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Original citation:
Rahman, MDA, Asyhari, AT, Azad, S, Hasan, MDM, Munaiseche, CPC & Krisnanda, M 2019, 'A cyber-enabled mission-critical system for post-flood response: Exploiting TV white space as network backhaul links', IEEE Access, vol. 7, 2927247, pp. 100318-100331.
https://dx.doi.org/10.1109/ACCESS.2019.2927247

DOI 10.1109/ACCESS.2019.2927247
ISSN 2169-3536

Publisher: IEEE

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 27, 2019, accepted June 11, 2019, date of publication July 8, 2019, date of current version August 8, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2927247

A Cyber-Enabled Mission-Critical System for Post-Flood Response: Exploiting TV White Space as Network Backhaul Links

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The work of M. A. Rahman and A. T. Asyhari has been supported in part by the Malaysian Ministry of Higher Education–Fundamental Research Grant Scheme (FRGS) grant no. RDU190165. A. T. Asyhari also acknowledges support from EPSRC under Global Challenge Research Fund for the project ''RHENIUM''. A preliminary version of this work was presented in part at the IEEE International Conference on Dependable, Autonomic and Secure Computing, Orlando, FL, 2017 [1]. We would like to acknowledge Mr. Qusay Medhat Salih for his cooperation on particularly the NS-2 simulation.

ABSTRACT A crucial problem in post-flood recovery actions is the ability to rapidly establish communication and collaboration among rescuers to conduct timely and effective search and rescue (SAR) mission given disrupted telecommunication infrastructure to support the service. Aimed at providing such proximity service (ProSe) for mission-critical data exchange in the post-flood environment, the majority of existing solutions rely heavily upon ad-hoc networking approaches, which suffer from restricted communication range and the limited scope of interaction. As an effort to broaden the ProSe coverage and expand integrated global-local information exchange in the post-flood SAR activities, this paper proposes a novel network architecture in the form of a cyber-enabled mission-critical system (CEMCS) for acquiring and communicating post-flood emergency data by exploiting TV white space spectrum as network backhaul links. The primary method of developing the proposed system builds upon a layered architecture of wireless local, regional and wide-area communications, and incorporates collaborative network components among these layers. The desirable functionalities of CEMCS are showcased through formulation and the development of an efficient global search strategy exploiting a wide range of collaboration among network agents. The simulation results demonstrate the capability of CEMCS to provide ProSe in the post-flood scenarios as reflected by reliable network performance (e.g., packet delivery ratio nearing 80%–90%) and the optimality of efficient search algorithm.

INDEX TERMS Cyber physical system, collaborative, CPS, cyber, flood management, mission-critical system, network, SAR, search and rescue, system architecture, TV white space, TVWS.

I. INTRODUCTION

The latest annual disaster statistical review [2] reports that natural hazards remain one of the major contributors to casualties in human population and destruction to community infrastructure. According to this report, flooding constitutes to one of the top shares of natural disasters with recorded events of more than one hundred and claiming more than three thousands lives worldwide in 2017. 12 killed 4731 and made 78 million people suffer. This statistics is only for 2016. Every year since 2006, the number of flood disasters have always been the biggest part of natural disasters. Collateral damage figures further emphasize unfavorable effects of flooding with approximately 55 million people being affected for the same year. Given a wide-spread of flooding occurrences and increasingly developed extreme weather cases [2], [3], a flood management and mitigation approach is critical to reduce the severe impact of flooding. Central to this approach is the emergency rescue network that is necessary to provide timely and rapid responses to the occuring disaster.

The associate editor coordinating the review of this manuscript and approving it for publication was Md. Zakirul Alam Bhuiyan.

It is generally understood that reliable efficient communications are critical in any search and rescue (SAR) activities related to the flood situations [1], [4], [5]. Various communications among the flood rescuers that combine environmental sensing and intelligent processing as well as use a variety of data-centric services can give a better situational awareness and faster response time, and accelerate emergency management. Unfortunately, establishing such Proximity Service (ProSe) [6] oriented emergency information exchange proves to be challenging for mission-critical post-flood SAR context due to the likely disruption and damage to the existing telecommunication operator's infrastructure and service.

The envisioned system to support post-flood emergency communication shall allow collaboration and offer real-time situation awareness in the absence of pre-established telecommunication infrastructure [1], [6]. Desirable fundamental characteristics include high resiliency, low cost, portability and ease of setup to adapt with the changing nature of flood scenarios and catchment areas. In addition to that, emergency rescue networks must establish fast and reliable communications for a variety of ProSe critical data, including environtmental sensing data, direct voice calls, video calls and data transfers. Most of the existing technological solutions (see, e.g., [1], [7], [8], [9]–[12]) have been developed based on ad-hoc networking approaches, which lack of extended communication range and have constrained scope of rescuers' interaction. The defficiency of long-range communication capability is seen as a major hurdle for rich interaction and collaboration to timely accomplish SAR objectives.

As a way of expanding and sustaining mission-critical ProSe in flood scenarios and addressing the issues of existing solutions, this paper proposes a cyber-enabled mission-critical system (CEMCS) as an innovative construction of collaborative wireless network architecture with three domains utilizing air, water and land networks to assist post-flood SAR operations. The system adopts a layered network architecture comprising wireless local communication (WLC), wireless regional communication (WRC) and wide area network (WAN). A key element of this architecture is the cognitive radio-oriented TV White Space (TVWS) [4], [13], [14] channels as network backhaul links. TVWS has gained interests in recent years as a new method of frequency access that drives and improves the delivery of wireless services due to low spectrum usage, excellent propagation characteristics, long-range coverage and better penetration of barriers [13]. As a result of this layered network construction, fully collaborative network components can be incorporated along the aforementioend layers to handle uncertainty of a flood disaster and its impacts. As a use case to evaluate the effectiveness of this network architecture, we formulate and develop an efficient global search strategy exploiting a wide range of collaboration among network agents. We then invoke numerical simulation to verify and validate the CEMCs network performance using evaluation metrics of packet delivery ratio, delay and overhead, and demonstrate the optimality of the resulting search teachnique.

The remaining parts of the paper are arranged as follows. We critically review related works in Section II. We then describe the overview of CEMCS along with the network model and architecture, its components, supporting technology and specific deployment for flood SAR in Section III. As a use case, we discuss formulation and development of the search algorithm to be used within CEMCS in Section IV. We validate the effectiveness of the proposed search technique in Section V and integration of CEMCS and search technique in Section VI. Finally, we outline the key contributions of this work in Section VII.

II. RELATED WORKS

Since previous decades a number of technologies utilizing wireless networks have been proposed to assist SAR activities in disaster scenarios. For example, the authors in [7] developed an Android-based prototype over ad-hoc wireless networks. This prototype provides emergency communication capability for SAR missions. Other varieties of ad-hoc network utilization have been considered in [8] where error-tolerant small topology models based on ad-hoc networks were proposed and developed for SAR missions. In the context of wireless ad-hoc networks, energy saving constitutes a crucial issue because in terms of temporal scale, reliable communications in areas affected by floods will require a long-lasting network. Another major disadvantage of such networks is coherence and signal integrity in hostile communication conditions (e.g., flood areas) because of their limited signal propagation range.

Several techniques embedding cyber-physical connectivity have been developed in the past few years for SAR activities. A cyber-physical network with sensing system has been studied in [15] for SAR operations in uncertain disaster environments. Bozkurt *et al.* [16] proposed a technique and technological platforms of cyber-enhanced working dog (CEWD) to improve the performance of SAR activities. Similarly, reference [17] presented mechanisms of real-time data distribution service (RDDS) by using a cyber physical system (CPS) in unpredictable environments, which facilitate reliable timely sensing data acquisition and transmission under dynamically-varying unpredictable CPS environments. The work in [18] focused on what is referred to as cyborg insect networks for inspection, mapping and wide region surveillance encapsulated under rubble SAR operation. A few other CPS-assisted SAR techniques have been proposed in [19], [20]. While the aforementioned works represent initiatives on using CPS to aid mission-critical rescue operation in unpredictable environments, the extent in which collaborative SAR activities exploiting three domain (3D) areas of air, ground and water appears to be limited. One of these limited efforts is given by our previous work [1] in which the system still relies on ad-hoc networking approach and has significant communication gaps among the micro networks.

In recent years unmanned aerial vehicles (UAVs) are gaining significant attention to improve the probability of fully successful SAR missions. The authors in [9] proposed a cooperative UAV model using adaptive concepts for SAR operation in an *a priori* unknown environment. In reference [10], a new technique was presented for task allocation by employing multiple vehicles during the decision-making process. More specifically, by leveraging upon a cooperative multi-vehicle system, a distributed approach for task allocation was introduced for improving the efficiency of SAR activities. A different type of cooperative SAR technique was also investigated in [11] where the authors employed micro aerial vehicles (MAVs) in urban post-disaster SAR activities and highlighted desirable functionalities of real-time mapping acquisition and interior navigation. The shortcoming of this work is mainly driven by the lack of collaboration among the rescuers and MAVs. Reference [12] described an ant colony-based optimization (ACO) method to acquire high level trajectories of a swarm of UAVs searching for a missing object at a minimal search duration. Herein the authors attempted to solve a minimum time search (MTS) problem using a variety of ACO approaches to determine nearly-optimal trajectories of the searching UAVs. A few other techniques have been proposed in [21]–[26], specifically for avalanche SAR missions. For instance, in reference [21], [22] an air-ground collaborative wireless network (AGCWN) was considered for utilization in the SHERPA project to improve the time taken for the avalanche SAR operation. For these hostile avalanche collaborative information exchanges, the design of wireless networks is primarily concerned with networking in the aerial spaces, despite establishing a few communication links to the ground.

As an attractive proposition for long-range communications, TV White Space (TVWS) spectrum [14] has recently gained research and development interests to be an aspirant in accommodating rapidly-growing demands of wireless data traffic. Due to favorable propagation attributes, the ultra-high frequency (UHF) band of TVWS communications is prospective to introduce assorted new wireless applications dependent on unlicensed dynamic spectrum access. For instance, TVWS-assisted communications is apparent in the development of urban smart grid networks (SGNs) as described in [27]–[29]. In these works, the authors employed TVWS for the purpose of establishing wireless regional area networks (WRANs), neighborhood area networks (NANs), switching system, smart metering, smart utility networks (SUNs) in the SGNs. Another development is given in reference [30] where the authors studied cognitive radio network concepts over TVWS spectrum for machine-to-machine (M2M) communications in smart metering applications. In reference [31], TVWS was investigated for a railway communication network. More specifically, the authors considered TVWS with attractive railway propagation characteristics to solve the spectrum scarcity problem.

In the context of disaster scenarios, TVWS deployment has been considered in Oxford Flood Network [4] where a portion of spectrum that is freed up by the digital switchover can be accessed to provide internet connectivity to sensors. This network architecture, however, has been designed for flood monitoring only and therefore primarily accommodated monitoring requirements. Line-of-sight (LOS) between stations is not indispensable of these frequencies, but the best channel for transmission has to be carefully selected within the ones that actually present the minimal noise at both the radio locations. The authors in [5] investigated TVWS-assisted intra-vehicular communications to manage the flow of emergency aid in the disaster-catchment areas. In this work, they only addressed wireless networks within vehicles (e.g., intra-vehicular communications) with a sole focus on assisting in transporting the aid and are therefore not fully suitable for extensive SAR activities.

Given the shortcomings of the aforementioned post-disaster SAR systems that operate based on micro-scale ad-hoc networking approaches as well as the potential of TVWS that appears underutilized in previous research, this work proposes a novel network architecture that combines a low-tier group of localized ad hoc networks and high-tier group of TVWS-assisted backbone networks for managing communications in extensive post-flood SAR operation. As detailed in Section III, the proposed network leverages upon layered architecture with divided functionalities in SAR tasks, communication hubs and control centre. This division allows for modular separation between intensive local data exchange within a local area network (LAN) and selective global mission-critical data communications among LANs as well as between LAN and control centre. The envisioned network structure aims to tackle three domains of challenges representing the ground-, water- as well as air-based communications as a result of disrupted and damaged telecommunication infrastructures in the post-flood scenarios.

III. OVERVIEW OF CEMCS

CEMCS is an alliance of three space domain (air, water, land) that collaborates to better achieve common goals and whose communications are supported by network technology. Hence, we envisage the utilization of CEMCS for a flood SAR application, intending to:

1) find and recover suffering flood victims
2) supply for primary medical aid and appliances
3) accommodate them to a safe place

In this section, we describe the wireless local communication (WLC), wireless regional communication (WRC) and wide area network (WAN) model.

A. ELEMENTS OF CEMCS NETWORK

The underlying network structure for the Flood Management and Rescue System (FMRS) that supports collaboration comprise multiple fundamental units, namely, Land Vehicle (LV), Water Vehicle (WV), Copter and Rescuer. Those units are coordinated globally via Control Center (CC) and regionally through Regional CC (RCC). Collaborative actions and synchronizations among these units would help respond quickly and effectively in the mission of recovering flood victims. Hence, this collaborative network among all the components has been designed with TV white space technology. Therefore, all the components are required to carry and communicate through TV white space devices. Features and tasks of these elements are discussed below:

1) RESCUER
Rescuers are an end user in our proposed network and expert on a particular rescue mission as well as has incomparable cognitive capabilities. They are directly engaged in the rescue operation. The highlight of rescuers' ability is given by the fact that they can closely reach to the victims in suffering and provide direct recovery actions. Their responsiveness of executing recovery actions as well as efficiency play a pivotal role in the success of SAR activities. In order to facilitate their intra-team communications via an access point, a white space device is carried by each of the rescuer team members.

2) DRONE
The main objective of drone is to collect information in less penetrable flooded areas and subsequently convey it for further actions by the rescues. Its paramount characteristics is given by the ability to monitor, explore and inspect the ground and water-covered areas from a certain altitude level using high-resolution video cameras. Whenever victims as an object of interest are detected, the precise position information can be forwarded to the relevant rescue agents. The recorded on-board videos can further facilitate post-flight investigation and examination. During real time search and rescue activities over the disaster environment, drone acts as prolonged flying eyes of the rescuer. This aerial vehicle is agile and highly movable as well as capable of penetrating sufficiently close to the surface, which in turn facilitate better resolution of the inspected area for victim detection.

3) WATER VEHICLE
The main objective of this component is to rescue victims in submerged area by the assist of drone and rescuer. The significant features of water rover are excellent manoeuvrability and the ability of navigating in shallow water and fast flowing water situations which enables the rescuers to act swiftly and safely during victim recovery. For rescuing activities, it is decorated with TVWS devices to exchange information with rescuers, others team as well as RCC. The team members of water rover collect disaster data through utilization of drones and perform relevant actions according to the obtained information.

4) LAND VEHICLE
This component is involved to rescue victims in muddy and shallow flood water condition. Like water rover, equipping it with drone that would remotely scan landscape after flood. When airborne, the drone can transmit live footage to the emergency response teams, helping them respond more quickly and effectively to floods where maps often become redundant. It carries portable TVWS device operating mode I or operating mode II.

5) RESCUE COPTER
The aim of rescue copter is to search victims and convey necessary materials like as fresh water, dry foods as well as fist aid box to the victims. It is among the most versatile and effective rescue tools, which have the capability to cruise over a terrain of considerable size and are equipped with tremendous instruments and inherent powerful flying ability over daunting climatic and geophysical situations. Therefore, a rescue copter can assist in rescue operation in village areas that are often isolated and less accessible by alternative vehicles. The activities of rescue copter is regulated by the RCC, which maintain inter-team communications in the cases of emergency such as transporting victims to clinics and hospitals.

6) RCC
The main objective of RCC is to take up-to-date of rescuing performance across the rescue teams within the same locality and supply any needful reinforcement. At the same time, RCC supervises the rescue copter and maintain information exchange with the central CC with regard to the flood condition and collect essential materials, medicals as well as tools from the control center. It is equally important for RCC to communicate all teams in his region, rescue copter and CC because of rapid search and rescue operation. As RCC is a regional database, therefore, according to the FCC, fixed TVWS device is required to establish a network and fixed devices are allowed to use 4 W of transmission power.

7) CC
In our proposed model, single CC serves as the ultimate governing authority of the rescue operation and globally coordinates actions of all the units. The main objective of the CC is to collect data from the RCCs and use them to find the optimal solution for search and rescue operation by giving commands, suggestion, relief and equipment's supplies for the rescue teams. Like RCC, the CC also needs fixed TVWS devices.

B. NETWORK ARCHITECTURE
A key point of this paper is on utilization of TVWS to assist SAR actions by bridging the missing inter-team communications among the local and regional networks. A tiered communication network approach is developed by following the procedures in [1]. In the established architecture, Wireless Local Communication (WLC), Wireless Regional Communication (WRC) and Wide Area Network (WAN) are designed based on TVWS. Fig. 1 depicts the network architecture of the FMRS. It is a three tier architecture where the first tier is engaged to information acquisition, second tier is engaged to

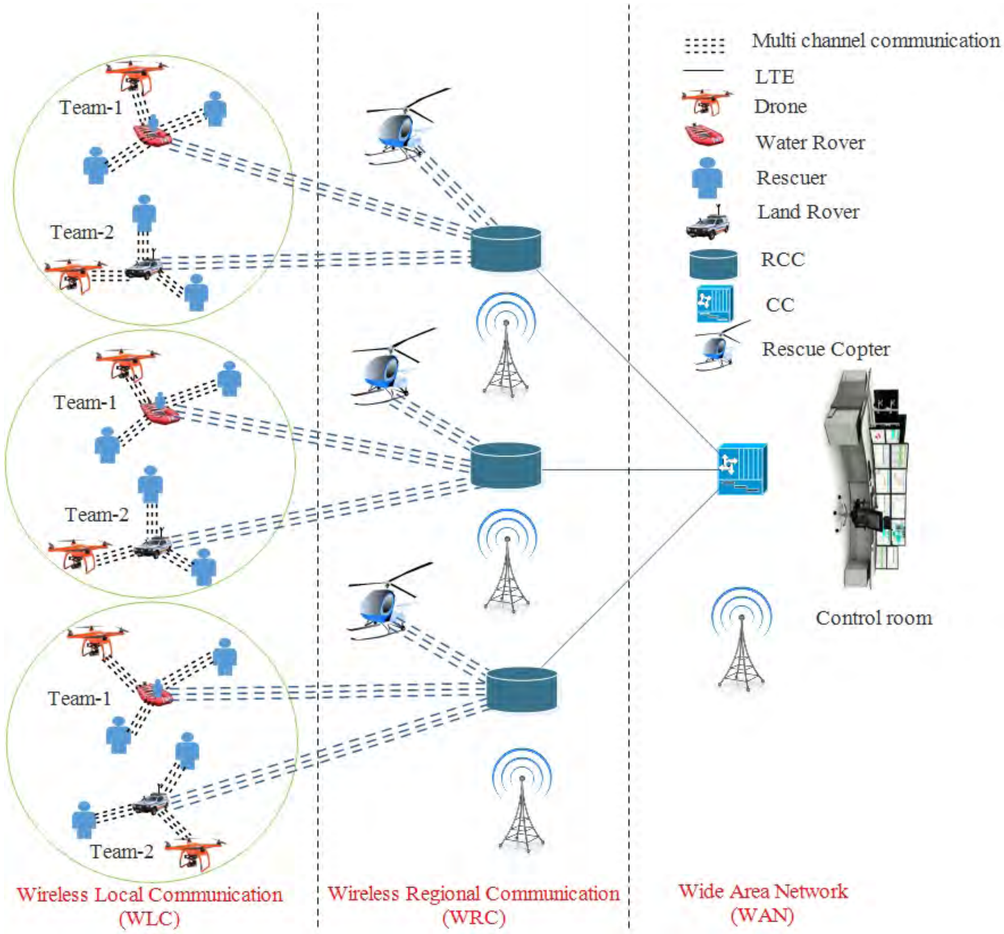


FIGURE 1. Channel diversity on CEMCS for FMRS exploiting TVWS.

data forwarding and team maintain and third tier is engaged in information processing for discovering optimum solution as well as provide basic need.

In this architecture each team consist of HRs, Rescue Copter (RC) and Water Rover/Land Rover (WR/LR). Usually, each rescuer collect or generates data about victims from the flood affected area, which is transmitted to WR or LR by developing a WLC. Hence, the data collection is proceed by two types of communication i.e., Intra-team and inter-team communication. The searching actions are directed through rescue teams and rescue copter that can be seen in Fig. 1.

As noted before, the second tier is involved in data acquisition from teams and forward them to the upper level. In this case, the WR/LR connect to the remote base station RCC and creates a WRC. The RCC receives data from different teams, thereafter, process and store this data. The saved data then can be further exploited by the teams and rescue copter. Moreover, following this information, the RCC gives direction to the teams in his region and also supply rescue copter for any emergency situation.

The data aggregator, employed through the RCC agents, connects to the CC and establishes WAN. There are many possible communication technologies to create a WAN, for instance, through wireless technology (licensed spectrum) or wired access (fiber-optics, cable). In this case, wireless technology LTE is a suitable candidate for build a WAN. As mention before, the third tier in this network architecture is engaged in data processing, finding optimum solutions for the rescuers and obtaining feedback from the rescuers. After receiving this data from RCC, the CC process the requisite data and store them in a database, after discovering optimum solution. Thereafter, periodically, it computes the best solution for one or more components as noted before. After that, these solutions are send to the rescuers via RCC to facilitate execution of SAR procedures in the most efficient manner.

C. TECHNOLOGY FOR FLOOD SAR (FSAR) : JUSTIFICATION OF TVWS

Herein we attempt to evaluate FSAR significant characteristics and choose appropriate technology for communication networks in the flood scenarios. We first mention some attractive features of TVWS as follows.

a. Propagation characteristics: TVWS offers superior signal propagation characteristics and with minimal equipment's can reach users in remote and rugged locations for SAR activities [13]. The spectrum

(UHF/VHF frequency band) of TV white space those frequencies that easily penetrate precipitation and bad weather areas which is very common in flood scenarios.

b. Penetration capability: Penetration is the magnificent feature of TV white space. In a typical home, a WiFi signal can penetrate up to two walls. At the same power, a TV white space signal can penetrate three fold than WiFi signal and obstacles, enabling whole home media distribution. This will simplify and enrich local area networking opportunities.
c. Better coverage: TVWS system has coverage range of around 10 km, significantly larger compared to a conventional Wi-Fi router with limited coverage of approximately 100 m under a certain setting. This TVWS development corresponds to what known as ''Super Wi-Fi'' considering the excellent outreach and capability to propagate beyond physical barriers, including buildings, rough terrains, hilly surfaces and trees.
d. Non-Line-of-Sight (NLOS) capacity: The requirement of having line-of-sight (LOS) propagation for most of microwave links often resulted in tall transmission towers, which can be costly and unfeasible. The TVWS technology offers an attractive proposition to microwave methods by adopting a lower portion of UHF band, which has a better penetration capability without installing extra costly infrastructure.
e. License exempt: TV white space is a license free technology and have ability to being quickly deployed with minimal infrastructure and hence can be facilitated flood rescue activities by resuming the communication in a short time. Hence can be facilitated flood rescue activities by resuming the communication in a short time.
f. Inexpensive: Since TV frequency band is rather a well-established networking system, an attractive point of TVWS technology includes a cheap deployment cost to facilitate data access to the disrupted disaster areas where other networking methods are simply unfeasible and difficult to deploy.

Real-time

g. information: This feature supported by TVWS devices is suitable for emergency cases to improve safety-critical information transfer over existing licensed systems. As an example, rescue attempts can be increased by setting remote video cameras in a disaster place to relay images towards a CC; or utilizing portable devices to supply real-time video conference and surveillance, point of view control information.

From the above discussion, TVWS technology is considered the ideal candidate to enable the deployment for communication in the flood scenarios due to its attractive characteristics.

The main drawback of the TV White space is the feasible unavailability of functional spectrum because of occupancy by incumbents. In order to cater this situation [28], [29], assignment of specific frequency slots in TVWS band based on priority seems to be a good solution. Herein the high priority channels (HPCs) can be leased for a limited time only by paying cognitive radio operators for exclusive rights of their uses from the geo-location database provider.

IV. PROPOSED EXPANDING NEIGHBORHOOD SEARCH TECHNIQUE FOR MULTI-VICTIM (ENST-MV)

Among the existing *SAR* techniques, *Probabilistic Search Techniques (PSTs)* [32] are the most popular techniques, which were utilized in many practical *SAR* operations [33]–[35]. However, most of these techniques are non-collaborative and they integrate a *Probability Distribution Map (PDM)*, which contains the probability values of the presence of a target(s) at various locations within the overall search area. In *PST*, the starting cell of a *SAR* operation for a team could be determined based on several parameters including *Point Last Seen (PLS)* and *Last Known Position (LKP)*, or could be determined randomly. If the target is not discovered in the current cell, the next visiting cell is selected based on the highest probability in the *PDM* within 1-level neighborhood.

Generally, *PSTs* utilize local information to find the next visiting cell and hence, it is unable to exploit collaborative efforts of multiple teams. Therefore, in *PSTs*, multi-team revisits of a single cell is highly likely. To overcome this problem, a collaborative searching approach is proposed in [22], called *15-a (Collaborative Search & Rescue)*, where *PDM* update is performed globally for all the teams and cell visiting information is also accumulated globally. In [22], the authors also proposed a new searching technique, called *Expanding Neighborhood Search Technique (ENST)*. The *ENST* is an enhancement over the *PST*, where the former performs searching up to α-level neighborhood instead of 1-level neighborhood like the latter to select the next cell, where $\alpha \in \mathbb{Z}^+$. An inherent characteristics of *ENST* is given by an expansive search function, starting from 1-level neighborhood and reaching until α-level neighborhood with an objective of discovering the most probable cell that may contain a Victim Point (VP). Therefore, an optimum value of α plays an important role in attaining improved performance in *ENST*.

However, *ENST* cannot be directly applied to the scenario that is taken into account in this paper since it assumes only one victim point and all the teams involved in a *SAR* operation perform a collaborative effort to find the target point. It is so because the *ENST* is solely designed for the *Avalanche Search & Rescue* operations, where generally an avalanche occurs at a particular point. Conversely, the scenario that is considered in this paper contains multiple victims points, which are distributed over a given area. Therefore, an enhancement over *ENST* is performed to incorporate multi-victim scenario and hence, called *ENST for Multi-Victim or ENST-MV*.

Analogous to *ENST*, the *PDM* is utilized to find the next cell and it is updated globally by exploiting the advantages

Algorithm 1 ENST-MV—Adapted and Modified From ENST in [22]

REMARK: x, x', y, and y' are x-coordinator, new x-coordinator, y-coordinator, new y-coordinator, respectively. β is number of victim(s)
Constant: α, β, $x' \leftarrow -1$, $y' \leftarrow -1$
Input parameter: x, y, $\mu \leftarrow 0$
assert($\alpha > 0$)
Select x' and y' based on *Point Last Seen*
Look for the victim in the current cell
if Victim discovered **then**
  $\beta - = 1$
end if
Update the probability of the cell based on the *Recursive Bayesian Estimator* in [22]
$x \leftarrow x'$
$y \leftarrow y'$
while $\beta \geq 1$ **do**
  for $\delta \leftarrow 1$ to α **do**
    for $j \leftarrow -\delta$ to δ **do**
      temp_x $\leftarrow x + \delta$
      temp_y $\leftarrow y + j$
      if temp_x or temp_y are outside the given area **then**
        continue
      else
        if probability of finding victim in the selected cell is greater than μ and the cell is not visited before **then**
          Assign temp_x and temp_y to x' and y', respectively
          Update μ value with the new probability
        end if
      end if
    end for
    for $j \leftarrow -\delta$ to δ **do**
      temp_x $\leftarrow x - \delta$
      temp_y $\leftarrow y + j$
      if temp_x or temp_y are outside the given area **then**
        continue
      else
        if probability of finding victim in the selected cell is greater than μ and the cell is not visited before **then**
          Assign temp_x and temp_y to x' and y', respectively
          Update μ value with the new probability
        end if
      end if
    end for
    for $j \leftarrow -\delta + 1$ to $\delta - 1$ **do**
      temp_x $\leftarrow x + j$
      temp_y $\leftarrow y + \delta$
      if temp_x or temp_y are outside the given area **then**
        continue
      else
        if probability of finding victim in the selected cell is greater than μ and the cell is not visited before **then**
          Assign temp_x and temp_y to x' and y', respectively
          Update μ value with the new probability
        end if
      end if
    end for
    for $j \leftarrow -\delta + 1$ to $\delta - 1$ **do**
      temp_x $\leftarrow x + j$
      temp_y $\leftarrow y - \delta$
      if temp_x or temp_y are outside the given area **then**
        continue
      else
        if probability of finding victim in the selected cell is greater than μ and the cell is not visited before **then**
          Assign temp_x and temp_y to x' and y', respectively
          Update μ value with the new probability
        end if
      end if
    end for
  end for
  if $x', y' \neq -1$ **then**
    return;
  else
    Select location at random: location $\in$ α-level neighborhood
  end if
  Look for the victim in the selected cell
  if Victim discovered **then**
    $\beta - = 1$
  end if
  Update the probability of the cell based on the *Recursive Bayesian Estimator* in [22]
end while

of the collaborative rescue effort. Dissimilar to *ENST*, the searching process will continue until all the victims are discovered. In *ENST-MV*, the next cell is selected through searching via 1-level neighborhood until reaching α-level neighborhood and the most probable cell is selected within the search region as the next visiting cell. The proposed searching approach is elaborated in Algorithm 1. As could be observed from the algorithm is that the process of searching starts by selecting a cell based on the *Point Last Seen*.

Once a cell visiting is complete, the next cell is selected within the α-level neighborhood. For that, two conditions are taken into account, namely *i*) the most probable cell where the victim could be found based on the *PDM* and *ii*) status of the visit is "false" according to the accumulated (globally or locally) cell visiting information. If both the conditions are satisfied, the next visiting cell is found. Conversely, which may occur only if all the cells are already visited, the next visiting cell is selected arbitrarily within an α-level neighborhood. Before leaving the current cell, visiting status of this cell is updated in a global table and its probability is revised based on the *Recursive Bayesian Estimator (RBE)* as in [22]. This procedure continues until all the victims, β are discovered as demonstrated in Algorithm 1.

A. VARIANTS OF ENST-MV

Similarly to *ENST* in [22], three variants of *ENST-MV* are proposed in this paper based on the PDM updating mechanism, namely: i) *No PDM Update (NPU)*, ii) *Local PDM Update (LPU)*, and iii) *Global PDM Update (GPU)*. Here, in *NPU*, as the name suggests, no *PDM* update occurs and it is memoryless. Hence, among the three variants of the *ENST-MV*, it is the simplest one in terms of implementation. In *NPU* cases, it is most likely that a single grid may experience revisiting multiple times. On the other hand, the *PDM* updates is performed locally within a team in case *LPU*. Similar to *NPU*, *LPU* is non-collaborative and hence, the *PDM* update information is never announced outside the team. Again, to prevent revisiting a cell, it accumulates visiting information per iteration. Once a cell visiting is complete, its probability is revised employing the *RBE* as mentioned earlier in the Section IV. Next, to reduce the searching time of the *SAR* activities, *GPU* supports both collaboration and cooperation. Here, the updated estimation of the probability of finding victims—which is calculated after visiting that cell employing the *RBE*—is announced globally to maintain consistency of the changing global probability map of the disaster area. In addition, cell visiting information is also accumulated globally, which is later employed in selecting a subsequent cell to visit, aiming at minimizing search duplication and overlapping.

V. PERFORMANCE EVALUATION OF ENST-MV

This section discusses the system model that is taken into account during numerical simulations (see Section V-A) and other relevant techniques that are compared with the proposed technique (see Section V-B).

A. SYSTEM MODEL

For our numerical simulation, a Euclidean area of 10 km $\times$ 10 km is considered in this paper, which is divided into an equal fixed cell size 0.1 km $\times$ 0.1 km later. The *PDM* of this area is generated considering two aspects as in [22]: *i*) all the cells must not be assigned identical probability value and *ii*) for maintaining continuity between the adjacent cells, a certain degree of relationship must be maintained between them with no drastic difference in terms of probability values.

In our simulation, the value of *VPs* is considered randomly from 1 to 10. Again, to introduce randomization in the selection process, a random variable ρ is generated according to Eq. 1, which draws a value from $[0, \tau]$; τ refers the highest probability received in the *PDM*.

$$\rho = \frac{(\frac{1}{1+e^{-5.5\times\vartheta}} - 0.5) \times \tau}{0.4959} \tag{1}$$

Here, $\frac{1}{1+e^{-5.5\times\vartheta}}$ is obtained from a modified *Sigmoid Function* where ϑ is a random variable with uniformly distribution that draws value from 0 to 1.

One of the noteworthy properties of ρ is that it has the tendency towards τ value. Therefore, the cells with higher probability values in the *PDM* have higher likelihoods of selecting as *VPs*. A certain cell is selected as a *VP* if its probability in the *PDM* is within a tolerance range of $\pm 10^{-6}$ to the value of ρ. Again, to eliminate selecting a certain cell every time for a certain ρ value, the coordinate value of x and y are chosen randomly. This procedure repeats until all the *VPs* are selected.

In the simulation, a number of teams are varied that are deployed to find the *VPs*, ranging from 1 to 20. Two constraints are imposed during the deployment process, namely *i*) only one team can visit a single cell at a certain time and *ii*) no concurrent cell visiting by more than one team is allowed. Moreover, when a team is utilizing the *ENST-MV*, it can choose the next cell within 4-level neighborhood since α is suggested as 4 in [22] to attain improved performance.

The proposed technique's performance will be measured by exploiting two metrics: *i*) *Average Number of Visited Cells* and *ii*) *Time Spend [hr]*. The time spend to discover all the victims is calculated as

$$\mu = \mu_p + \mu_c + \mu_t. \tag{2}$$

Here, the parameter μ_p is the preparation time, i.e., the time requires in packing before shifting to the next cell and is considered as a constant value in our simulation. Conversely, μ_t varies and denotes the time requires to reach the next cell from the current cell in traveling, which mainly depends on the distance between the current cell and the next cell and the movement speed, ϑ_C. Again, μ_c denotes the searching time of cell by a team, which can be calculated as $\mu_c = \sigma_c/\vartheta_V$ where σ_c and ϑ_V denote the area of the cell and the average time taken for searching that cell, respectively. In the simulation, all the aforementioned parameters such as ϑ_V, τ_p and ϑ_C are assigned 10 m/s, 180 s and 1.5 m/s, respectively.

B. OTHER CONSIDERED TECHNIQUE

In order to measure the proposed searching technique's performance, it is compared with other two relevant prominent techniques: *i*) *Random-Search-Technique (RST)* and *ii*) *Probabilistic-Search-Technique (PST)*. In *RST*, the next cell selection is performed randomly within 1-level neighborhood. Therefore, the *PDM* is not required for this technique and hence, it is simple in terms of implementation compared to other techniques. For the comparison, three variants of *RST* are proposed, such as: *i*) *No-Memory (NM)*, *ii*) *Local-Memory (LM)*, and *iii*) *Global-Memory (GM)*. Here, *NM* does not take the previous cell visiting knowledge into account. Therefore, it is highly likely that a same cell can be visited repeatedly. In case of *LM*, the information of the self-visited cell is accumulated and utilized in the next cell section process. Conversely, *GM* collects all information of a cell that is visited by the previous teams (i.e., a collaborative approach) and employs it to select the next cell.

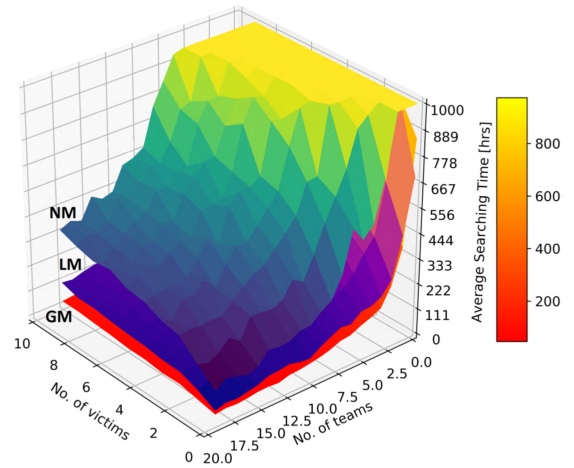
Again, similar to *ENST-MV*, *PST* selects the next cell exploiting a probabilistic technique. The primary difference between them is: the next cell selection within first-level neighborhood is based on latter technique, and it is chosen within α-level neighborhood in the former technique. Alike the proposed technique, three variants of this technique are proposed which are discussed in details in the Section IV-A.

C. FINDINGS AND DISCUSSIONS

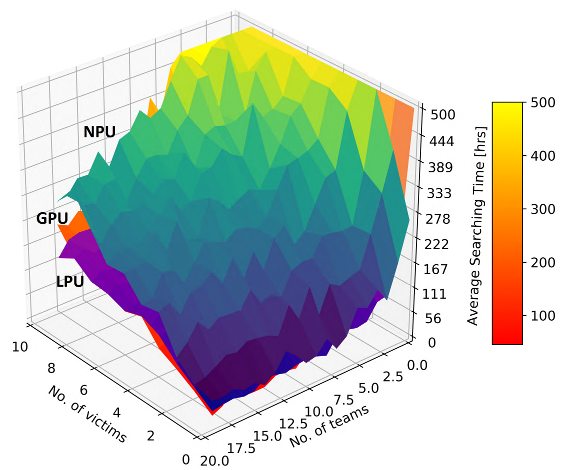
The Figures 2a, 2b and 2c exhibit the time spend [hr] of by different teams in discovering various number of *VPs* for all three compared *SAR* techniques, namely *RST*, *PST*, and *ENST-MV*, respectively. As could be observed from the figure is that when a number of teams are more and a number of *VPs* are few, lower time is spent in discovering all the victims. In oppose to that, it increases with increasing number of *VPs* and decreasing number of teams for all compared techniques.

The *RST* shows the lowest performance compared to the other two techniques due to selecting the next visiting cell randomly. Again, *NM* spends the highest amount of time in discovering the *VPs* among the three variants of *RST*. On the other hand, *LM* demonstrates considerably better performance over *NM* as it accumulates cell visiting information locally and utilizes it in the next cell selection. Thus, it eliminates likelihood of revisiting a cell by the same team. However, a cell still may experience revisit by one or multiple team(s) due to the absence of collaboration among the teams. *GM* resolves this issue by accumulating cell visiting information globally and hence, demonstrates the best performance among the three variants. Average spend time by 20 teams for discovering 10 *VPs* for *NM*, *LM*, and *GM* are 415.12, 380.1, and 295.67, respectively.

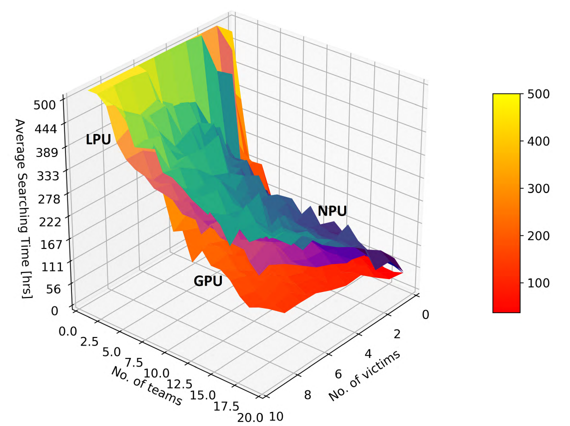
In compare to *RST*, *PST* exhibits better performance in discovering *VPs* within a short period of time. It happens due to utilizing the *PDM* in discovering the next visiting cell. The *PDM* is also utilized in our proposed technique, *ENST-MV*. However, it demonstrates the superior performance over all the compared techniques due to its new searching strategy. In *ENST-VM*, the most probable cell within the α-level neighborhood is chosen as the next visiting cell instead of 1-level neighborhood like *PST*.



(a) Time spend [hr] for the *RST* with respect to various number of victims and various number of teams.



(b) Time spend [hr] for the *PST* with respect to various number of victims and various number of teams.

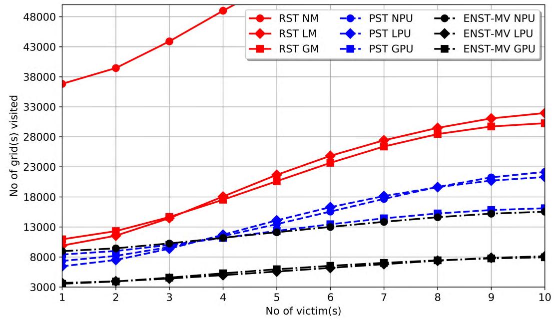


(c) Time spend [hr] for the *ENST-MV* with respect to various number of victims and various number of teams.

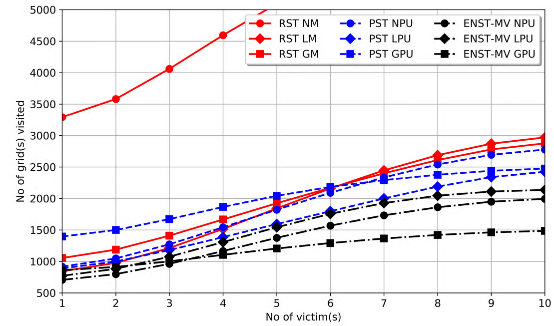
FIGURE 2. **Time spend [hr] for the compared *SAR* techniques.**

Again, for both *PST* and *ENST-MV*, three variants are proposed (see Section IV-A and Section V-B), where *NPU* and *LPU* are non-collaborative approaches and *GPU* is collaborative approach. Among the three variants, *NPU* receives the poorest performance due to ignoring the *PDM* update and cell visiting information during the next cell selection process. This approach spends around 326.46 hours and 267.7 hours to discover 10 *VPs* for 20 teams using *PST* and *ENST-MV* approaches, respectively. Even *LPU* demonstrates superior performance over *NPU* due to updating the *PDM* locally and utilizing local cell visiting knowledge during next cell selection. In this case, 20 teams spend around 265.59 hours for *PST* and 153 for *ENST-MV* in discovering 10 *VPs*. Again, since *GPU* utilizes the collaborative approach, it outperforms the other two variants. In *GPU*, the *PDM* is updated globally and cell visiting knowledge is also accumulated globally, which are later utilized for selecting the next cell. It spends around 228.31 hours and 121.06 hours for 20 teams to discover 10 *VPs* for *PST* and *ENST-MV* approaches, respectively.

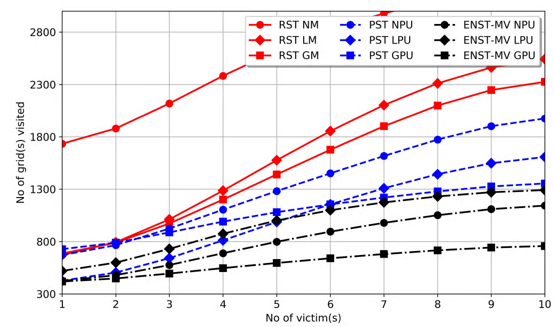
In Fig 3a, 3b, and 3c, average number of visited cells for all the compared techniques are exhibited with respect to various number of victims for 1, 10, and 20 teams, respectively. As could be observed from the figures is that the average number of visited cells follow the similar trend which is observed for average searching time. In other words, if three techniques are ordered based on their performance, *RST* exhibits the poorest performance, *PST* demonstrates some improvements over *RST*, but it fails to overpower *ENST-MV*. The reasons are similar to those which are mentioned previously for time spend metric. Again, among the several variants of the compared techniques, the one which utilizes the collaborative approach, i.e., *GPU*, outperforms other two non-collaborative approaches, namely *NPU* and *LPU* due to the same reasons which are elaborated before for average searching time.



(a) Average number of visited cells with respect to number of victim(s) for 1 team.



(b) Average number of visited cells with respect to number of victim(s) for 10 teams.



(c) Average number of visited cells with respect to number of victim(s) for 20 teams.

FIGURE 3. Average number of visited cells for the compared *SAR* techniques.

VI. PERFORMANCE EVALUATION OF CEMCS

This section evaluates the performance of the proposed collaborative CEMCS network model through numerical simulation. NS-2 is widely preferred simulator among the networking research community, so it has been used for the simulation experiments. The first and foremost task is to design the scenario which will be resemble with the flood affected area, as we discussed in the Figure 1. Then the network performance metrics will be considered which assists to measure the performance of CEMCS network model. Finally, two experiments will be conducted in order to show the effectiveness of the utilization of TVWS and the consistency of the proposed network model. All the aforesaid aspects will be discussed in the following sub-sections:

A. NETWORK SCENARIOS

The considered network size is 10^2 km, where the entire area is divided in to 1000×1000 grids. Each grid is considered as 10^2 m, which can be easily search by a rescuer. A Control Center (CC) is placed in the center of the area, where all the rescuers can send their searching information in to the server in a multi-hop manner. Three access points of the three Regional Control Centers (RCC) are placed in the network in such a way where APs can directly communicate to the sever. There are three teams are placed inside a RCC. The rescuer can communicate with others through the AP of the team such as water vehicle and/or land vehicle. Moreover, the rescuers, drones, rescue capture, water and land vehicles are mobile so that they can move from one region to another. However, the RCC and CC remain static.

B. PERFORMANCE METRICS

A simulation study has been carried out to measure the performance of network based on the standard network performance metrics like packet-delivery-ratio (PDR), overhead and delay. The definition of the considered metrics are providing bellow:

PRD: it is the ratio between the number of received packets by the server (denoted as P_{Rec}) and transmitted packets (denoted as P_{trans}) by the rescuers. The more PDR means the performance of the network is good. Mathematically, it can be defined as:

$$PDR = \frac{P_{Rec}}{P_{trans}} 100 \tag{3}$$

Overhead: In the network two types of data are transmitting during communication: i) Data Packets (i.e., the real payload) and ii)Signaling Packets (i.e., the packets which are transmitting in order to establish networks connection). The overhead is the ratio between the total number of Data Packets (denoted as N_D) and the summation of the total number of N_D and the total number of Signaling Packets (denoted as N_S). The more overhead means the performance of the network is poor. Mathematically, it can be defined as:

$$Overhead = \frac{N_D}{N_D + N_S} \tag{4}$$

Delay: it is the average required time in order to transmit packets from source to destination. It considers all possible delays due to buffering at route discovery phase, queuing at the interface queue, transmission time and delays induced by routing activities. It can be expressed in the following way:

$$Delay = \frac{\sum_{n=1}^{N}(A_i - S_i)}{N} \tag{5}$$

where, A_i is time when packet received at destination (the arrival time), S_i is time when packet transmitted by source (the sending time), N refers the total packets received by servers of the CC.

C. EXPERIMENTS

Based on the above network scenario, we have conducted two experiments in order to measure the performance of the proposed model by exploiting TVWS technology. In the first experiment, we will show the effectiveness of TVWS in our considered scenario. The concept of TVWS as adopted from Cognitive Radio Networks (CRNs), where there are two users can be utilised the spectrums of the TVWS. One user is called Primary User (PU) who is the real user of the networks and another one is called the Secondary User (SU) who can use the spectrum while the PU is inactive. In the considered scenario, we assume that the PU will be always inactive as the flood affected area is normally in the remote area. All the actors are represented as SUs here. Therefore, we assume that the TVWS spectrums are always available for the SUs and we can get the benefits of multi-channels in this context. We also considered a prominent routing protocol for CRNs in this simulation named as Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) [36]. In order to get the more information about the CRNs, we refer the readers to read the papers [37] and [38].

TABLE 1. Simulation parameters.

Parameters name	Values
Propagation model	Two-ray ground model
Area Size	1000 x 1000 grids
Mobility model	Random way-point model
Data traffic model	CBR over UDP
Performance measuring metrics	PDR, delay and overhead
Routing protocol	D2CRP
Simulation times	1000s
Number of channel	[2, 4, 6,8]
Minimum MN speed	2 m/s
Maximum MN speed	6 m/s
Minimum data rate	0.54 mbps
Maximum data rate	2.7 mbps
Number of run of each experiment	5

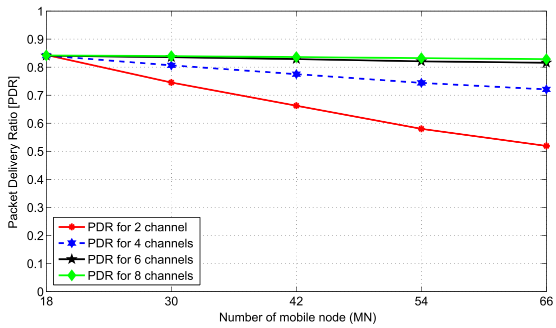


FIGURE 4. PDR vs MN performed on different channels.

In the first experiment, the results have been collected in three figures. Each figure corresponds to a performance metric with a variation of number of channel and MN speed (i.e., the rescuers, drone and so on). In all the graphs, x-axis represents the number of mobility nodes (MN) and y-axis indicates the value of performance metric. The varying number of channels set is {2, 4, 6, 8}. Simulation parameters are depicted in Table 1.

Fig. 4 is depicted the simulation results for PDR by varying the number of channels and number of mobility node (MN). The first important observation that as the MN increases, the PDR decreases for all three number of channels. Therefore, the packet loss percentage will increase whenever the network is denser. Performance of the two channels is reducing regularly while the PDR is increasing in the case of 4, 6 and 8 channels. The second important observation is the superiority of increasing channels in terms of the packet delivery ratio over the lower number of channels. Lower number of channels achieves the lower packet delivery ratio and the higher packet loss percentage.

Fig. 5 shows the variation of the delay time for 2, 4, 6 and 8 channels. The lower number of channels consistently shows the higher delay time. As less channel needs more time in route discovery, it produces more delay time, therefore the delay time for less channel is longer than more channels. From the above study on delay time, 8 channels have the shortest delay time as compared to 6, 4 and 2 channels, it means that the more channels have high reliability than the less channel.

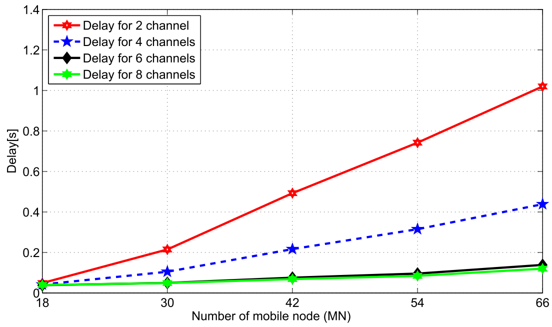


FIGURE 5. Delay vs MN performed on different channels.

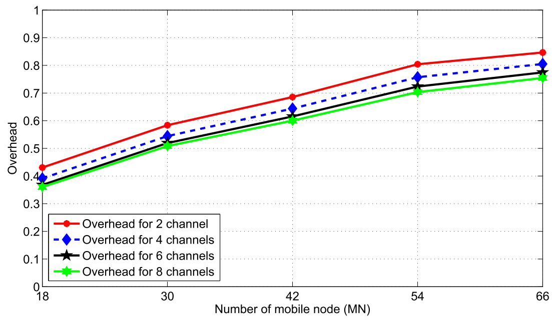


FIGURE 6. Overhead vs MN performed on different channels.

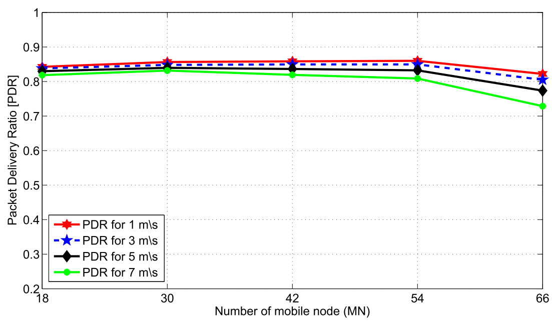


FIGURE 7. PDR vs MN performed on different speeds.

Fig. 6 depicts the results for the routing overhead. As the node density increases, more nodes would be involved in sending the packets from source to the destination. Therefore, routing overhead also increases for all number of channels. Eight channels have the lowest overhead as compared to 6, 4 and 2 channels, it means that the number of channels increases, the overhead decreases, therefore more channels are better than less channel

On the other hand, we have analyzed the performance of the network by varying the speed of mobility nodes (MN speed) in the second experiment. The simulation set is similar like first experiment, however, the differences: MN speed set is {1 m/s, 3 m/s, 5 m/s and 7 m/s}.

Fig. 7 shows the simulation results for PDR by varying the mobility node (MN) speed and number of mobility node (MN). The figure presents that as the MN increases, the PDR decreases for different node speeds. In the simulation process, the MN speed 1 m/s has the highest PDR as compared

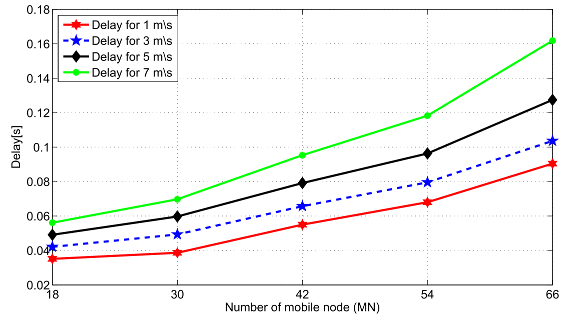


FIGURE 8. Delay vs MN performed on different speeds.

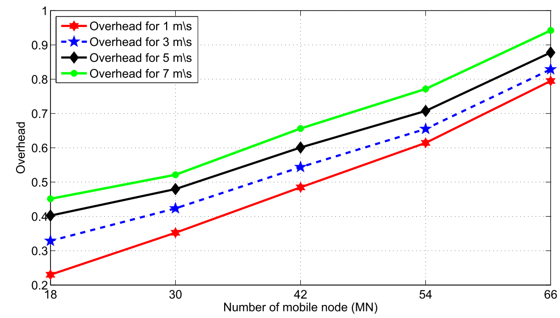


FIGURE 9. Overhead vs MN performed on different speeds.

to 3 m/s, 5 m/s and 7 m/s even by escalating the number of MN. With the increase in MN speed, the PDR decreases. When the MN speed decreases, the PDR increases slightly.

Fig. 8 depicts the simulation results for delay time with a variation in the MN speed and number of MN. As the number of nodes (MN) increases, the delay time also increases for all node speed. With the decrease in node speed, the delay time decreases.

Fig. 9 presents the simulation results for routing overhead by differing the MN speed and number MN. As the MN increases, the overhead also increases periodically for all node speed. With the decrease in node speed, the routing overhead decrease.

Based on the first experiment: with the increasing number of channels, the PDR increases, delay time and routing overhead decreases, therefore the performance of multi channels is better than the single channel. Again, based on the second experiment: with the decrease in node (MN) speed, the PDR increases, delay time and routing overhead decreases, therefore node speed 1 m/s has high performance as compared to 3 m/s, 5 m/s, 7 m/s. However, overall performance is good even high speed while we exploit multiple channels. Thus it can be concluded that by exploiting TVWS, the performance of the network specially in digester scenarios are significantly improved.

VII. CONCLUSION

We have presented an overview, description and evaluation of the CEMCS model that exploits TVWS spectrum as network backhaul links to support rapid and effective post-flood SAR activities. The proposed network model has been aimed to extend the ProSe for mission-critical data exchange, which includes acquisition of victims information, transmission and storage of the collected information, and development of the follow-up rescue activities. The capability of the proposed CEMCS model has been evaluated through numerical simulation of the network performance (packet delivery ratio, delay and overhead) as well as implementation of global search algorithm exploiting the collaborative nature of the network agents. Results of the simulation have shown favorable performance of CEMCS, e.g., in terms of packet delivery ratio nearing 80-90% and optimality of efficient search algorithm.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Qusay Salih for his cooperation in particularly the NS-2 simulation. A preliminary version of this paper was presented in part at the IEEE International Conference on Dependable, Autonomic and Secure Computing, Orlando, FL, USA, 2017 [1].

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