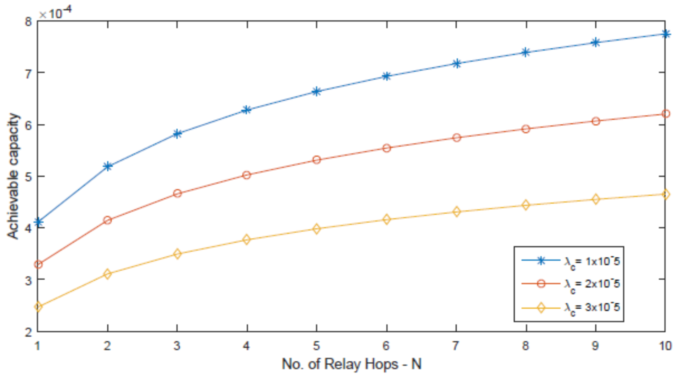

Fig. 5. Multi-hop D2D system capacity and number of relay hops

be noted that there is an exponential increase in the outage probability of both cellular and D2D system when the cellular spatial density increases. But the effect of λ_d is more on the cellular system when compared to the D2D system. The outage performance of the D2D system is better than the cellular system with respect to λ_d.

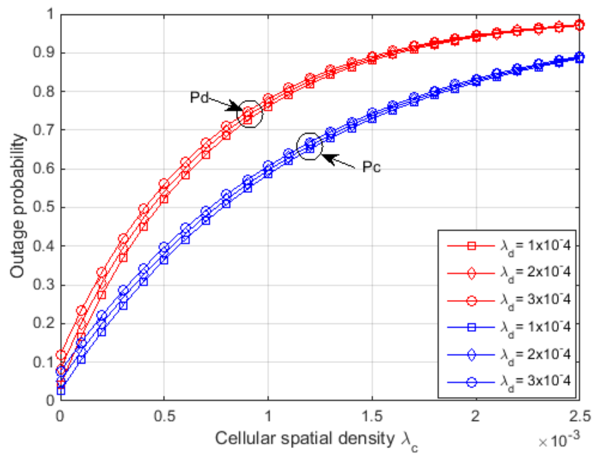

Fig. 6. Outage parbability Vs cellular spatial density

As power can be the one of the main constrain in disaster area and the results of Fig.7 shows the power efficiency of multi-hop D2D system. According to the proposed architecture the power efficiency is defined as the ratio of throughput and transmit power. In D2D communication, if transmitter is far away from receiver, transmission via a direct link consumes much power. While in this case, increasing the number of relay hops can effectively enhance power efficiency, because the required power of each relay link decrease considerably as shown in the simulation results. So the relay assisted proposed architecture of D2D communication system is a power saving system as well, especially when D2D users are for away from each other in disaster situations.

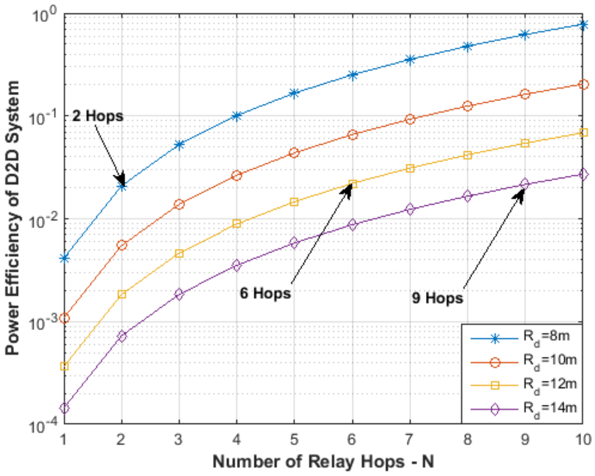

Fig. 7. Power efficiency performance of multi-hop D2D system

VI. Conclusion

In this paper, we have briefly introduced the concept of D2D communications and its applications as well as the potential benefits in disaster situations. We have discussed the state-of-the-art research works on D2D communication and proposed a way to protect communication system at the time of disaster. Proposing public safety network architecture using D2D, reuse resources of cellular users near the base station, we analyse the optimization of spatial density and transmit power capacity to multi-hop D2D system in non-functional area with the help relay assisted network. The results show that the proposed architecture enhances the performance of D2D network, both in system and power efficiency. The results remain preliminary with many challenges still to be investigated. Therefore, we have also identified some potential future research topics in disaster communication area like energy efficiency in term of energy harvesting, data offloading and empower relay for better cover area.

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