IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

SPECIAL SECTION ON SUSTAINABLE INFRASTRUCTURES, PROTOCOLS, AND RESEARCH CHALLENGES FOR FOG COMPUTING

Received February 25, 2019, accepted April 22, 2019, date of publication April 29, 2019, date of current version May 10, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2913909

An Energy-Efficient Clustering and Routing Framework for Disaster Relief Network

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This work was supported in part by the Newton Prize 2017 and in part by the Newton Fund Institutional Link through the Fly-by Flood Monitoring Project under Grant ID 428328486, which is delivered by the British Council.

ABSTRACT The lack of communication between local authorities, first aid responders, and the population that are present in a natural disaster area, represents critical aspects which can compromise relief operations in saving human lives. During natural disasters (earthquakes/tsunamis), the typical telecommunications network infrastructure in the affected area could be damaged or unfunctional. This can seriously compromise the efficiency of first aid operations. In this paper, we propose a device-to-device (D2D)-based framework which, starting from some basic information such as positions and battery level of victim's devices, could provide communication from a disaster area towards a functional area. This framework, utilized by a base station located in a functional area, organizes users of disaster area into clusters of users and for each cluster select a gateway. This framework permits also, to evaluate the optimal transmission power for each gateway in order to maximize the energy efficiency in the area and to create a multi-hop path from the disaster area to relay node minimizing the end-to-end delay. The simulations results demonstrate that our proposed approach outperforms either random policy assignment and static policies assignment in both power allocation and routing path creations.

INDEX TERMS Disaster communications, device-to-device communications, disaster relief networks.

I. INTRODUCTION

During the last few years, serious natural disasters such as earthquakes, tsunamis, floods and storms, causing large-scale disasters such as destruction of buildings and infrastructures, have been observed worldwide. These have rendered people homeless and claimed the lives of hundreds of thousand people [1]. Indeed, according to United Nations Office for Disaster Risk Reduction (UNISDR), during the last twenty years the majority of disasters, in terms of frequency percentage is represented by floods (43,4%) followed by storms (28,2%), earthquakes (7.8%) and other types. However, they have different impact in terms of number of victims, which in the worst case (i.e. earthquake) corresponds to an average of at least thirty thousand deaths per year [1].

In such situations, providing effective and timely response to first aid requests can save many human lives. The major challenge faced by first aid responders, is the timely localization of victims within the disaster area. Usually, this is possible through the huge amount of first aid requests generated over the telecommunications network infrastructure in the disaster area. However, factors like *i)* low availability and reliability of network infrastructure, *ii)* loss of Power/Energy and *iii)* limited resources and services, could strongly impact telecommunications network infrastructure [2], [3]. Indeed, due to earthquakes/tsunamis telecommunications network infrastructure could be partially or totally destroyed.

In this perspective, recently a number of research efforts and standardization activities such as the International Telecommunication Union - Telecommunication Standardization Bureau (ITU-T) with its Focus Group on Disaster Relief System [4], ETSI TErrestrial Trunked RAdio (TETRA) [5] and the 3GPP with the Proximity

The associate editor coordinating the review of this manuscript and approving it for publication was Maria Gorlatova.

Service (ProSe) for critical communications [6], have been started. In parallel some technical solutions, which allow affected people to communicate with their families, have been designed. For example, Facebook activated its Safety Check [7] feature which enables people to give quick safety status updates to their family and friend during the disaster. Interesting are also the cases of M-Urgency [8] and SafeCity [9] which enable users to live stream reports and real-time positions of crimes and crisis. However, most of the present disaster management systems rely on an existing network infrastructure which, as stated before, could not be fully or partially available after a natural disaster.

The diffusion of powerful multimedia devices such as smartphones and tablets, has grown exponentially in the last decade. In particular, according to the Wireless World Research Forum, in 2020 seven trillion of wireless devices will serve seven billion of people [10]. In addition, according to Cisco forecast, there will be 11.6 billion mobile-connected devices by 2021, including Mobile-to-Mobile (M2M) modules, which exceed the worlds projected population at that time (7.8 billion). As much, there will be a high density of devices sharing the scare physical radio resources and generating a huge amount of data traffic, i.e. monthly global mobile data traffic will be 49 exabytes by 2021 [11]. This is creating the need for a new cellular technology referred to as 5G [12]. In particular, one of the most promising technologies which is being considered as support for the upcoming 5G architecture is the paradigm of Device-to-Device (D2D) wireless communication. D2D communications in wireless network are termed as the direct communication between two devices, providing a wide range of advantages such as offloading of cellular data traffic, efficient usage of radio spectrum and higher system throughput due to short distance communications, without the use of a pre-existent network infrastructure [13], [14]. For this reasons, since also a disaster scenario is characterized by high density of users and limited resources due damages to Information and Communication Technology (ICT) Infrastructure, D2D has been recently considered a key enabling technology for the creation od Disaster Relief Networks [15], [16]. Another factor which must be considered into a disaster scenario, is the run out of energy. Indeed most of communication devices present in a disaster area run on battery and then recovery of power supply and power saving or energy efficient mechanisms, result to be critical aspects for disaster relief network. The concept of Wireless Energy Harvesting (WEH) attracts great attention by research community. In particular, due to its capability to convert RF radio signals into energy, WEH is regarded as promising solution for wireless constrained network [17]–[19]. In addition several Energy-Efficcient (EE) configurations have been proposed in literature [20]–[23]. For the best of our knowledge, most of these works only focus on developing EE solution in the sense of reducing the energy consumption of each user's device or in clusters of users in order to prolong network lifetime. However, energy reduction does not necessary means that the power is *efficiently* used for transmissions. For this reason we propose an EE Routing and Clustering method for a disaster scenario where we consider EE as the maximum ratio between achievable rate and the power consumed for transmissions [24]. In addition, this paper provides a possible framework which, starting from some basic available information of nodes in a disaster area, i.e. nodes position and battery level, is able to provide a data path flow to each user toward a functional area or an help request collection point.

The remainder of this paper is organized as follow: State of the Art about proposed solutions for recovery in disaster scenarios and related issues are presented in Section II. Section III present the system model and proposed approaches for EE communication and routing path creation. Optimization algorithms and corresponding performance analysis for EE cluster and routing path creations are presented in section IV and V respectively. Finally conclusions are provided in Section VI.

II. STATE OF THE ART

In a disaster situation (earthquakes/tsunamis), most of the communication network infrastructures are completely destroyed. In these scenarios, a quick and coordinated response must be given in order to improve the efficiency of rescue teams in saving as much as possible lives. Then is necessary to establish persistent and reliable communication links between victims and first aid responders [25]. In addition, since emergency situation may be ongoing for some time, system should have to stay usable for extended period.

During the last decades several technical solutions, based on ad-hoc networks, MANET's, mesh networks satellite communications and opportunistic networks, have been proposed as valid candidates for addressing the problem of communications between victims and first aid responders in disaster scenarios.

ARTEMIS and CodeBlue represent some of the first proposed solutions for triaging of victims and efficient coordination of rescue teams. Although both solutions are based on the usage of sensors deployed into the area of interest, they adopt different procedures for data collection and transmission. In particular, for triage data transmission, the first one exploits agents that move through a reliable deployed wireless ad-hoc network [26]. In the second one, data transmission is performed through the wireless sensor network created by deployed sensors [27].

A system based on a MANET for triage data transportation is represented by the Mobile Agent Electronic Triage Tag System. In this case, mobile agents, which store and carry triage information about victims, are created. Data transportation is performed through the creation of an end-to-end connection between source and destination, over a MANET network created by mobile device [28].

The Tactical Medical Coordination System (TacMedCS), developed for a military context application, is able to capture and display in real-time data relative to casualties in the battle field. In that case casualty data is collected through handheld devices. Such data, in conjuction with GPS position of the victim, is then sent via a satellite communication. IEEE 802.11 mesh communications can also be established between the different handheld units for their collaboration [29].

Another approach is represented by M-Urgency [8] and SafeCity [9]. These applications, in contradiction with the previous ones which, only monitor victims and do not provide features to actively locate or to communicate with them, enable iOS or Android users to stream live reports of crises situations (video as well as audio) over the cellular network to a local public safety answering point. They also provides real-time position through GPS or Wi-Fi fingerprint to ensure an appropriate help.

Recently also Facebook activated its Safety Check feature to enable people to give quick safety status updates to their family and friend during the disaster [7].

Although all these solutions could be beneficial in supporting first aid operations we can identify two critical aspects based on their operational way: *i)* the deployment of dedicates devices and repeaters to supply an infrastructure, which may require a long time [26]–[28], *ii)* the need of a pre-existing or dedicated communication infrastructure which could be not fully available or able to accept the huge amount of requests. [7]–[9], [26]–[29].

A different approach which could overcome these issues, is represented by the Haggle Electronic Triage Tag (Haggle-ETT) system. It creates electronic triage tags (ETTs) and transmit them using wireless opportunistic communications, without requiring a direct connection between end users [30]. Indeed, it is based on Haggle which is a search-based data dissemination framework for mobile opportunistic communication environments, making easy to share content directly between intermittently connected mobile devices [31].

Opportunistic networks exploit physical proximity between mobile nodes to enable direct communication between them. They typically exploit ad-hoc enabling technologies like WiFi-direct or Bluetooth, and support dissemination of messages through multi-hop spacetime paths, i.e., multi-hop paths that develop both over space - as in conventional ad hoc multi-hop networks - and over time - by exploiting contact opportunities between nodes that become available over time due to their mobility [32]. Nodes can store, carry and forward messages; routes from the sender and the destination are build dynamically, making opportunistic networks robust to disruptions. A first performance analysis about the usage of opportunistic networks in disaster scenario has been presented in [33]. In this work, authors assumed the need of communication between a disaster area, in which no available network infrastructures are present, and an healthy area where triage data and/or aid request should arrive. In that case, opportunistic communications are performed through mobile devices of either victims or first aid responders. Simulations were conducted in order to obtain performance evaluation in terms of message delivery ratio, network overhead and cost per message, as function of opportunistic routing protocols, number of generated request, rate of request generation and their dimensions.

A more general concept of infrastructure-less communication network is represented by the D2D paradigm. Indeed, D2D communications were initially proposed as a new underlay paradigm for enhancing the performance of Long-Term Evolution (LTE) networks. It is defined as a direct communication between two mobile users without traversing the Base Station (BS) or core network. Generally communications can occur either on cellular licensed or unlicensed spectrum and the resource control plane could be either autonomous or controlled by the BS [13]. Then, due to its high level of versatility, recently D2D paradigm has considered a key enabling technology for the creation od Disaster Relief Networks [15]. One of the first works on how exploiting D2D communication in a disaster scenario was presented in [34]. Here, the authors proposed a novel D2D based messaging solution for a disaster situation. The proposed solution consisted of a D2D session, controlled by the BS through special broadcast signals. Users for which the received signal strength is under a predefined threshold, will use D2D communication for transmitting their messages to other nodes in their proximity. Then this messages will be transmitted by these relay nodes to BS over the conventional network infrastructure. Compared with the default Random Access Channel (RACH) based messaging mechanism, this approach resulted in reducing the energy consumption for those nodes with bad channel condition. Indeed, they use short range communication requiring less energy than a direct transmission over cellular infrastructure, for which higher power than usual is required in order to overcome the uplink path loss. Also the probability of successful transmission is improved.

A public safety network architecture using D2D communication system was proposed in [35]. In this case, authors considered a scenario in which there is a functional area with a working BS and a disaster area where BS is fully injured and UEs have no radio resource. However, exploiting the multi-hop concept of D2D paradigm, users from disaster area are able to: *i)* communicate with each other; *ii)* communicate with nodes of the functional area, which acts as Relay Nodes (RN) towards the functional BS. Then, an implicit coverage is provided to a non functional area. Indeed, it is shown that the relaying system is able to increase the capacity, reduce the transmission power for mobile host and extend the system coverage area.

As mentioned earlier, in addition to the need of providing coverage, another critical aspect in a disaster scenario is related to the inevitable power consumption of device in performing transmission. Therefore, recovery of power supply is highly relevant. Taking that into account, in [36] the authors have recently proposed a D2D-based disaster management architecture including WEH and node clustering. Authors considered a public safety scenario in which the BS of a functional area desires to transmit its information to a destination located into a non-functional area out of its coverage range. Due to the physical barrier between source and destination, the BS selects a Relay Node (RN) which will assist the information transmission via D2D communication. For such relay-assisted communication, they derived the optimal position in which the relay node should be located, in order to guarantee the minimum outage probability. In that scenario they considered an WEH process to transfer energy from safety area to disaster area, and guarantee no loss of energy on both relay and nodes of the disaster area. Finally they proposed a procedure through which nodes in the disaster area self-organizes themselves in groups of clusters in order to reduce the average energy consumption in the disaster area. In this context they assumed that in each cluster a UE Cluster Head (UERCH) which acts as coordinator of the cluster. Each UERCH use short range communication for D2D intra-cluster transmission and long range communication for inter-cluster communication and WEH transmission. It is elected with the procedure reported in [15], [37].

III. SYSTEM MODEL AND PROBLEMS FORMULATION

From the previous State of Art analysis, we can observe that Disaster Scenario environment problems are similar to the ones related to a Wireless Sensor Network (WSN). In a disaster scenario, we have several nodes spreaded in a disaster area which need to communicate both with a safe area, in order to require help, and each other in order to exchange local informations.

However, disaster scenarios are more critical to address in real life than WSNs. Indeed, starting from nodes with no a priori established positions, is necessary to create a network infrastructures with as much as possible long lifetime duration and with high reliability, in order to guarantee a good communication between victims and first aid responders. Furthermore, as well as for the WSNs, in a disaster scenario the energy of nodes is a crucial aspect to consider. Indeed, a node with a low energy risks to remain isolated and unreachable by aid responder.

From previous works [15], [34]–[37], it is observed that a good way to save energy in that situations is to adopt a D2D communications between closest nodes and organizes them in clusters. These works proposed energy efficient solutions for CH elections and cluster creation, labeling as energy efficient a solution which reach the minimum of energy consumption. However, energy reduction does not necessary means that the power is efficiently used for transmissions. For this reason we propose an Energy Efficient Routing and Clustering method for a disaster scenario where we consider energy efficiency as the maximum ratio between achievable rate of the cluster and the power consumed for transmissions.

In addition, this paper provides a possible framework which, starting from some basic available information of nodes in a disaster area, i.e. nodes position and battery level, is able to provide a data path flow to each user toward a functional area or a help request collection point.

In the following subsections we will describe, the System model and related assumptions in III-A, Gateway (GW) selection procedure in III-B and finally, EE problems formulation for node clustering and optimal routing paths creation in III-C and III-D respectively. For a sake of good comprehension, the approaches proposed for solving problems formulated in III-C and III-D, will be explained in Section IV.

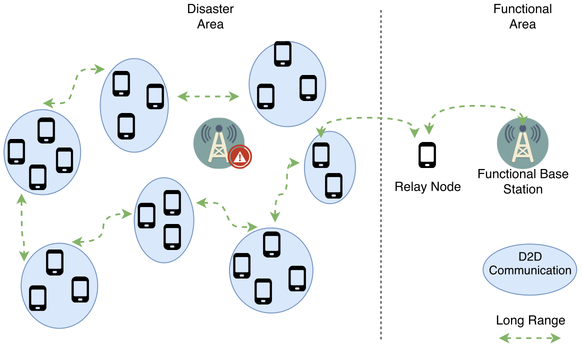

FIGURE 1. Typical considered scenario.

A. SYSTEM MODEL

As illustrated in Fig. 1, we consider a disaster scenario in which a base station has been fully damaged and then victims are not able to communicate their status or request help. In order to save energy, in contrast with the previous works [15], [36], [37], in our scenario nodes do not actively participate in the construction on cluster hierarchy sending beacon messages, but they stay in LISTEN mode in order to receive directives from an external entity located in a functional area.

In particular we assume the followings:

- A set of N User Equipment (UE) are distributed according to an homogeneous Poisson Point Process (PPP) Φ with spatial density λ_{ue} over a circular disaster area of ray R;
- The energy levels of UEs are uniformly distributed in a range $[E_{min}; E_{max}]$;
- As in [36] we assume that, through a RN, a BS located in a functional area is able to establish a communication in disaster area;
- The users can activate an emergency application which permit the external BS to know their positions and battery level;
- Each node in the disaster area is provided with a long-range communication system for CHs and a short range communication system for D2D inside the cluster;
- Each cluster will consist of I^k nodes and one gateway which serves as CH;
- Each gateway can communicate both in Downlink and Uplink with one or more Gateways (GW) through long range communication in a TDM duplexing mode;
- Each gateway performs a transmissions among its nodes in a TDM duplexing mode both in Uplink and downlink through short-range. This means that there is no intra-cluster interference;

Algorithm 1 Algorithm for GWs Election

```
Input: Positions and levels of charge of $N$ nodes
Output: Set of selected GWs $G_{sel}$
1:  Initialize $G_{sel} = \emptyset$
2:  Consider the subset $G_{cand} = \{n \in N \mid E_n \geq E_{av}\}$;
3:  Descendent sorting of $G_{cand}$ based on distance from RN;
4:  for $i = 1$ to $|G_{cand}|$ do
5:      take $D_{ib} = dist(n_i, RN)$
6:      create $D2D_i = \{n_j \in G_{cand}; j \neq i \mid dist(n_j, n_i) \leq d_{D2D}\}$
7:      create $G2G_i = \{n_j \in G_{cand}; j \neq i \mid dist(n_j, n_i) \leq d_{G2G} \vee dist(n_j, n_i) > d_{D2D}\}$
8:      create $RN_{close} = \{x \in G2G_i \mid dist(x, RN) \leq D_{ib}\}$
9:      if $(|RN_{close}| \neq \emptyset)$ then
10:         create $UPDATE = \{n_i;\ D2D_i;\ \overline{RN_{close}}\}$
11:     else
12:         create $UPDATE = \{n_i\}$
13:     end if
14:     $G_{cand} = G_{cand} - UPDATE$
15:     $G_{sel} = G_{sel} \cup n_i$
16: end for
17: return $G_{sel}$
```

B. GATEWAYS ELECTION

As stated before, the BS knows positions and energy levels of all nodes in the disaster area and the RN's position. The first task is to perform the gateway selection. The full procedure is summarized in Algorithm 1 and described in the sequel. The aim of the algorithm is, to select the minimum number of the gateway which are able to cover as much as possible all the disaster area and, at the same time, to give the possibility to construct paths towards the relay.

Since all nodes have the functionalities to serve as gateway, the BS needs to reduce the list of candidates. Given the fact that $E_{av} = \frac{1}{N}\sum_{i=1}^{N} E_i$ the average energy of all nodes in the disaster area, a first coarse selection is performed selecting those nodes for which energy is greater than the average, i.e. $E_n > E_{av}$. This constitutes the set of nodes labeled as G_{cand}. Intuitively this selection constraint promotes the maximum network lifetime. For each node present in G_{cand}, the BS evaluates its relative distance from RN and sorts them from farthest to closest. After that, a fine selection procedure is performed among nodes of this subset. Starting from the farthest node, indicating with d_{G2G} the maximum communication range at which two GWs are supposed able to communicate, i.e. long-range communication, and with d_{D2D} the maximum of short-range communication used for intra cluster transmissions, as indicated in lines 6 and 5 of the algorithm, for the i-th node in G_{cand}, BS creates other two subsets labeled as $D2D_i$ and $G2G_i$ respectively. The most important is $G2G_i$ since it contains nodes that are in the d_{G2G} range but not in the d_{D2D} range. From those nodes which are in $G2G_i$ set, as indicated in line 9, the BS maintains only nodes for which their distance from the RN is less or equal the distance between the RN and the i-th node itself, labeling this subset as RN_{close}. However, there is the possibility that this subset results empty for two main reason: *i)* the $G2G_i$ set resulted empty; *ii)* nodes in $G2G_i$ are not closer to RN than the i-th node itself. Instructions from line 9 to 13 was defined to take into account this possibility. This block of instructions results in a set called $UPDATE$, which is a set of nodes that is not necessary in the successive steps of gateway selection. At the end of the process all the selected GWs are grouped into the G_{sel} set.

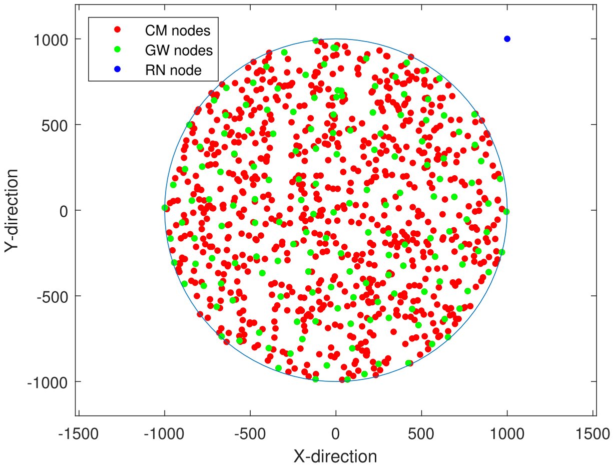

FIGURE 2. Typical Network Scenario after gateway selection.

Summarizing, the above described procedure provide the possibility to:

- Save energy from all nodes in cluster creation since this operation is performed by BS itself;
- Obtain the sufficient number of gateways able to cover all disaster area;
- Guarantee highest lifetime of the network in the disaster area by selecting GWs from a subset of node with higher energy;
- Construct multi-hop paths towards the RN also for farthest GWs;
- Reduce the number of communications between GWs since not all the candidates are selected;

In Fig.2 a typical scenario after GWs selection is illustrated, where the green spots represent the selected GWs, the red spots represent the Common Nodes (CN) and the blue spot represents the RN of functional area. In the next subsection we will propose a strategy for cluster association and routing path creation.

C. CLUSTERS CREATION

After the Gateway selection phase nodes must be assigned to a cluster. Fig.3 shows the same scenario as in Fig.2 in which for each selected gateway the correspondent D2D range has been plotted. From these figure we can observe that some CNs are located in multiple gateway areas. Then, if we suppose that all D2D communications between GW and its

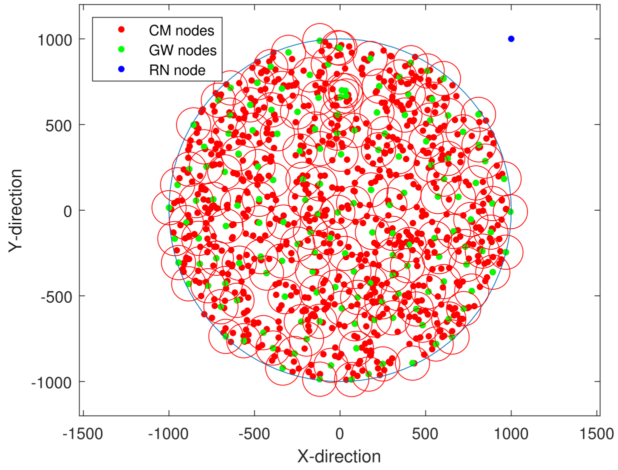

FIGURE 3. **Gateways and their maximum D2D range.**

respective CNs are performed using the same level of power, we could face the following issues:

- In downlink phase, nodes in common areas could receive a lot of interference and then they could not be able to decode their data correctly;
- In uplink phase, GWs can also receive interference from those nodes which are not associated with it and then will be unable to decode data correctly as well;

As a consequence the transmission energy is not employed efficiently. Furthermore this reduce drastically the network lifetime since retransmissions could be necessary. A solution could be a Power control strategy. In particular controlling the power used by both GWs and CNs for D2D communications could improve the efficiency of the transmissions and then reduce the waste energy. Then each gateway will be informed about the power that it should use for the D2D downlink transmissions. The same level of power will be used of its associated CNs which will be informed during a synchronization phase.

Let's assume that K GWs are selected and then K corresponding cluster must be formed. Each cluster will be formed by I^k nodes where $\sum I^k \leq N - K$. The inequality is for considering the probability that not all nodes will be covered.

With the suppression of intra-cluster interference, we consider data received from a generic m node in cluster k', this can be expressed as:

$$y_{mk'} = \sqrt{P_{mk'}} g_{mk'} x_{k'} + \sum_{k \neq k'} \sqrt{P_{mk}} g_{mk} x_k + \omega_0; \qquad (1)$$

where P_{nk} represents the received power at node m from the gateway k in D2D transmission, g_{mk} represents the channel gain, x_k is the message transmitted from GW k and $\omega_0 \sim \mathcal{N}(0, \sigma^2)$ represents the additive white noise at each node. We suppose that the transmitted message respect the condition $\|x_k\|^2 \leq 1$. For signal propagation we use the same assumption of [38] This means that, indicating with P_k the power employed for D2D transmissions by gateway k, the received power is expressed as $P_{mk} = P_k \cdot d_{mk}^{-\alpha}$, where d_{mk} is the distance between gateway k and user m, and α is the path loss exponent. Furthermore g_{mk} is extracted form the Suzuki distribution which is modeled as follow [39]:

$$f_S(r) = \frac{r}{\sqrt{2\pi\sigma^2}} \int_0^\infty \frac{1}{\omega^3} exp\left(-\frac{r^2}{2\omega^2} - \frac{(ln(\omega) - \mu)^2}{2\omega^2}\right) d\omega \qquad (2)$$

Suzuki fading, is a combination of Rayleigh and Log-normal distributions, representing small-scale and large-scale fading components respectively. In (2) the terms μ and σ^2 are the mean and variance of the Log-normal distribution, respectively.

Then, from Eq. (1), the achievable rate $R_{mk'}$ of the generic user m in the cluster k' can be expressed as:

$$R_{mk'} = \log_2\left(1 + \frac{P_{mk'}|g_{mk'}|^2}{\sum_{k \neq k'} P_k |g_{mk'}|^2 + \sigma^2}\right). \qquad (3)$$

Hence the sum achievable rate of each cluster is

$$\begin{aligned} R_{k'} &= \sum_{m=1}^{I^{k'}} R_{mk'} \\ &= \sum_{m=1}^{I^{k'}} \log_2\left(1 + \frac{P_{mk'}|g_{mk'}|^2}{\sum_{k \neq k'} P_{mk} |g_{mk'}|^2 + \sigma^2}\right). \qquad (4) \end{aligned}$$

Since $P_{k'}$ is the power employed by the gateway k' for transmitting in D2D mode inside the cluster, and indicating by $\mathbf{P} = [P_1; P_2 : \cdots ; P_K]$, EE maximization problem is formulated as follow:

$$\max_{\mathbf{P}>0} \frac{\sum_{m=1}^{I^{k'}} \log_2\left(1 + \frac{P_{mk'}|g_{mk'}|^2}{\sum_{k \neq k'} P_{mk}|g_{mk'}|^2 + \sigma^2}\right)}{P_{k'}^{tot}} \qquad (5a)$$

$$\text{s.t. } P_{k'} \leq P_{D2D}, \qquad (5b)$$

$$R_{mk'} \geq R_{th}, \quad m = 1; \cdots, I^{k'}, \qquad (5c)$$

$\forall k = 1, \ldots, K$, where $P_{k'}^{tot} = \eta P_{k'} + P_{k'}^{cir}$ is the total power consumption of the k'th cluster, $\eta > 1$ and $P_{k'}^{cir}$ are the reciprocal of the drain efficiency of the amplifier and non-transmission power of the gateway, respectively. The constraint (5b) makes sure that GWs and then CNs do not exceed the maximum power used for D2D communication. The constraint (5c) represents the minimum QoS of the node in each cluster. It is clearly seen that the problem (5) is the non-convex problem since the objective function is non-concave and the QoS constraints (5c) are non-convex.

D. ROUTING PATHS CREATIONS

At the end of optimization process for cluster creations, a Gateway k' will use an amount of Power $P_{k'}$ which will be used to serve a set of $I^{k'}$ users.

In a general scenario, during the uplink phase, each gateway should perform the following ordered operations:

(I) waiting all cluster members upload their data;
(II) waiting data arrived from other GWs for which it represents a next-hop node;
(III) forward data to the next-hop gateway;

Since the transmissions are performed in TDM duplexing fashion, step (I) will be completed after a time $T_{D2G}^{k'}$, which is the time after all the nodes have completed their transmission to gateway. Generally it depends on the scheduling policy adopted in each cluster. Here, without loss of generality, we assume that each cluster adopt a Round Robin (RR) scheduler and then assign a time slot of duration T_D to each user. This means that $T_{D2G}^{k'} = T_D \cdot I^{k'}$. Supposing that the gateway k' serves a number of $N_{guest}^{k'}$ GWs also in a TDM mode with a time slot of duration T_G, step (II) will be completed after an amount of time equal to $T_{G2G}^{k'} = T_G \cdot N_{guest}^{k'}$. Finally, indicating with k'' the next-hop of gateway k' and with $N_{guest}^{k''}$ the number of GWs which serves as as next-hop, step (III) will be completed after an amount of time equal to $T_{G2G}^{k''} = T_G \cdot N_{guest}^{k''}$. Then the total amount of time $T_{FW}^{k'}$ for completing whole data forwarding procedure (I) to (III) is written as

$$\begin{aligned} T_{FW}^{k'} &= T_{D2D}^{k'} + T_{G2G}^{k'} + T_{D2G}^{k''} \\ &= T_D \cdot I^{k'} + T_G \cdot N_{guest}^{k'} + T_G \cdot N_{guest}^{k''} \end{aligned} \tag{6}$$

Assuming that data flow of gateway k' follow a path composed of a set of $\mathcal{N}_{k'}^{hop} = \{1, \ldots, N_{k'}^{hop}\}$ where $N_{k'}^{hop} \geq 0$ next-hops before reaching the RN, from Eq.(6) the total end-to-end delay of a generic node into the cluster is given by

$$\begin{aligned} T_{Tot}^{k'} &= T_D \cdot I^{k'} + T_G \cdot N_{guest}^{k'} + T_G \cdot \sum_{k'' \in \mathcal{N}_{k'}^{hop}} N_{guest}^{k''} \\ &= T_D \cdot I^{k'} + T_G \cdot \left(N_{guest}^{k'} + \sum_{k'' \in \mathcal{N}_{k'}^{hop}} N_{guest}^{k''} \right) \end{aligned} \tag{7}$$

Then we formulate the path optimization problem as:

$$\min \left[\max_{k' \in K} \left[T_D \cdot I^{k'} + T_G \cdot \left(N_{guest}^{k'} + \sum_{k'' \in \mathcal{N}_{k'}^{hop}} N_{guest}^{k''} \right) \right] \right] \tag{8}$$

Interestingly, this optimization problem will represent the good trade-off between the minimum number of next-hop and traffic load to intermediate GWs.

IV. DISTRIBUTED OPTIMAL EE PERFORMANCE AND ROUTING PATH

In this section, solutions proposed for solving problems (5) and (8) will be provided in IV-A and IV-B respectively. For each of them we proposed a distributed approach which, in addition to be more practical for such multi constrained problems, the result is more robust and scalable than a centralized one.

A. DISTRIBUTED OPTIMAL POWER ALLOCATION FOR EE MAXIMIZATION

In this section, we provide a distributed manner for solving the EE maximization problem given in (5). This approach is implemented by applying Block Coordinate Descent (BCD) procedure [40].

Firstly, all transmit powers of gateways are randomly initialized as $\{P_k^0\}, k = 1, \ldots, K$.

For cluster k, a power allocation scheme is proposed in order to optimize the variable of power P_k. Meanwhile, the power allocations of other clusters are fixed.

To this end, let us define $\mathbf{P}_{[k']} = [\bar{P}_1, \ldots, \bar{P}_{k'-1}, P_{k'}, \bar{P}_{k'+1}, \ldots, \bar{P}_K]^T$ where $\bar{P}_k, \forall k \neq k'$ are fixed, which are received at the cluster k'. Then the EE maximization problem for the cluster k' is given as

$$\max_{\mathbf{P}_{[k']} > 0} \frac{\sum_{m=1}^{I^{k'}} \log_2 (1 + P_{k'} \phi_{mk'})}{P_{k'}^{tot}} \tag{9a}$$

$$\text{s.t. } P_{k'} \leq P_{D2D}, \tag{9b}$$

$$R_{mk'}(\mathbf{P}_{[k']}) \geq R_{th}, \quad k' = 1; \cdots, I^{k'}, \tag{9c}$$

where $\phi_{mk'} = |g_{mk'}|^2 / (\sum_{k \neq k'} \bar{P}_k |g_{mk'}|^2 + \sigma^2)$. Interestingly, the subproblem (9) is semi-concave problem with a concave-linear objective function and convex constraints. However, the problem (9) is still difficult to solve since the logarithmic concave-linear function of objective function.

Next, we provide a semi closed-form solution for the subproblem (9) [41]. Firstly, the problem (9) can be transformed by Dinkelbachs approach [42], which finds the optimal added variable as $\tau > 0$:

$$\max_{P_{k'} > 0} \sum_{m=1}^{I^{k'}} \log_2 (1 + \phi_{mk'} P_{k'}) - \tau P_{k'}^{tot} \quad \text{s.t. } (9b), (9c) \tag{10}$$

Then, the constraint (9c) can be relaxed by setting $\hat{P}_{k'} := \sigma^2 (2^{R_{th}} - 1)/\phi_{mk'}$. Therefore, the power variable change $P_{k'} = \tilde{P}_{k'} + \hat{P}_{k'}$ where $\tilde{P}_{k'} > 0$ and then (10) is equivalent as

$$\max_{\tilde{P}_{k'} > 0} \sum_{m=1}^{I^{k'}} \log_2 \left(a_{mk'} + \phi_{mk'} \tilde{P}_{k'} \right) - \tau \tilde{P}^{tot}(\tilde{P}_{k'}) \tag{11a}$$

$$\text{s.t. } \tilde{P}_{k'} \leq \hat{P}_{D2D}, \tag{11b}$$

where $a_{mk'} = 1 + \hat{P}_{k'} \phi_{mk'}$, $\hat{P}_{D2D} = P_{D2D} - \hat{P}_{k'}$ and $\tilde{P}^{tot}(\tilde{P}_{k'}) = \eta \tilde{P}_{k'} + P_{k'}^{cir}$.

Problem (11) admits a closed-form solution with the level quality of λ:

$$\tilde{P}_{k'}^{*} = \left[\frac{1}{\ln 2.(\tau \eta + \lambda)} - \frac{a_{mk'}}{\phi_{mk'}} \right]^{+}. \tag{12}$$

Here and after, $[x]^+ = \max\{0, x\}$. If

$$\sum_{k=1}^{K} \left[\frac{1}{\ln 2.\tau \eta} - \frac{a_{mk'}}{\phi_{mk'}} \right]^{+} \leq \hat{P}_{D2D}$$

Algorithm 2 Algorithm for Distributed Power Allocation

```
Input: Set of GWs $G_{sel}$ by Algorithm 1. Appropriate random
    the initial power ($\mathbf{P}^{(0)}$). Set $\kappa = 0$ and the maximum
    number of iteration $N_{iter}$.
Output: Optimal power allocation $\{\mathbf{P}^*\}$.
Repeat:
for $k' = 1$ to $K$ do
    Solve the subproblem (9) for cluster $k'$ by implementing bisection search above.
    return $P^*_{k'}$ as the $k'$th entry of ($\mathbf{P}^{(\kappa)}$) for the next iteration.
end for
Update the vector power allocation for all cluster.
Set $\kappa := \kappa + 1$.
return ($\mathbf{P}^*$) when the convergence requirement is satisfied or the algorithm reach to the maximum number of iteration.
```

then $\lambda = 0$. Otherwise, $\lambda > 0$ such that

$$\sum_{k=1}^{K}\left[\frac{1}{\ln 2.(\tau\eta+\lambda)}-\frac{a_{mk'}}{\phi_{mk'}}\right]^{+}=\hat{P}_{D2D}, \tag{13}$$

which can be easily located by the bisection search.

In short summary, the problem in (9) is solved by the following steps

- *Initialization.* Solve (11) for initial $\tau > 0$. If its optimal value is higher than zero set $\underline{\tau} = \tau$ and reset $\tau \leftarrow 2\tau$ and solve (11) again. Otherwise (its optimal value is less than zero) set $\bar{\tau} = \tau$. We end up by having $\underline{\tau}$ and $\bar{\tau}$ such that the optimal value of (11) is positive for $\tau = \underline{\tau}$ and is negative for $\tau = \bar{\tau}$. The optimal τ for zero optimal value of (11) lies on $[\underline{\tau}, \bar{\tau}]$ so from now we locate it by bisection in the next stage;
- *Bisection.* Solve (11) for $\tau = (\underline{\tau} + \bar{\tau})/2$. If its optimal value is positive reset $\underline{\tau} \leftarrow \tau$, otherwise (its optimal value is negative) reset $\bar{\tau} \leftarrow \tau$. Process until $\bar{\tau} - \underline{\tau} \leq \epsilon$ (tolerance) to have the optimal value of (11) is zero.

This step is implemented for all GW of each clusters. Then, BCD procedure terminates when the power variables of all cluster are convergence (unchanged).

The proposed distributed approach, via BCD procedure for power allocation of EE maximization problem, is summarized in Algorithm 2.

B. DISTRIBUTED OPTIMAL ROUTING PATH CREATION

In this section we provide a Particle Swarm Optimization (PSO) algorithm for solving the path optimization problem III-D:

$$\min\left[\max_{k'\in K}\left[T_D\cdot I^{k'}+T_G\cdot\left(N^{k'}_{guest}+\sum_{k''\in\mathcal{N}^{hop}_{k'}}N^{k''}_{guest}\right)\right]\right] \tag{14}$$

PSO is one of metaheuristic optimization techniques inspired by natural life behavior like bird flocking and fish schooling [43], [44]. Indeed, in nature this groups of animals cooperate in order to reach a common objective. In particular each component of the group will adjust its behavior, i.e. position and velocity, using the group information. Then, a PSO includes a set of a predefined number, say N_p, of particles. Each particle i has a position X_i and a velocity V_i in a dimensional space of dimension D and represents a solution of the optimization problem. Iteratively each particle is evaluated through a fitting function used to evaluate the quality of the solution. The value obtained through the fitting function represents the personal best of the particle, i.e. $Pbest_i$, which is compared with the global best value, i.e. $Gbest_i$. After this comparison each particle adjust its position and velocity along each dimension according with the following equations:

$$\begin{aligned}V_{i,d}(t) = w\cdot V_{i,d}(t-1)+c_1\cdot r_1\cdot\big(Xpbset_{i,d}-X_{i,d}(t-1)\big)\\ +c_2\cdot r_2\cdot\big(Xgbest_{i,d}-X_{i,d}(t-1)\big)\end{aligned} \tag{15}$$

and

$$X_{i,d}(t)=X_{i,d}(t-1)+V_{i,d}(t) \tag{16}$$

where (15) and (16) represent velocity and position along dimension $d \leq D$ of the particle respectively, w is the inertial weight, c_1 and c_2 are two non-negative constants called acceleration factors and r_1 and r_2 are two different uniformly random distributed numbers in the range [0, 1].

As mentioned in section (III-B), at the end of gateway selection phase, we have a set of GWs which could serve the whole interested area. Since the positions of each of them is known, as well as the position of the RN which will support the communication with the BS in the healthy area, for each gateway we construct the set *nextHop* (GW_i) through the Algorithm (3). In particular, from that algorithm for each gateway GW_i, we obtain a set $nextHop(GW_i)$ composed of GWs in its *G2G* range, and for which their distance from Relay Node (RN) is less than node itself. In addition we assume that GWs can directly communicate with RN when they are in its communication range, i.e. RN_{range}. In that case we add RN into $nextHop(GW_i)$ set.

As explained in section (III-D) each gateway waits to receive data from both its inner nodes and GWs. After the reception is completed, it forwards received data to its next hop. However if we assume that the next hop forwarding start when all nodes have received data from all their respective inner nodes, observing problem (8), for each gateway the first term of the objective function, i.e. $T_D \cdot I^{k'}$, became constant which depends from the node which highest number of associated node, i.e. $\max_{k'\in K} T_D \cdot I^{k'}$. Since this term is a constant, as fitting function we use the second part of the objective function:

$$N^{k'}_{guest}+\sum_{k''\in\mathcal{N}^{hop}_{k'}}N^{k''}_{guest} \tag{17}$$

Algorithm 3 Algorithm for Gateway's *nextHop* () Set Creation

```
Input: Positions of all GWs $GW\_POS$ and Relay node $RN\_POS$.
Output: $nextHop\,(GW_i)$ of each gateway
for $i = 1$ to $|GW\_POS|$ do
    create $GW_{i,next} = \{GW_j \in GW\_POS; j \neq i \mid dist(GW_j, GW_i) \leq d_{G2G} \vee dist(GW_j, RN\_POS) < dist(GW_i, RN\_POS)\}$
    if $(dist(GW_i, RL\_POS) \leq RN_{range})$ then
        update $GW_{i,next} = GW_{i,next;RN\_POS}$
    end if
    return $nextHop(GW_i)$
end for
```

TABLE 1. Simulation parameters.

Parameter	Value
Cell Radius (Km)	1
N (average number of nodes)	1000
$G2G$ range (m)	200
$D2D$ range (m)	100
$D2D$ maximum Transmission Power (mW)	100
P_{circ} (mW)	160
NF (dB)	9
η (Drain efficiency)	$\frac{1}{0.388}$
Bandwidth (MHz)	40
Pathloss exponent α	4
Variance of Log-normal shadowing σ^2 (dBm)	0
Mean of Log-normal shadowing μ (dBm)	-67.8

Then, during each iteration of PSO each particle goodness is evaluated through the fitting function. If this value is less than $Pbest_i$ then we update the respective $Pbest_i$. Also $Gbest$ is updated as well if the result from the fitting function for a generic particle result is less than $Gbest$.

As in [45] the initial set of particle has been created in a random fashion. In particular for each gateway a random number from a uniform distribution in the range [0; 1], say R_{next} has been extracted. Each element in $nextHop(GW_i)$ has been numbered from 1 to $|nextHop(GW_i)|$ and then the index for the next hop selection, ID_{next}, has been selected as $ID_{next} = ceil(R_{next} \cdot |nextHop(GW_i)|)$. During the update of the position through Eq. (16) if the result is less than 0 another random number is extracted and assigned. If greater than 1 the value 1 has been assigned. Finally we observed that no changes to the solution after 200 iterations and then we select the number of iterations as PSO stop criterion.

V. NUMERICAL RESULTS

In this section we show the numerical results regarding the two algorithms implemented for power allocation and path creation implemented in the proposed framework. For this purpose we divided this section two subsections. Subsection V-A contains the performances obtained by the optimization algorithm for EE Power allocation and subsection V-B provides the performances of PSO based path creation. Main simulation parameters are summarized in Table 1. The maximum transmit power of each GW is 100 mW. The noise power at the receivers is $N_0 = 290 \cdot k \cdot B \cdot NF$, where k, B and NF are the Boltzmann constant, the system Bandwidth and the noise figure at 9 dB respectively. We compared the results obtained either in power allocation and path allocation with the one obtained from random policy and fixed policy.

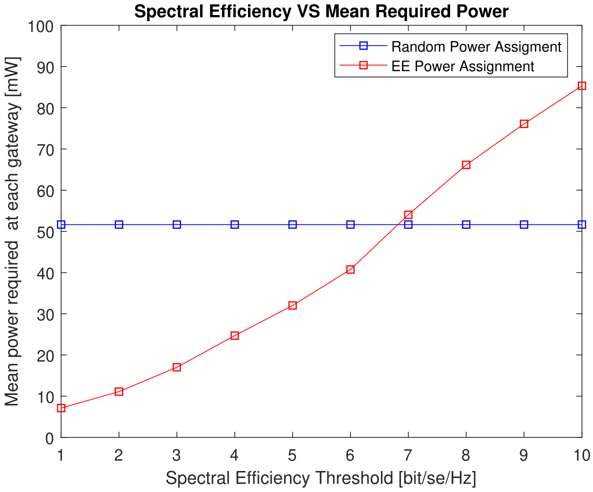

FIGURE 4. Mean required transmission power by each gateway.

A. EE POWER ALLOCATION

In this subsection we present the results obtained using Algorithm (2). As explained in previous subsection, the main input arguments of this algorithm are the set of gateways obtained from Algorithm 1, the initial transmitting Power is uniformly distributed among all GWs and the QoS constraint should be satisfied by each node in the disaster area. A first set of experiments were conducted by assuming that a Suzuki fading is independently generated over each transmission link with related parameters listed in Table 1. In Fig. 4 we plot the mean transmitting power required by each gateway in the network necessary for an energy efficient power allocation. As shown in this figure, the level of required power increase with the increase of the QoS constraint (9c). This aspect results to be in line with the optimization problem (9) this is because to increase the spectral efficiency an increase of the transmission power is required. However, in the majority of cases, the required power is maintained lower than the mean power assigned in a random fashion.

In addition, from Fig. 5 we can observe how the proposed algorithm is more efficient than the random power allocation. In Fig. 5, we plot the product between the EE ratio and the available bandwidth. As we can observe, increasing the required QoS constraint results in decreasing the EE ratio. This is because, as illustrated in Fig. 4 more transmitting power is necessary, i.e. more power consumption. However, from both figures we can observe that there is a critical point in which the random assignment result to be more efficient than the new power allocation algorithm. Basically this is

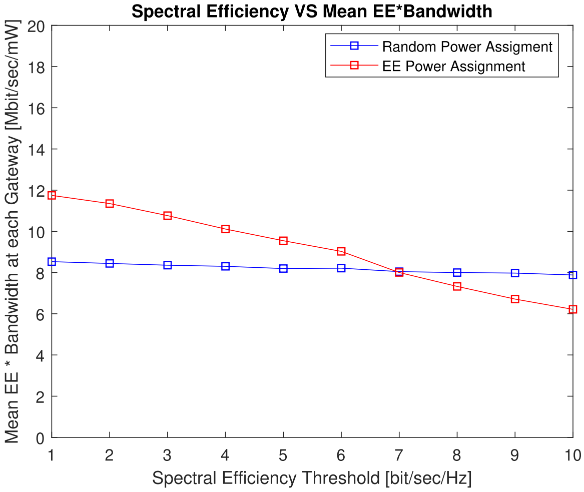

FIGURE 5. Mean EE X Bandwidth product reached by each gateway in the network.

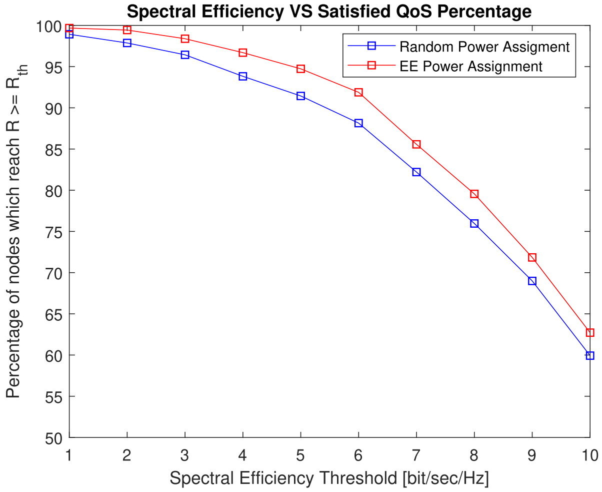

FIGURE 6. Average percentage of nodes in the network for which QoS constraint are satisfied.

due to the fact that the Algorithm (2) tends to increase the mean power allocated in order to reach the level of QoS constraint, which due to channel conditions is not possible to satisfy the maximum transmission power, i.e. some nodes needs the maximum transmitting power. However how can be possible to see form Fig. 6 the percentage of node for which the QoS constraint is satisfied results to be higher by Algorithm (2) than random power assignment. This means that the algorithm reaches suboptimal solutions in order to maintain the QoS constraint.

For completeness, from Fig. 7 we can observe that in contrast to the usage of a fixed amount of energy employed for transmissions, the proposed algorithm is able to select the proper level of energy which maximizes the EE. Although some points exist in which the EE algorithm result to have the worst performance respect to the usage of a fixed level of power, also in these cases we observed that even if the EE is lower, the percentage of QoS constraint respected is the highest using the power allocated by EE algorithm.

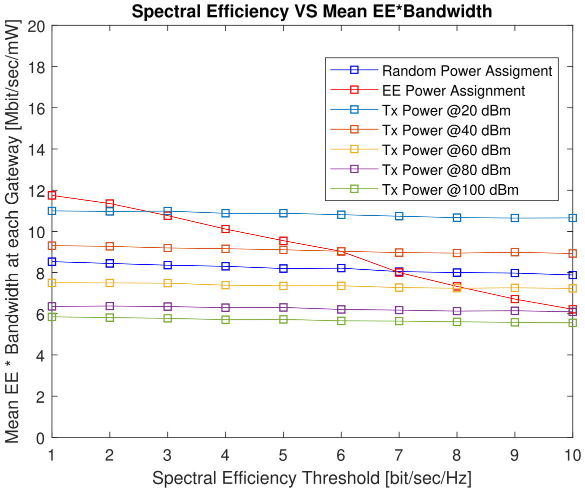

FIGURE 7. Mean EE x Bandwidth. Comparison with fixed levels of power.

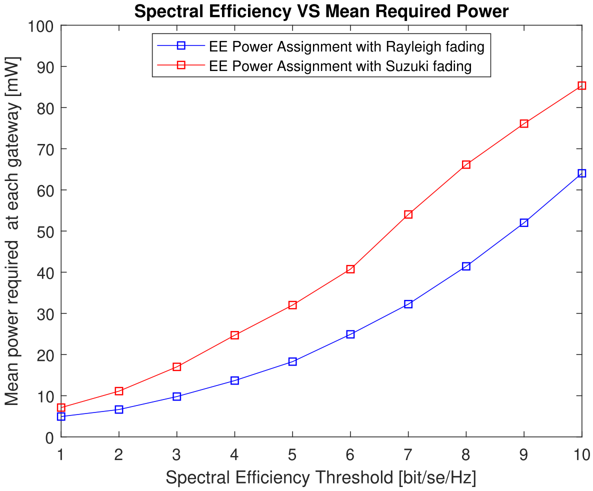

FIGURE 8. Mean required transmission power by each gateway.

Finally, from Figs. 8 to 10, we highlight the dependence of the optimization algorithm from the propagation channel model. In particular we can see how using the Suzuki fading performances result to be worst than the ones obtained by using the Rayleigh fading, i.e. more mean power required, less EE and less percentage of nodes with guaranteed QoS. This is due to the fact that Suzuki fading model takes into account the long-term fading contributions in signal corruption. This results in more required transmitting power. However all performance indicator looks to be scaled by a constant factor.

B. PATH CREATION

In this section we show the performance of the path optimization. Parameters for PSO implementation, as for [45], are taken same as in [43], [46] and are summarized in Table 2.

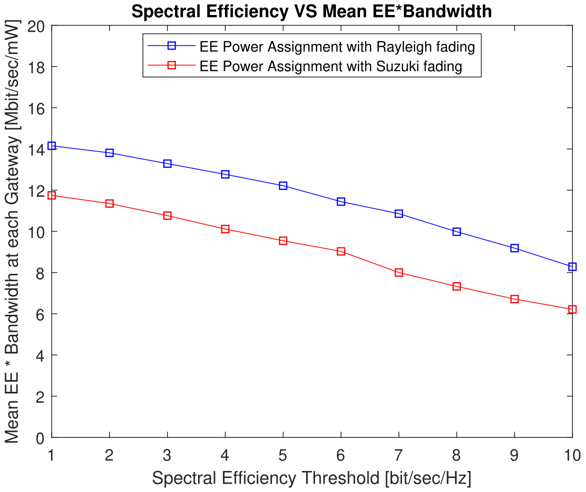

FIGURE 9. Mean EE x Bandwidth product reached by each gateway in the network.

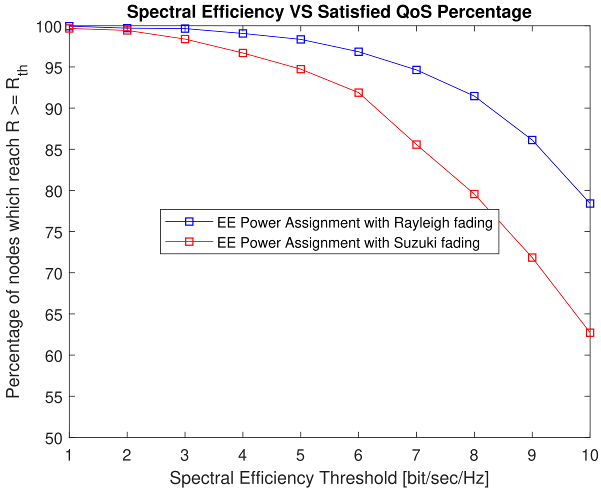

FIGURE 10. Average percentage of nodes in the network for which QoS constraint are satisfied.

TABLE 2. Simulation parameters.

Parameter	Value
N_p	60
$N_{iterations}$	200
C_1	1.4962
C_2	1.4962
w	0.7968
V_{max}	0.5
V_{max}	-0.5

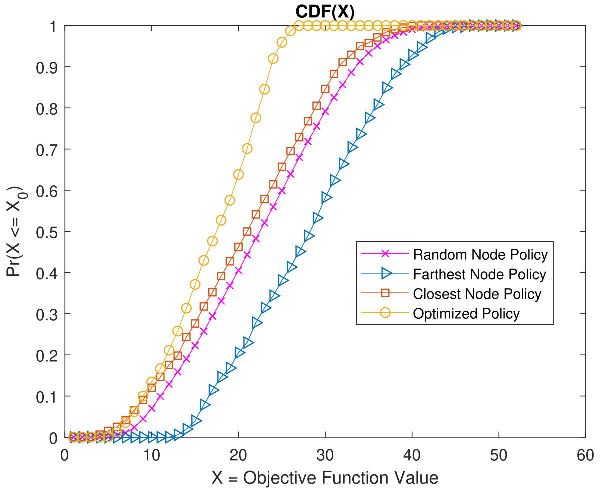

FIGURE 11. CDF of path distributions.

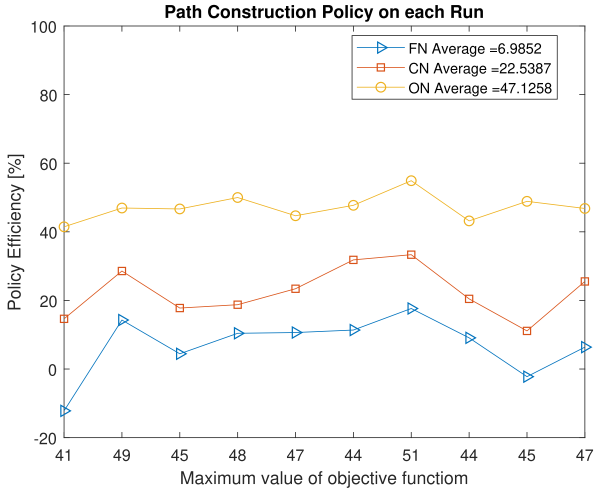

FIGURE 12. Policy efficiency in path length reduction.

As performance evaluation index we used: *i)* the cumulative distribution function (CDF) of path length in the disaster area, *ii)* the policy efficiency (PE). In particular, indicating with $D_{max,R}$ the path with maximum delay obtained through random next-hop assignment, and with $D_{max,i}$ the path with maximum delay obtained through another policy, *i*-policy, we defined the PE as follows:

$$PE_i = \frac{D_{max,R} - D_{max,i}}{D_{max,R}} \tag{18}$$

As comparative policies we considered the Closest Node (CN) policy, the Farthest Node (FN) policy and the Optimal Node (ON) policy in which, the closest node, the farthest node and the optimal node from PSO optimization, are selected from each gateway and from its *nextHop*(GW_i) set respectively.

Simulations were performed through a *MATLAB* code and results are illustrated in Figs. 11 and 12. In order to obtain results with small confidence intervals a set of *nRun* $=$ 10 simulation runs over the same area has been performed. For a sake of simplicity we do not plot the confidence intervals.

From Fig. 11 we can observe how the best policy is obtained through PSO optimization process, i.e. ON policy. For the FN policy, while it could be intuitively chosen as the best policy since each node try to forward data over the farthest node, which is the closest to the relay node, it is the worst scenario. This results could be explained by analyzing the forwarding procedure followed by each node. Indeed, since each node has to wait data from gateway to which it represents a next hop, the FN policies results in increasing the waiting time from node closer and closer to the relay node, creating a bottle-neck effect. In addition it represents the most energy expensive policy since each gateway uses more power than a CN policy for data transmission, and node closer to the relay node could require a huge amount of computation energy. For CN policy, it is interesting to see that to require less transmission energy, it shows a path reduction respect to the random policy. It could be a good policy if the implementation of PSO optimization process is not possible at BS station and only GWs positions are available.

Finally in Fig. 12 we illustrate the results regarding the PE. In particular, from this figure we reported $D_{max,R}$ value of each simulation run along x axis, i.e. *nRun* values, versus the PE of each policy. Also in this case, we can observe how the best value is obtained through the ON policy followed by CN policy. In addition it is interesting to observe how variation of PE from one simulation run to another is slower for ON policy. This means that each time the algorithm is instantiated it tries to reach the best optimal configuration which could be applied in the interested area.

VI. CONCLUSION

In this article, we highlight the importance of a network infrastructure in a natural disaster. After analyzing ICT related issues which could be faced in this context, we proposed an EE framework for natural disaster scenario management based on D2D communications. In particular, we considered a disaster scenario in which a BS was fully damaged and then victims are not able neither to communicate their status nor request help. Exploiting D2D communications, coverage is provided by another BS located into a functional area. Through our proposed framework and the usage of a relay in its coverage area, starting from basic informations such as position and battery level on nodes in disaster area, functional BS is able to: *i)* select sufficient number of gateways to cover all disaster area through the mean of cluster creation, *ii)* assign the proper level of transmission power to each gateway in order to maximize the energy efficiency of the whole area, *iii)* construct multi-hop path for guaranteeing the data delivery, both in downlink and uplink, minimizing the end-to-end delay. In this context we defined the energy efficiency as the ratio between achievable rate and the power consumed for transmissions. Simulations were performed in MATLAB in order show how our proposed approach better outperforms respect to random policies assignment and static policies assignment either in power allocation and routing path creations.

REFERENCES

[1] UNISDR. *United Nations Office for Disaster Risk Reduction, Disaster Statistics*. Accessed: Feb. 2019. [Online]. Available: https://www.unisdr.org/we/inform/disaster-statistics

[2] K. Ali, H. X. Nguyen, Q. T. Vien, and P. Shah, "Disaster management communication networks: Challenges and architecture design," in *Proc. Pervasive Comput. Commun. Workshops (PerCom Workshops)*, Mar. 2015, pp. 537–542.

[3] T.-C. Le, Q.-S. Nguyen, D.-L. Nguyen, B.-C. Huynh, and T.-C. Dinh, "Design of public safety network and emergency alarm for smart trade centre," *EAI Endorsed Trans. Ind. Netw. Intell. Syst.*, vol. 5, no. 15, pp. 1–8, Sep. 2018.

[4] ITU-T. *Focus Group on Disaster Relief System (FG-DR and NRR) Network Resiliency and Rocover*. Accessed: Feb. 2019. [Online]. Available: https://www.itu.int/en/ITU-T/focusgroups/drnrr/Pages/default.aspx

[5] ETSI. *Terrestrial Trunked Radio (TETRA)*. Accessed: Feb. 2019. [Online]. Available: https://www.etsi.org/technologies/tetra

[6] 3GPP. *LTE for Critical Communication*. Accessed: Feb. 2019. [Online]. Available: http://www.3gpp.org/news-events/conferences/1468-lte-for-critical-communications

[7] (2015). *Safety Check*. Accessed: Feb. 2019. [Online]. Available: https://www.facebook.com/about/crisisresponse/

[8] S. Krishnamoorthy and A. Agrawala, "M-Urgency: A next generation, context-aware public safety application," in *Proc. 13th Int. Conf. Hum. Comput. Interact. Mobile Devices Services (MobileHCI)*, 2011, pp. 647–652. [Online]. Available: http://doi.acm.org/10.1145/2037373.2037475

[9] *SafeCity Get Live Information from the Society*. Accessed: Feb. 2019. [Online]. Available: http://safecity.nl/

[10] K. David, D. Dixit, and N. Jefferies, "2020 vision," *IEEE Veh. Technol. Mag.*, vol. 5, no. 3, pp. 22–29, Sep. 2010.

[11] "Cisco visual networking index: Global mobile data traffic forecast update, 2016–2021," Cisco, San Jose, CA, USA, White Paper. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[12] G. Fettweis and S. Alamouti, "5G: Personal mobile Internet beyond what cellular did to telephony," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 140–145, Feb. 2014.

[13] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1801–1819, 4th Quart., 2014.

[14] N.-S. Vo, T. Q. Duong, H. D. Tuan, and A. Kortun, "Optimal video streaming in dense 5G networks with D2D communications," *IEEE Access*, vol. 6, pp. 209–223, 2018.

[15] G. Fodor, S. Parkvall, S. Sorrentino, P. Wallentin, Q. Lu, and N. Brahmi, "Device-to-device communications for national security and public safety," *IEEE Access*, vol. 2, pp. 1510–1520, Dec. 2014.

[16] Z. Kaleem, N. N. Qadri, T. Q. Duong, and G. K. Karagiannidis, "Energy-efficient device discovery in D2D cellular networks for public safety scenario," *IEEE Syst. J.*, to be published.

[17] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[18] T. X. Doan, T. M. Hoang, T. Q. Duong, and H. Q. Ngo, "Energy harvesting-based D2D communications in the presence of interference and ambient RF sources," *IEEE Access*, vol. 5, pp. 5224–5234, 2017.

[19] Y. Liu, L. Wang, S. A. R. Zaidi, M. Elkashlan, and T. Q. Duong, "Secure D2D communication in large-scale cognitive cellular networks: A wireless power transfer model," *IEEE Trans. Commun.*, vol. 64, no. 1, pp. 329–342, Jan. 2016.

[20] Z. Sheng, H. D. Tuan, T. Q. Duong, H. V. Poor, and Y. Fang, "Low-latency multiuser two-way wireless relaying for spectral and energy efficiencies," *IEEE Trans. Signal Process.*, vol. 66, no. 16, pp. 4362–4376, Aug. 2018.

[21] Z. Sheng, H. D. Tuan, A. A. Nasir, T. Q. Duong, and H. V. Poor, "Power allocation for energy efficiency and secrecy of wireless interference networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 6, pp. 3737–3751, Jun. 2018.

[22] Z. Sheng, H. D. Tuan, T. Q. Duong, and H. V. Poor, "Joint power allocation and beamforming for energy-efficient two-way multi-relay communications," *IEEE Trans. Wireless Commun.*, vol. 16, no. 10, pp. 6660–6671, Oct. 2017.

[23] V.-D. Nguyen, T. Q. Duong, H. D. Tuan, O.-S. Shin, and H. V. Poor, "Spectral and energy efficiencies in full-duplex wireless information and power transfer," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 2220–2233, May 2017.

[24] L. D. Nguyen, H. D. Tuan, T. Q. Duong, O. A. Dobre, and H. V. Poor, "Downlink beamforming for energy-efficient heterogeneous networks with massive MIMO and small cells," *IEEE Trans. Wireless Commun.*, vol. 17, no. 5, pp. 3386–3400, May 2018.

[25] L. D. Nguyen, A. Kortun, and T. Q. Duong, "An introduction of real-time embedded optimisation programming for uav systems under disaster communication," *EAI Endorsed Trans. Ind. Netw. Intell. Syst.*, vol. 5, no. 17, pp. 1–8, Dec. 2018.

[26] S. P. Mcgrath *et al.*, "ARTEMIS: A vision for remote triage and emergency management information integration," Tech. Rep., 2003.

[27] K. Lorincz, "Sensor networks for emergency response: Challenges and opportunities," *IEEE Pervasive Comput.*, vol. 3, no. 4, pp. 16–23, Apr. 2004.

[28] R. Martí, S. Robles, A. Martín-Campillo, and J. Cucurull, "Providing early resource allocation during emergencies: The mobile triage tag," *J. Netw. Comput. Appl.*, vol. 32, no. 6, pp. 1167–1182, 2009.

[29] W. Diane. (Nov. 2007). *Tactical Medical Coordination System (TacMedCs)*. [Online]. Available: https://apps.dtic.mil/docs/citations/ADA477535

[30] A. Martín-Campillo, J. Crowcroft, E. Yoneki, R. Martí, and C. Martínez-García, "Using Haggle to create an electronic triage tag," in *Proc. 2nd Int. Workshop Mobile Opportunistic Netw. (MobiOpp)*, 2010, pp. 167–170. [Online]. Available: http://doi.acm.org/10.1145/1755743.1755775

[31] E. Nordström, P. Gunningberg, and C. Rohner, "A search-based network architecture for mobile devices," Tech. Rep., 2009.

[32] L. Pelusi, A. Passarella, and M. Conti, "Opportunistic networking: Data forwarding in disconnected mobile ad hoc networks," *IEEE Commun. Mag.*, vol. 44, no. 11, pp. 134–141, Nov. 2006.

[33] A. Martín-Campillo, J. Crowcroft, E. Yoneki, and R. Martí, "Evaluating opportunistic networks in disaster scenarios," *J. Netw. Comput. Appl.*, vol. 36, no. 2, pp. 870–880, 2013.

[34] M. Hunukumbure, T. Moulsley, A. Oyawoye, S. Vadgama, and M. Wilson, "D2D for energy efficient communications in disaster and emergency situations," in *Proc. 21st Int. Conf. Softw. Telecommun. Comput. Netw. (SoftCOM)*, Sep. 2013, pp. 1–5.

[35] K. Ali, H. X. Nguyen, P. Shah, Q. Vien, and N. Bhuvanasundaram, "Architecture for public safety network using D2D communication," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNC)*, Doha, Qatar, Apr. 2016, pp. 206–211.

[36] K. Ali, H. X. Nguyen, Q. Vien, P. Shah, and Z. Chu, "Disaster management using D2D communication with power transfer and clustering techniques," *IEEE Access*, vol. 6, pp. 14643–14654, 2018.

[37] K. Ali, H. X. Nguyen, P. Shah, and Q.-T. Vien, "Energy efficient and scalable D2D architecture design for public safety network," in *Proc. Int. Conf. Adv. Commun. Syst. Inf. Secur. (ACOSIS)*, Oct. 2016, pp. 1–6.

[38] H. Ghavami and S. S. Moghaddam, "Outage probability of device to device communications underlaying cellular network in Suzuki fading channel," *IEEE Commun. Lett.*, vol. 21, no. 5, pp. 1203–1206, May 2017.

[39] H. Suzuki, "A statistical model for urban radio propogation," *IEEE Trans. Commun.*, vol. 25, no. 7, pp. 673–680, Jul. 1977.

[40] P. Tseng, "Convergence of a block coordinate descent method for non-differentiable minimization," *J. Optim. Theory Appl.*, vol. 109, no. 3, pp. 475–494, 2001. doi: 10.1023/A:1017501703105.

[41] L. D. Nguyen, H. D. Tuan, T. Q. Duong, and H. V. Poor, "Beamforming and power allocation for energy-efficient massive MIMO," in *Proc. 22nd Int. Conf. Digit. Signal Process. (DSP)*, Aug. 2017, pp. 1–5.

[42] W. Dinkelbach, "On nonlinear fractional programming," *Manage. Sci.*, vol. 13, no. 7, pp. 492–498, Mar. 1967. [Online]. Available: http://www.jstor.org/stable/2627691

[43] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. IEEE Int. Conf. Neural Netw.*, vol. 4, Nov. 1995, pp. 1942–1948.

[44] D. Bratton and J. Kennedy, "Defining a standard for particle swarm optimization," in *Proc. IEEE Swarm Intell. Symp.*, Apr. 2007, pp. 120–127.

[45] P. Kuila and P. K. Jana, "Energy efficient clustering and routing algorithms for wireless sensor networks: Particle swarm optimization approach," *Eng. Appl. Artif. Intell.*, vol. 33, pp. 127–140, Aug. 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0952197614000852

[46] N. C. Sahoo, S. Ganguly, and D. Das, "Simple heuristics-based selection of guides for multi-objective PSO with an application to electrical distribution system planning," *Eng. Appl. Artif. Intell.*, vol. 24, no. 4, pp. 567–585, 2011.

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