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A Socio-physical and Mobility-Aware Coalition Formation Mechanism in Public Safety Networks

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Abstract

In this paper, the problem of socio-physical and mobility-aware coalition formation among the trapped users and the first responders in public safety networks is addressed towards guaranteeing users' connectivity, stability, and energy-efficient communication. Each user is associated with some social, physical and mobility-related characteristics and attributes in a public safety network. Users' social attributes mainly refer to the communication interests with the neighbors based on their profiles and objectives, while their physical characteristics are the energy availability, the energy consumption rate and the average received signal strength from the neighbors for each user. The profile of each user is completed by a mobility pattern that characterizes the moving behavior of the specific user. Those types of characteristics are considered to constitute a weighted profile for each user, based on which the coalition-head selection and the coalition formation processes are performed in a distributed manner with reduced information exchange among the users. As the time evolves, given users' mobility, the conditions in the public safety network change dynamically, thus a coalitions' remedy methodology is introduced. Finally, the performance of the proposed approach is evaluated via modeling and simulation and its superiority compared to other existing approaches in the literature is illustrated.

Keywords: Socio-physical characteristics; mobility; public safety networks; coalition formation; energy efficiency.

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1. Introduction

Public Safety Networks (PSNs) have emerged as the key solution to a successful response to emergency and disaster events, such as acts of terrorism, natural disasters, and technological accidents. PSNs support the wireless communication in the field of operations among the first responders and the trapped users, within the affected geographical area in the case of tactical and emergency scenarios [1]. Traditionally, PSNs have relied on the TETRA or APCO systems [1], which provide high-quality voice services, with the drawback of low data rate comparable to the 2G networks [2]. Nowadays, the improved mobile devices' capabilities raise the demand of sharing multimedia content to facilitate more efficient rescuing operations, thus broadband communication in PSNs arises more as a requirement rather than as a desire. Towards this direction, the Third Generation Partnership Project (3GPP) has considered the Long-Term Evolution (LTE) to support and facilitate the broadband services in PSNs [3]. However, the communication infrastructure is often damaged during the occurrence of a disaster event, thus 3GPP also envisions Device-to-Device (D2D) mode of communication as the key driver in emergency situations [4].

1.1 Related Work

In [5], [6], the authors introduce an architecture utilizing the relay assisted transmission in PSNs using D2D communication to enhance the capacity and power saving of the network. In [7], the authors discuss the main technical challenges and solution approaches in order D2D communication to meet the PSNs' requirements. The idea of mobile infrastructure is introduced in [8], where moving small cells are deployed in areas where no network coverage is available or the network's infrastructure is completely or partially destroyed. The authors' goal is to provide network services to out-of-coverage users by creating connections with neighboring in-coverage cells, which will act as relays. A similar philosophy is followed in [9], where the authors consider the Cells on Wheels, which are strategically placed in a damaged area to support coverage and capacity demands. The idea of mobile infrastructure is also considered in [10], where the Aerial evolved Node BS (AeNBS) is introduced, towards dealing with the coverage and capacity issues that arise in a damaged area. The specific problem addressed in [10], refers to the radio link failure and the handover completion under the deployment of AeNBS.

Though the aforementioned research works have reported and confirmed significant results in improving the coverage and the capacity in PSNs, still a dynamic and resilient operations environment and framework are missing, that properly and effectively supports the communication among the various involved teams, e.g., first responders' and trapped users, in a public safety network. Our work aims at exactly dealing with these challenging issue, and filling the corresponding gap in the literature.

1.2 Paper Contributions

In this paper, it is the first time in the PSNs' literature to the best of our knowledge, that a socio-physical and mobility-aware coalition formation mechanism for supporting D2D communications in PSNs is proposed. Specifically, the users of a public safety network create collaborative unions/partnerships based both on their physical and social characteristics to improve their connectivity and energy-efficient communication. Towards efficiently creating the coalitions among the users, their mobility patterns are considered as well. For example, in a disaster scenario, the trapped users try to escape from the damaged area, while the first responders move closer to the damaged area to provide help and facilitate the evacuation. Users with similar mobility pattern have higher chances to belong to the same coalition and establish a stable communication over the time, while they ultimately aim at the same objective. Furthermore, their energy availability, as well as their energy consumption rate are adopted as parameters in the coalition formation process, so as to allow the devices/users with improved energy potential to act as relay/coalition-head for the rest of the users within the coalition, therefore supporting a collaborative and long-lasting communication environment. Physical characteristics of the users are captured via their physical positions and their communication channel gain conditions. The notion of communication interest [11], [12] among the users is also adopted to create homogeneous coalitions, where the users have common interests and goals, as they are presented either by their social associations or the common operation objective.

The joint consideration of the aforementioned physical and social parameters and characteristics, facilitate the creation and operation of a novel efficient communication paradigm in public safety networks. The latter is driven by the proposal and definition of a distributed framework for the creation of coalitions among the users. Based on weighted combinations of the aforementioned parameters and through the definition of appropriate operational conditions, the coalition-heads are selected, while the membership of each user to a specific coalition is determined. In order to treat the dynamic nature and continuously changing communication environment, under the scenarios considered within a PSN, specific maintenance operations are devised. These refer either to the coalition remedy in cases of small-scale changes in users' physical characteristics or in more drastic actions that would drive the coalition release and recreation. Given the distributed nature of the proposed approach, this framework enables the realization of autonomic user-centric management under physical disasters and emergency situations. Finally, detailed numerical results are provided that demonstrate the performance and operational effectiveness and efficiency of the proposed framework, along with its flexibility and adaptability under various scenarios.

1.3 Outline

The outline of the paper is as follows. Section 2 elaborates on the details of the adopted system model. In Section 3, the socio-physical and mobility-aware characteristics and properties of the users are presented, towards explaining the criteria of the coalition formation among them. In Section 4, the operation details of the introduced coalition-head selection process and coalition formation framework are discussed in detail. Additionally, the coalitions' remedy policy is presented and the conditions for releasing the coalitions and recreating them as the system evolves are highlighted. The performance of the proposed framework is evaluated through modeling and simulation in Section 5. Finally, Section 6 concludes the paper.

2. System Model

We consider a Long-Term Evolution (LTE) based PSN consisting of several mobile users as well as by an evolved NB (eNB). The set of users is denoted by $U = \{1,...,\mathrm{u},...,|\mathrm{U}|\}$. The eNB serves and covers a specific region $\Re$, as presented in Fig. 1, where the users reside. We consider that the users have different profiles within the PSN, e.g., elderly trapped people, adult trapped people and first responders. Without loss of generality and for presentation purposes only, let us consider in the following three different users' profiles within the examined PSN, namely A, B, C. Thus, each user u is characterized by her profile, e.g., u_A, u_B, u_C, which contributes to the coalition formation process, as it is explained later in Sections 3 and 4.

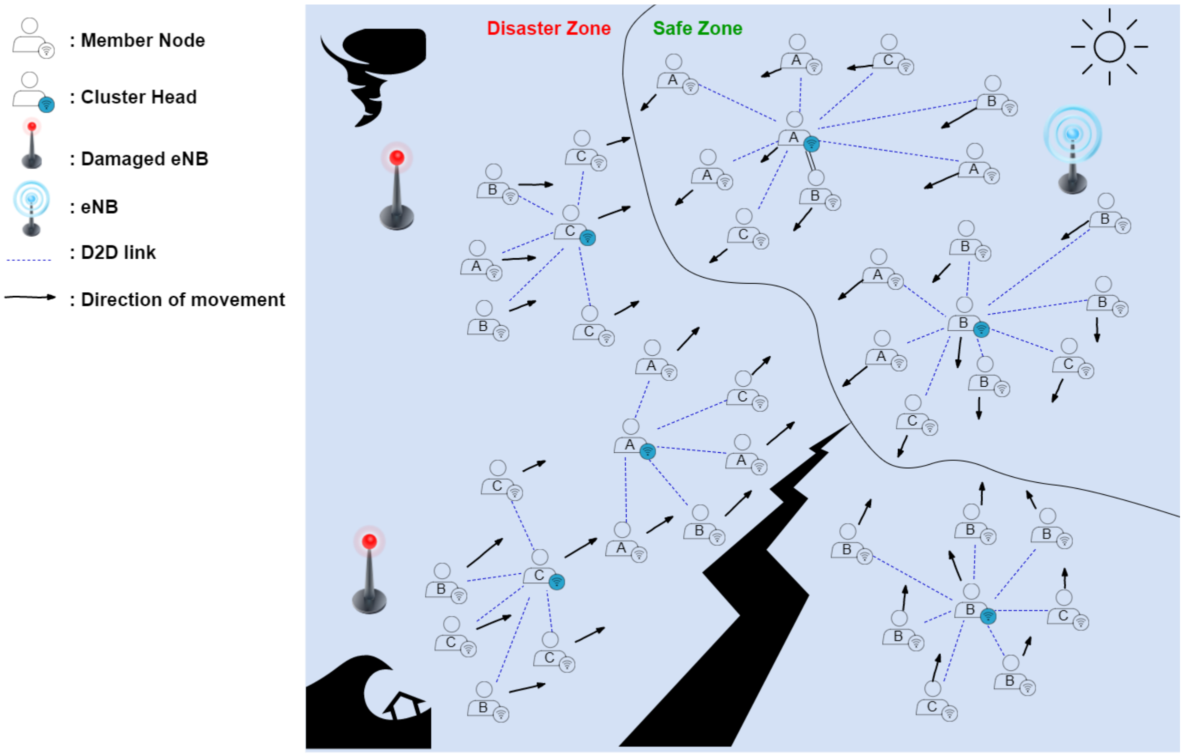


Figure 1. Public Safety Network topology

Furthermore, the mobile device of each user is characterized by its energy availability $E_u, \forall u \in U$ and its energy consumption rate R_u.

Each user is assumed to be characterized by a mobility pattern within the PSN, mainly represented by the moving direction, i.e., angle, $\varphi_u, 0 \le \varphi_u \le 2\pi$, with the horizontal axis in a two dimensions area, as presented in Fig. 1. Though different speeds may be considered, in the following for simplicity and without loss of generality, same speed is assumed for all users and therefore their actual positions at the next time slot are determined based on their current position and the moving direction, which in the rest of this paper will be referred as mobility pattern. Towards improving the energy-efficiency of trapped users' and first responders' communication, prolonging the battery life of their mobile devices (which is crucial under the circumstances of emergency situations) and enabling the collaboration among them, the concept of coalition formation among the users is introduced. The users are assumed to create $|C|$ coalitions among each other, and the corresponding set of coalitions is denoted by $C = \{1, ..., c, ..., |C|\}$. For each coalition c, a coalition-head $ch_c, ch_c \in U$ is selected and being responsible to collect the data from its coalition-members $|U_c|, |U_c| \le |U|$ while eventually forwarding this information to the eNB for further processing and dissemination. An orthogonal multiple access (OMA) technique is adopted for users' transmission, e.g., OFDMA, thus the only existing interference to the users' transmission stems from the thermal noise components and the users' control signals, which is treated as Additive White Gaussian Noise (AWGN) process, with constant power density. In Table 1, the key notation used throughout this paper is presented.

3. Socio-physical and Mobility Characteristics

In this section, a detailed analysis of the socio-physical and mobility characteristics of the PSN users is provided. These characteristics will be considered later in Section 4 to create the coalitions and select the coalition-head. In a nutshell, each user within the PSN is characterized by the following parameters and attributes: 1) relative direction $RD_{u,u'}, u, u' \in U$, 2) number of neighbors within user's $u, u \in U$ transmission range N_u, 3) energy availability E_u, 4) energy consumption rate R_u, 5) average received signal strength $\bar{P}_{rec,u}$ from user's u N_u neighbors and 6) interest ties $i_{u,u'}, u, u' \in U$ of user u with each one of her neighbors N_u. In the following, we discuss users' socio-physical and mobility characteristics in more detail.

Table 1. Notation

U	Set of users
$\lvert U \rvert$	Number of users
E_u	Energy availability of user *u*
R_u	Energy consumption rate of user *u*
φ_u	Moving direction of user *u*
C	Set of coalitions
$\lvert C \rvert$	Number of coalitions
ch_c	Coalition-head of coalition *c*
$\lvert U_c \rvert$	Number of coalition members of coalition *c*
$RD_{u,u'}$	Relative direction among user *u* and *u´*
N_u	Number of neighbors within user's *u* transmission range
$\bar{P}_{rec,u}$	Average received signal strength at user *u*
$i_{u,u'}$	Interest tie among user *u* and *u´*
RD_{thr}	Relative direction threshold
$AgRD_u$	Aggregate relative direction of user *u*
$P_{u,u'}$	Received power at the user *u* from user *u´*
$P_{tran,u'}$	Transmission power of user *u´*
G_u	Antenna gain of user's *u* device
$d_{u,u'}$	Distance among user *u* and *u´*

3.1 Relative Direction

As discussed in Section 2 each user is characterized by her mobility pattern, i.e., φ_u. Users with similar mobility pattern may have the same goal within the PSN, e.g., the trapped users' mobility direction is to move away from the damaged area after a physical disaster or a terrorists' attack has happened. Therefore, based on user's mobility pattern $\varphi_u, \forall u \in U$, the relative direction between two users is defined, as follows.

$$RD_{u,u'} = |\varphi_u - {}_{u'}|, \forall u, u' \in U \quad (1)$$

3.2 Neighbour Discovery and Identification

Based on users' relative direction, i.e., $RD_{u,u'}, u, u' \in U$, each user determines the number of neighbors with similar mobility pattern, among the ones that are within transmission/communication range. Therefore, a threshold RD_{thr} is introduced towards determining the number of neighbors N_u of user u, as follows.

$$RD_{u,u'} \leq RD_{thr}, \forall u, u' \in U \quad (2)$$

Based on the number of neighbors, each user determines the aggregate relative directions $AgRD_u$ among the entire set of relative directions values $RD_{u,u'}$ of her neighbors N_u by calculating the variance with respect to zero, i.e., var_0.

$$AgRD_u = \mathrm{var}_0\left(RD_{u,1}, ..., RD_{u,u}, ..., RD_{u,N_u}\right) = E\left[\left(RD_{u,u'}\right)^2\right] \quad (3)$$

The main rationale behind calculating the variance of the relative directions values with respect to each user's $u, u \in U$ neighbours N_u is that a low value of relative direction $RD_{u,u'}, u, u' \in U$ indicates that user u tends to diverge relatively less from her neighbours. On the contrary, a high value of $RD_{u,u'}$ indicates that user u moves away (has a different mobility pattern) from her neighbours. At this point, it should be noted that users with low variance in relative directions with respect to her neighbours are favoured in becoming coalition-heads, due to the fact that they present a stable behaviour, in terms of mobility, with respect to their neighbours.

3.3 Energy Availability and Consumption Rate

As mentioned before, each user's device is battery-enabled and characterized by a corresponding energy availability, i.e., E_u. The energy availability of all users $|U|$ in the examined PSN is normalized, thus $E_u \in [0,1]$. A value E_u close to one indicates high energy availability of user's device, while a value of E_u close to zero indicates low availability. Furthermore, each user device is characterized by a different energy consumption rate R_u based on its technical characteristics, operation mode and personalized user's usage (e.g., multiple applications running in parallel). The energy consumption rate of users' devices is normalized, thus in principle $R_u \in [0,1]$, where values close to one represent increased energy consumption rate.

3.4 Average Received Signal Strength

Each user receives the signal from her neighbors N_u, while the average received signal strength is defined as follows.

$$\bar{P}_{rec,u} = \frac{\sum_{u'=1}^{N_u} P_{u,u'}}{N_u} \quad (4)$$

where $P_{u,u'}$ is the received power at the user u when the user u' transmits with power $P_{tran,u'}$. Based on Friis formula, we have $P_{u,u'} = P_{tran\,u'} G_u G_{u'} \left(\frac{\lambda}{4\pi d_{u,u'}}\right)^2$, where $G_u, G_{u'}$ are the antenna gains of users' u, u' devices, λ is the wavelength and $d_{u,u'}$ is the distance between the user u

and u'. It is noted that the user with increased average received signal strength is favored in becoming a coalition-head, due to her improved communication conditions with her neighbors.

3.5 Interest Ties

In the proposed framework, the interest ties measure the strength of the relation among the users, who may have different profiles in the PSN. Based on users' interest to communicate with each other, the metric of interest tie $i_{u,u'}$, between u,u' users is introduced. It is noted that $i_{u,u'} \in [0,1]$ where the values close to one indicate high communication interest.

4. Coalitions Formation

In this section, the coalition-head selection and the coalitions formation processes are described. As part of the overall coalition creation and maintenance process, the coalitions' remedy policy due to the dynamic changes of the environment is defined, while the conditions for the coalitions' release and recreation are discussed.

4.1 Coalition-Head Selection

Initially, all the users that do not already participate in a coalition (i.e., "not connected" status), broadcast a *hello message* including their identification information, i.e., $ID = u$, their direction, i.e., φ_u, and their profile p, e.g., A, B, C, as follows.

$$Hello\ Message = \{u, \varphi_u, p\} \quad (5)$$

Then, all users are able to determine the number of their neighbors, i.e., N_u. This includes all users being within the transmission range $d_{range,u}$ of the user u under consideration and simultaneously satisfying condition (2). Subsequently, each user determines the aggregate relative direction $AgRD_u$ and the average received signal strength $\bar{P}_{rec,u}$ while creating her interests vector with her N_u neighbors $\boldsymbol{i_u} = \lfloor i_{u,1}, ..., i_{u,N_u}$. To share this information with her neighbors each user broadcasts an information message containing the following information.

$$Information\ Message = \{u, AgRD_u, E_u, R_u, \bar{P}_{rec,u}, \boldsymbol{i_u}\} \quad (6)$$

Based on that information message, each user u determines a weight for herself and for each one of her neighbors (i.e., N_u), as follows.

$$w_u = a_{AgRD} AgRD_u + a_E (1 - E_u) + a_R R_u + a_{\bar{P}_{rec}} \frac{\bar{d}_u}{d_{range,u}} \quad (7)$$

where $\bar{d}_u = \frac{\sum_{u'=1}^{N_u} d_{u,u'}}{N_u}$, $a_{AgRD}, a_E, a_R, a_{\bar{P}_{rec}} \in [0,1]$ and $a_{AgRD} + a_E + a_R + a_{\bar{P}_{rec}} = 1$. Then, the coalition-head ch_c of the coalition c is the mobile user with the minimum weight w_u, i.e., $ch_c = \underset{\in U' = \{1,...,|U_c|\}}{\arg\min}\ w_u$. It is noted that the coalition-head is determined in a distributed manner, i.e., each user is able to decide if she is a coalition-head given the broadcasted information message (6) and announce her role to her N_u neighbors. Thus, no centralized coordination is needed for the coalition-head selection process.

4.2 Coalitions Formation

After the identification of the candidate coalition-heads within the PSN, the distribution of the members to the coalition-heads is determined. Towards this direction a new metric ω_{u,ch_c} is introduced which considers the interest ties and mobility relation of the coalition-heads and the potential coalition-members, as follows.

$$\omega_{u,ch_c} = w_{RD} \frac{RD_{u,ch_c}}{RD_{thr}} + w_i \left(1 - i_{u\ ch_c}\right) \quad (8)$$

where $w_{RD}, w_i \in [0,1]$ and $w_{RD} + w_i = 1$. Each user may have multiple coalition-heads within her neighbor users N_u. Thus, the user selects to connect to the coalition-head that has the minimum weight ω_{u,ch_c}. Given that the user determines the coalition-head who she wants to be associated with, she sends a connection request. On the other side, each coalition-head collects all the connection requests from the potential coalition-members, sorts their ω_{u,ch_c} values in decreasing order and keeps the top $|U_c|$ coalition-members. The coalition-head ch_c along with the coalition-members $|U_c|$ create the coalition c. The reason for allowing only $|U_c|$ users to participate in the coalition stems from the need of having coalitions with a balanced number of members, so as not to overload with a transmission overhead the coalition-head. Please note that $|U_c|$ can be a predefined configurable parameter that could potentially control and impact the maximum size of each coalition. The users that were not accepted by the coalition-head that they had selected to be connected to, select the next in their list of potential coalition-head to pair with. If a user is not accepted by any coalition-head, then she becomes a coalition-head by herself.

4.3 Coalitions Remedy, Release, and Recreation

After the coalition-head selection and the coalitions formation processes are realized, the coalition-members send their information to the coalition-head, who forwards them to the eNB. Given users' mobility, a user may lose her connectivity with the coalition-head as the time evolves, i.e., the latter does not belong anymore to the neighbors N_u of user u. In that scenario, the user turns her status to "not connected" and a coalition's remedy action should be performed. Specifically, the user that is in the "not connected" status, searches for a new coalition-head to get connected to, from the available coalition-heads in her neighbors N_u. Thus, the process described in Section 4.2 is repeated for this user. However, as time evolves, the coalitions remedy process discussed above may not solve the problem of users that lose their connectivity with their coalition-heads, thus many users may remain "not connected" to any coalition-head, driving the overall system to inefficient stages. Therefore, specific conditions in order to decide the coalitions' release and recreation should be defined.

Condition 1: If the number of the initially connected users $|U_c|^{(t)}$ to the coalition-head coalition c at time slot t is less than $|U_c|^{(0)} \cdot x\%$, then release the coalition.

It is noted that the condition 1 considers the specific ID of the initially connected users to the ch_c and not only their absolute number. Also, the time slot that the coalitions were created is considered as $t = 0$.

Condition 2: If the energy availability $E_{ch_c}^{(t)}$ of the coalition-head ch_c at time slot t is less than $E_{ch_c}^{(0)} \cdot y\%$, then release the coalition.

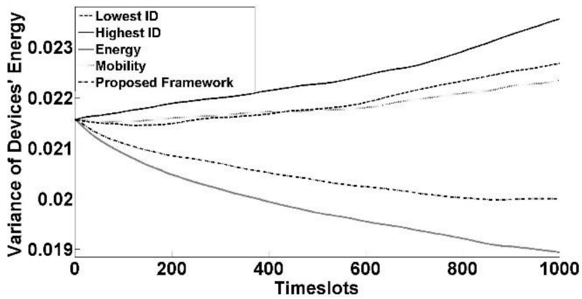
Please note that factors x and y can be arbitrarily chosen based on experimentation and specific application scenario requirements, and do not affect the functional characteristics of the introduced framework. The energy availability of each user as the time evolves is determined based on her energy consumption rate, i.e., $E_u^{( )} = E_u^{(t-1)} - t \cdot R_u$. If any of the conditions 1 and 2 hold true for at least one coalition in the PSN, the coalitions are released and recreated following the analysis in Sections 4.1 and 4.2.

5. Numerical Results

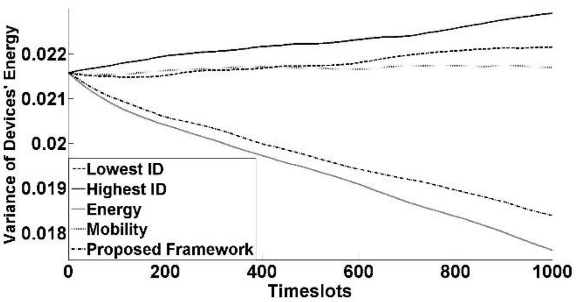
In this section, a detailed numerical evaluation of the proposed framework is conducted through modeling and simulation, in terms of operation and performance effectiveness and efficiency. For our simulations, we considered a wireless public safety network consisting of $|U|$ mobile users (their number is differentiated per each examined use case scenario). The $|U|$ users are randomly distributed within an 8000m x 8000m area, while the eNB is chosen to reside at a location close to the edge of that area. The duration of each timeslot is *t=0.5msec* and users' direction φ_u ranges from 0 rad to 6.2 rad (360 degrees). The relative direction threshold is assumed $RD_{thr} = 90°$. The initial normalized energy availability E_u of each user falls is the range [0.5,1], unless otherwise explicitly stated. Also, for demonstration purposes, we consider that $|U_c| = 15$, $a_{AgRD} = 0.33$, $a_E = 0.33$, $a_R = 0.33$, $a_{\bar{P}_{rec}} = 0.33$, $w_{RD} = 0.5$, $w_i = 0.5$. Also, we consider *x*=80% and *y*=40% for the conditions of the coalitions' release. In order to provide realistic results for a PSN, we consider that the $|U|$ users are randomly assigned to three different profiles, i.e., A, B, C. We assume that the users of the same profile have high communication interest among each other, e.g., $i_{u,u'} = 0.9$, while regarding inter-profile interests (i.e. users with different profiles), we assume low communication interest, e.g., $i_{u,u'} = 0.3$.

Furthermore, in order to quantify the coalitions formation importance in a PSN, and provide an in-depth evaluation, we compare five different clusters/coalitions formation mechanisms. Specifically, we consider two conventional clustering schemes existing in the literature, that is: a) Lowest ID and b) Highest ID, and three different variations of our proposed framework detailed below. Highest-ID and Lowest-ID clustering schemes both utilize the unique ID of each node of the network to assign the role of the cluster head in each area of the simulated environment. This unique ID is interpreted as an integer number. Highest-ID and Lowest-ID clustering refer to the selection of the node of the network with the highest and lowest id value respectively to assume the role of the cluster-head [13], [14]. With reference to our introduced framework the following variations are evaluated and compared: a) Proposed Framework: This refers to the implementation and application of the complete proposed coalition formation mechanism, where the mobility relation and the communication interest among users are equally considered, i.e., $w_{RD} = w_i = 0.5$, b) Energy: This variation is based on the proposed framework stripped however of any mobility aware mechanism, and c) Mobility: This variation is also based on the proposed paradigm but it is relieved of any energy aware element. It is noted that the two latter clustering algorithms are considered to illustrate the comparison between the proposed framework and the two approaches solely based on energy or mobility. The goal is to provide evidence that, even if each of these variations performs well in its own field, the proposed framework appears to be a well-balanced solution that assimilates the benefits of both.

Fig. 2(a) and Fig. 2(b) illustrate the variance of the devices' energy as the time evolves, i.e., for 1,000 consecutive timeslots, considering the five comparative clusters/coalitions formation approaches mentioned above. For the simulation, a set of 400 devices has been considered, i.e., $|U| = 400$. Specifically, in Fig. 2(a) it is considered that the devices' energy consumption rate R_u ranges from 0.7 to 1, while in Fig. 2(b) from 0.9 to 1. The results reveal that the difference in the available energy distribution of the devices increases in Lowest ID, Highest ID, and Mobility frameworks, while decreases in the proposed framework and the Energy-based clustering algorithm, as the time evolves. This observation essentially shows that the proposed framework and the Energy-based clustering algorithm lead to more balanced states where similar energy availability among the devices is maintained. On the other hand, the Lowest ID, Highest ID and the Mobility-based clustering algorithms lead to some devices overspending energy, while other underspending, therefore having uneven and unfair energy consumption. In the latter case, some devices will run out of battery well before others. In contrast, in the proposed framework and the Energy-based clustering algorithm, the lifetime of the network increases, i.e., the first devices will run out of battery at a later time compared to the three other comparative algorithms. This observation is also explicitly confirmed by the corresponding results provided later in Fig. 4. Furthermore, it is worthwhile noting that the proposed framework achieves similar results to the Energy-based clustering since both are characterized by a decreasing curve of the variance of the devices' energy while their differences are of the 10^{-3} order of magnitude. Moreover, the differences among the five comparative scenarios are greater in the results presented in Fig. 2(a) compared to the ones in Fig. 2(b), due to the fact that in the latter all the devices are characterized by almost the same rate of energy consumption, i.e., $R_u \in [0.9,1]$, thus the overall network shows an energy stability. In contrast, the results presented in Fig. 2(b), consider greater differences among the devices' rate of energy consumption, i.e., $R_u \in [0.7,1]$, thus a priori the devices have more unbalanced energy consumption compared to Fig. 2(b).



(a)



(b)

Figure 2. Variance of the devices' energy as a function of the timeslots

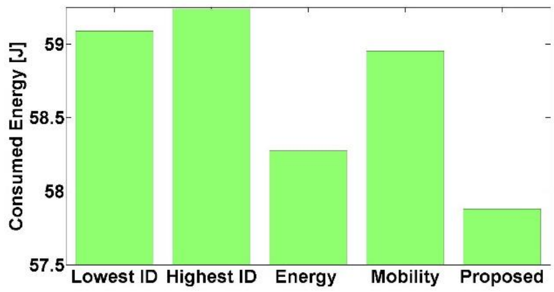


Figure 3. Total energy consumption for all the comparative frameworks

Fig. 3 depicts the total energy consumption of the devices (for demonstration purposes we considered $|U| = 300$) considering the five comparative frameworks. We run our simulations over 1000 timeslots, so as to get representative results. The results reveal that the Lowest ID and the Highest ID clustering algorithms achieve similar devices' energy consumption, due to the fact that they adopt a similar philosophy in the cluster formation process. Also, those two algorithms lead the devices to overspend their available energy given that they do not consider the mobility and energy characteristics of the devices while formulating the clusters/coalitions and selecting the cluster-head. The Mobility-based clustering algorithm achieves lower energy consumption compared to the two previous frameworks, given that it considers the mobility characteristics of the users/devices to form the coalitions. The Energy-based clustering algorithm performs better compared to the three aforementioned algorithms regarding the devices' energy consumption, due to the fact that the energy characteristic of the devices is the key factor to form the clusters over the time. The main benefit of the proposed framework is that it combines the benefits of the Energy and Mobility-based clustering algorithms via considering both the devices' energy and mobility characteristics, thus it achieves the lowest total energy consumption compared to all the comparative frameworks, as the time evolves. However, it is noted that the difference in the consumed energy between the proposed framework and the energy-based clustering algorithm is relatively small, because the main energy savings stem from the consideration of the devices' energy characteristics in the clustering algorithm, while the consideration of the mobility characteristics provides an additional slight benefit as the system evolves, by providing more coherent coalitions.

Fig. 4 presents the number of devices that run out of battery as the time evolves for all the comparative scenarios. The total number of the considered devices/users in the public safety network is $|U| = 400$, and the simulations run for 1000 timeslots. Based on the previous discussion, the Lowest ID, Highest ID and Mobility-based clustering algorithms lead the devices to fast energy drain, thus the number of devices that run out of battery increases more rapidly compared to the Energy-based clustering mechanism and the proposed framework. On the other hand, the two latter approaches present similar behavior

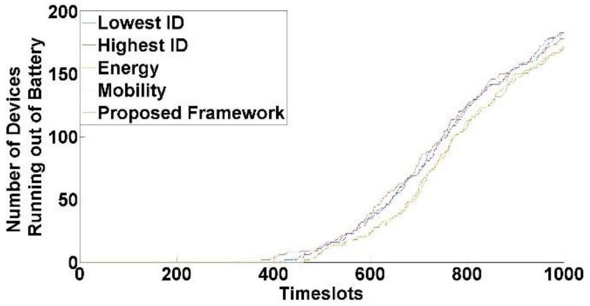


Figure 4. Number of devices running out of battery vs. timeslots

with respect to the number of devices that run out of battery, given that the absolute difference in total consumed energy over the time is not large, as presented in Fig. 3. However, it is noted that the proposed framework achieves to prolong the battery-life of the public safety network and guarantee the connectivity of the devices for a longer time period.

Following the previous analysis, Fig. 5 presents the average cluster/coalition lifetime measured in timeslots as a function of the number of the users/devices in the examined public safety network. It is noted that the clusters are mainly recreated due to the great mobility of the users and less due to their energy characteristics which change more slowly over the time compared to the users' mobility characteristics. Thus, the clustering algorithms that do not consider users' mobility characteristics (i.e., Lowest ID, Highest ID and Energy-based clustering algorithm) to build the coalitions, conclude to recreate the clusters more often. In contrast, the Mobility-based clustering algorithm achieves the best results in terms of increasing the average cluster lifetime given that it creates the clusters solely based on the devices' mobility characteristics. The proposed framework achieves similar benefits and results very close to the Mobility-based mechanism due to the fact that it jointly considers devices' mobility and energy characteristics in order to build the coalitions and select the coalition-head.

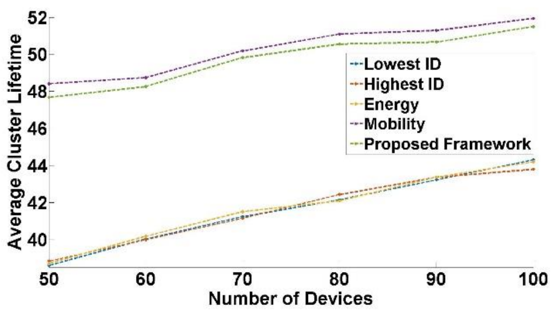


Figure 5. Average cluster lifetime as a function of the PSN size (number of users/devices)

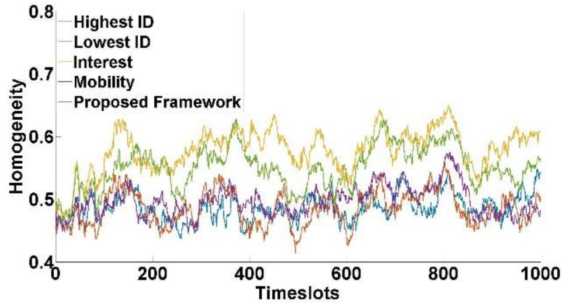


Figure 6. Average coalition's homogeneity vs. timeslots

In the last part of the provided evaluation analysis, we compare the homogeneity of the created coalitions under five different comparative scenarios. The metric of homogeneity is defined as the average value of all the devices' interest of communication with the corresponding coalition-head considering all the available coalitions in the public safety network. The difference of the examined algorithmic procedures, i.e., comparative scenarios, lies on the way the coalition-heads select the coalition members. On the Lowest ID and the Highest ID approaches, the coalition-head selects the devices with the lowest or highest IDs respectively to join its coalition. The algorithm labeled Interest, makes only use of the interest of communication in the same process (see equation (8)), while the Mobility labeled one utilizes only the direction of users'/devices' movement. The two latter variations are simply realized by zeroing out the appropriate weights, i.e., w_{RD} and w_i, in the coalition formation process, i.e., equation (8). The results reveal that the Lowest ID, Highest ID, and Mobility approaches do not succeed to form homogeneous collations, where the users have mutual interest to communicate with their coalition-head, who in an emergency event of public safety networks will lead the coalition from the communication process perspective. On the other hand, the Interest algorithm and the proposed framework achieve higher and similar with each other coalitions' homogeneity as the time evolves, due to the fact that they both consider users' interest ties while creating the coalitions.

6. Conclusions

From a communications network perspective, public safety networks refer to a wireless network used by emergency services. To goals of the critical missions at hand, are better served by the development of context-aware communications networks which facilitate reconfiguration, resilience, and efficient and effective adaptability to the continuously dynamic environment and operational conditions. In this paper, the problem of socio-physical and mobility-aware coalition formation among the users in a public safety network is addressed. The goal of creating the coalitions is to guarantee users' connectivity, stability, and energy-efficient communication. Each user is characterized by some social, physical and mobility characteristics. The social characteristics are expressed via the communication interest among the users, who have different profiles, e.g., elderly trapped people, first responders, etc. The physical characteristics include users' energy availability, consumption rate and the average received signal strength. The mobility characteristics refer to users' mobility pattern, i.e., moving direction. Those characteristics are utilized to build each user's weighted profile, which is further used to perform the coalition formation and coalition-head selection processes. The latter are of distributed nature with reduced necessary exchanged information among the users. Also, the appropriate methodology is introduced regarding the coalition remedy, release, and recreation. Extended evaluation and comparative analysis are performed towards illustrating the main benefits of the proposed framework in terms of energy saving, prolonging users' devices battery-life, the stability of the created coalitions and scalability of the proposed framework.

Part of our current and future work is the consideration of multiple available wireless network protocols, e.g., BLE, RFID, cellular LTE, etc., in a public safety network. A reinforcement learning technique will enable the trapped users to select the most beneficial wireless network protocol in terms of connectivity and energy-efficiency. Finally, the study and capturing of the behavior of the users of a PSN into Quality of Experience functions towards representing their behavior in terms of gain seeking or risk-averse behavior under various emergency events, e.g., natural disaster, terrorist attacks, etc, is of high research and practical importance.

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