



Performance evaluation of hybrid disaster recovery framework with D2D communications

Enver Ever^{a,*}, Eser Gemikonakli^b, Huan X. Nguyen^c, Fadi Al-Turjman^{d,g}, Adnan Yazici^{e,f}

^a Computer Engineering, Middle East Technical University, Northern Cyprus Campus, 99738, Mersin 10, Güzeyurt, Turkey

^b Department of Computer Engineering, Faculty of Engineering, University of Kyrenia, Girne, Cyprus

^c Middlesex University, London NW4 4BT, UK

^d Artificial Intelligence Dept., Near East University, Nicosia, Mersin 10, Turkey

^e Department of Computer Engineering, Middle East Technical University, Ankara, Turkey

^f Department of Computer Science, Nazarbayev University, 010000 Nur-Sultan, Kazakhstan

^g Research center for AI and IoT, Near East University, Nicosia, Mersin 10, Turkey

ARTICLE INFO

Keywords:

Public safety networks

D2D communications

Relay nodes

Tandem queues

Analytical Modeling

ABSTRACT

Public Safety Networks (PSNs) provide assistance before- and post-disaster events. With the help of technological advances, PSNs are able to cope with both natural and man-made disasters, protecting people, environment and property. Effective communications, better situational awareness, lower response times and greater emergency efficiency are essential to an effective response to emergencies and disasters. Long Term Evolution (LTE) has been chosen to be the key technology for public safety networks. In this study, a performance model is presented for the PSN frameworks which use cooperative devices with LTE device to device (D2D) communications features. Mobile stations that are out of cellular network coverage range use D2D communications, where mobile stations which are in a healthy area can act as relay nodes to provide information about the location of potential victims to a central system. Since relay nodes have the potential to become bottlenecks for relatively high scale disasters, the interaction between the relay node and the base station is critically considered in this study. The analytical model and solution are suitable for assessing the quality of service for PSNs with similar infrastructures. Results obtained from the analytical model are presented comparatively with those from discrete event simulations for validation. The maximum discrepancy between the results obtained from the analytical model and the simulation results is less than 1.4%, which is within the confidence interval of the simulation.

1. Introduction

Information and communication technologies provide vital services and systems for our daily lives, and available technologies should affect us more with the emergence of IoT in Smart City, Smart home, and e-health applications [1–7]. Public safety networks (PSNs) are another very important area that communication technologies can help. Unfortunately, many people around the world are affected by disasters such as earthquakes, tsunamis, volcanic eruptions and floods. Although communication services and other types of information exchange services are in high demand for the aftermaths, the communication infrastructure is generally damaged to a large extent, making services totally or partially unavailable. Game theory based approaches to energy harvesting, backup power provision strategies to prolong the communication services, adoption of new techniques to reduce damage to large-scale infrastructures, and new frequency allocation techniques in

event of communication outages are proposed in studies such as [5, 8–10], respectively. However, these studies do not consider the bottleneck analysis of proposed infrastructures. Recent major disasters around the world include the earthquake in Haiti (2010), the earthquake and tsunami in Japan (2011), the Nepal earthquake (2015), the Fort McMurray Canada wildfires (2016) and the forest fires in Athens (2018) [5,9,11–13]. First responders, such as law enforcement, firefighters and emergency medical personnel, must match emergency events as well as catastrophic disasters. Apart from first responders, military organizations, volunteer groups, non-government organizations and other local and national organizations can also contribute to disaster response [14,15]. Although processes used for preparations of disaster scenarios are improving, the annual average of victims caused by disasters between years 2006–2015 is 69,827 [16]. For most of these disasters, unfortunately, people could not act as observers mainly because of the lack of knowledge and distribution of available

* Corresponding author.

E-mail addresses: eever@metu.edu.tr (E. Ever), eser.gemikonakli@kyrenia.edu.tr (E. Gemikonakli), h.nguyen@mdx.ac.uk (H.X. Nguyen), fadi.alturjman@neu.edu.tr (F. Al-Turjman), adnan.yazici@nu.edu.kz (A. Yazici).

<https://doi.org/10.1016/j.comcom.2020.01.021>

Received 12 November 2019; Received in revised form 3 January 2020; Accepted 11 January 2020

Available online 21 January 2020

0140-3664/© 2020 Elsevier B.V. All rights reserved.

technological advances. Therefore the citizens and teams responsible from emergency services at the sites could not be alerted, and details of disasters in respective locations could not be communicated timely.

The technologies that can be used to transmit critical public safety information must be present, efficient and reliable, since they are required by the first responders to save lives. It is a challenging task to provide desired levels of quality of service (QoS) for the scenarios where the numbers of incoming requests may become extensive. Therefore, bottleneck analysis should be carried out for the proposed infrastructures in order to clarify their efficiency especially for large scale disasters.

Over the past decade, the technologies used in commercial networks have seen significant improvements. Given that many of the current public safety communication networks, such as terrestrial trunked radio (TETRA), TETRA for police (TETRAPOL), or Association of Public-Safety Communications, are lagging in terms of the support for advanced data rate services, there is a growing interest of governments, public safety operators and research communities to improve the capabilities of Public Safety Networks [17]. At the same time, as it is increasingly adopted by all major operators all over the world, and is expected to be an important part of the 5G solution for future networks, Long Term Evolution (LTE), specified by the Third Generation Partnership Project (3GPP), is chosen as the next appropriate communication technology to support PSN in US and Europe [18].

When state-of-the-art communications infrastructures are considered to be used in the event of natural disasters, the potential malfunctioning or failure of crucial components (power grids and telecommunication networks) should also be taken into account [8,10]. In cases where the network infrastructure is completely or partially damaged, Device-to-Device (D2D) communication lends itself as a candidate to provide public safety and disaster relief services.

In [18] discussions are provided for possible directions and challenges to evolve the LTE network architecture toward 5G in order to support emerging public safety scenarios. Studies such as [8], and [19] use simulations for evaluating various measures such as security throughput and energy price. As part of their future studies, the authors of [6] propose to use ns-3 discrete-event network simulator to perform a bottleneck analysis for the cloud head which would expect to receive high volumes of requests in cases of high scale disasters. In this study, similar to [8,18,19], and [6] D2D communication is envisaged in order to present a framework that can be used to relieve disasters using the advances in mobile device technologies. Unlike the existing studies, an analytical framework is also proposed for the scalability analysis. Data management can become a challenging issue in disaster situations, and distributed databases can be employed under various connectivity conditions because of their ability to adopt to the changing environment. Therefore, a distributed database application is also employed where information is gathered from users in pre-disaster situations for locating potential victims, and obtaining medical information using D2D communication. Assessing the performance of these systems is essential to understand the capacity of the system under consideration. For example, in the event of a large-scale disaster, the infrastructure should be able to cope with a potentially high number of incoming requests. Analytical models and simulations are known to be very effective in specifying potential bottlenecks for these types of distributed systems. The proposed framework is therefore modeled as a queuing system and the scalability as well as QoS-related issues are studied in detail. A simulation study is also conducted to verify the results of the analytical model presented. The contributions of this work can be summarized as follows:

- In our hybrid approach presented in this study, the location of users is obtained before the possible disaster (proactive mode), as well as just after a disaster (reactive mode). Subsequently, the most available up to date location information is used. The use of proactive and reactive modes improves the possibility of locating potential victims.

Table 1

List of abbreviations.

Abbreviation	Explanation
rn	relay node
bs	base station
L_{rn}	Buffer capacity of the relay node
L_{bs}	Buffer capacity of the base station
σ	Arrival rate of requests to the relay node
μ_{bs}	Mean service rate of the base station
μ_{rn}	Mean service rate of the relay node
ρ_{rn}	Traffic load of the relay node
ML_{rn}	Mean Queue Length of the relay node
ML_{bs}	Mean Queue Length of the base station
R_{rn}	Response Time of the relay node
RT_{bs}	Response Time of the base station
γ_{rn}	Throughput of the relay node
γ_{bs}	Throughput of the base station

- To the best of our knowledge, this is the first study to conduct an analysis of scalability and bottleneck analysis by analytical modeling of distributed D2D PSN services.
- A detailed and critical analysis of the characteristics of the system is presented for the efficient use of PSNs using similar infrastructures, where the interaction between two systems with different characteristics should be configured for better scalability. The threshold analysis carried out allows us to examine the system load and specify various system characteristics such as buffer size, and the service capacity both for the relay nodes and LTE.
- The model is verified through the use of discrete event simulations. The results obtained from the simulation and analytical model are in good agreement.
- The results obtained show that the utilization of the system (the intensity of traffic per node) becomes the main dominant factor instead of parameters such as queuing capacity, since the system can become unstable very rapidly. In turn, this also shows the importance of a scalability study, since the potential number of victims is the main factor for the utilization to raise beyond the levels that the systems in interaction can cope with.

The abbreviations used in this paper are listed with their explanations in Table 1. The rest of the paper is organized as follows. Existing related studies on PSNs are considered in Section 2. Section 3 explains the disaster recovery system considered. Section 4 discusses in detail the modeling approach used for the interaction between the relay nodes and the base station. The analytical solution approach employed is considered in Section 5. Numerical results are presented with discussions in Sections 6 and 7 concludes the paper.

2. Related work

D2D is considered as the key technology to offload traffic from the network, to extend the coverage of the existing infrastructure and more importantly to allow communications even when the network infrastructure is not available due to failures which may be caused by various types of disasters [6,8,17,20].

In [20], the key requirements, challenges and solution approaches are discussed for LTE D2D communications, with a focus on PSN applications. A procedure of clustering-based integration is presented for operations of both cellular and ad-hoc based communications. Simulation results are presented for numbers of user equipment increasing from 20 to 500 and the probability of transmission from 0.1 to 0.5. Although the results are presented for energy efficiency and the time required for clustering, the issues related to queuing, capacity analysis and scalability for each cell have not been considered.

In [6], a software defined network (SDN) based architecture is presented to support hierarchical D2D communications. The main aim of this study is to reduce the number of requested LTE communication

links, in order to improve the system in terms of energy consumption. For this purpose, a hierarchical D2D communication architecture is proposed where a central SDN controller takes the responsibility of communicating with the cloud head. The local and central controllers also enable the architecture to work in case of infrastructure damage and hotspot traffic situations, therefore introducing fault tolerance. In this work the authors propose to simulate the scenarios considered using the ns-3 discrete-event network simulator as the future work in order to analyze the computational load incurred by the cloud heads. In other words, as a part of their future works, authors propose to perform the bottleneck analysis for the cloud head which would expect to receive high volumes of requests in cases of high scale disasters. Their proposed simulation results are presented in the following study [21]; however, their main focus is on energy consumption related issues.

A heterogeneous network communication architecture is presented in [17], where PSNs and commercial operators share existing infrastructures as well as spectrum. The numerical results are presented using MATLAB simulations. A variable number of commercial users are considered and using physical layer characteristics, performance measures such as the normalized rate of unsatisfied requests are presented. Queuing related issues, which are particularly important for the specification of hotspot situations, especially when relay nodes are used, are not taken into account in simulations. MATLAB is employed in [22] as well for vehicular ad-hoc network simulator as well as analytical results used for validation purposes. Studies such as [22], and [4] also consider intelligent systems for foreseeing emergency situations. However, the main focus is on enabling safe driving environments for vehicles using random multi-hop dynamic topology rather than PSN.

Please note that the game theory based approaches to model competitions among different service providers are becoming popular in studies such as [1,8] and [19]. Disaster recovery communications where the cellular network coexists with D2D mobile nodes are also considered in [8]. This time, the possibility of energy harvesting is also being explored. While one of the specified cells is considered to be in a healthy area, the other is located in a disaster zone. Users in the healthy area are expected to assist those in the disaster area by acting as energy harvesting relays. In cases where user equipment (UE) may belong to different service providers, a Stackelberg game formulation is presented, since the UE may need to pay a price as an incentive to the base station (BS) causing energy trading and interference pricing. The simulation results are also presented in [8] to show that the D2D network is able to obtain higher utilities and lower prices during the energy trading phase.

In [19], the same infrastructure is considered this time for security related aspects. Secure wireless-powered D2D communication is investigated in the presence of multiple eavesdroppers, where a hybrid BS in a cellular network contributes to the power efficiency of D2D network and at the same time serves as cooperative jammer to interfere with potential eavesdroppers. Stackelberg equilibrium formulation is employed in this study as well. Simulation results are provided in terms of security throughput and energy price to validate the proposed jamming scheme and highlight the importance of energy trading interaction between cellular and D2D networks.

Apart from the research works which focus on effective communications in case of disasters, a number of studies in the literature such as [3,23], and [24] consider the use of mobile devices and the advancements in communication technologies in application level to ease the disaster recovery process. A variety of methods, such as evacuation warning and safe-path finding, are employed for the distributed systems involved. It is possible to classify these studies as proactive and reactive applications. When proactive approaches are considered, the information about the potential victims, their location and medical condition are collected prior to disasters. Instead, reactive approaches attempt to use the available infrastructure to locate potential victims during and after the events of the disaster.

When proactive methods are considered where the services are prepared prior to a disaster for the consequences, many of the existing

studies mainly focus on informing and alerting users for evacuation. In [24], an early warning and evacuation application is proposed using OpenStreetMap, which provides a free editable map of the world. Using the facilities of the OpenStreetMap, users are informed about disasters and safe paths outside the disaster zones. Similarly, in [25], a genetic algorithms based approach is proposed to find the optimum route for the people in need. An android application named as MyDisasterDroid is proposed which heavily uses the geolocation feature of Android. The performance related issues for the distributed applications are not taken into account in these studies.

The study in [3] improves these implementations further by minimizing the user interactions and introducing a more reactive approach. The only type of interactions needed in their proposed platform called TeamPhone is from the rescue team members to check for people in need. However, in case of a disaster, a rescue team member would need to walk around the collapsed buildings in order to use TemPhone platform effectively to find people potentially under a wreckage. This procedure can significantly slow down the rescuing process and introduce risks for the rescue team members by requiring them to be around potentially dangerous areas while searching for people. Wi-Fi Direct is employed to create P2P connections for sending and receiving emergency messages between mobile devices. A test-bed with mobile stations is employed for the evaluation purposes. Another reactive implementation which uses the Google Android platform is presented in [23]. An ad-hoc cloud solution which also employs the LTE Direct technology is proposed for disaster recovery. Although the cloud system proposed is similar to the server side of the system considered in this study, the collection of information prior to the disaster events is not considered.

For the queuing related issues of these systems, existing studies in the literature focus on the D2D communications and underlying cellular networks rather than the possible PSN scenarios. In [26], similar to this study, the performance of cellular and D2D integration is investigated. However, instead of focusing on flows between D2D and cellular systems, queuing systems are employed for various routing modes of D2D connections. Exact numerical analysis is supported with an approximate decomposition and iteration approach. Important performance measures such as end-to-end average throughput, average delay, and dropping probability are presented. Since the performance measures are obtained from an approximate decomposition approach, an in-house discrete-event simulation framework is used for validation. The more recent study [27] considers D2D communication together with relay assistance of cellular systems, enhancing the traffic offloading capacity of the LTE advanced (LTE-A) based infrastructures. This configuration is very effective for PSNs as well. Especially, when the BS infrastructure is partially available, D2D assistance can improve the availability of services. In this study as well the main focus is on the D2D portion of the integration. The main aim is to present a relay node selection strategy for D2D communications which would in turn provide improvements in terms of performance. Queuing theory is employed in this work as well for an approximation to compute end-to-end delay. Similar to our work, a tandem system is considered for the analysis of interaction between a D2D-capable UE which is the source of the information, and a relay capable UE which is used to forward the information from D2D-capable UE to a destination. The solution presented is in product form which requires approximations unlike the exact solution methods. Therefore, MATLAB simulations are also employed to verify the results presented using the analytical approximation.

The PSN concept attracts a lot of attention and interest from engineers and researchers since it can significantly change the way we deal with natural and man-made disasters. Improving their implementation can practically mean increasing the likelihood of saving more lives. Issues related to the performance of these infrastructures should be studied very carefully to identify potential weaknesses, bottlenecks, and congestion zones. Most existing studies in the literature which use

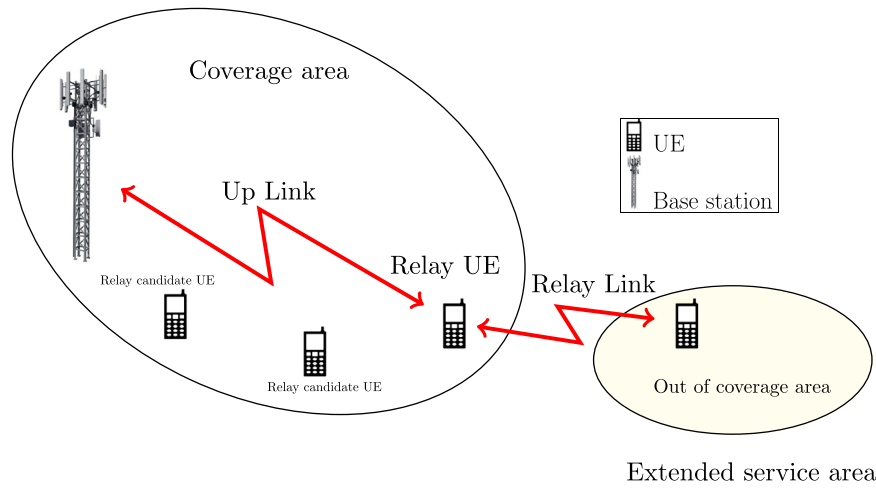


Fig. 1. Disaster recovery system under study.

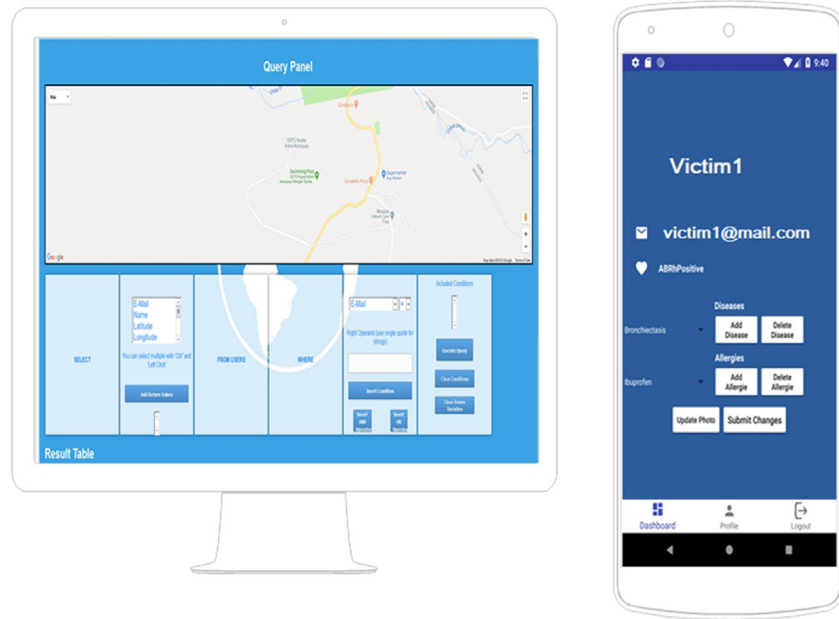


Fig. 2. The central system and mobile application.

simulations and analytical models for evaluation of PSN, and the D2D related infrastructure do not consider queuing related issues which may be critical in especially for scenarios where a relay node is to deal with traffic generated in a specific region. Studies that use queuing theory related approaches primarily provide product form expressions for computation of specific parameters instead of the complete representation of BS state space to relay node interaction. In our study, the focus is on the interaction between the BS and the underlying relay nodes that can become responsible for the large-scale transmission of emergency messages in the event of natural disasters. Unlike existing studies, a two-dimensional continuous Markov chain is used to model both the BS and the relay node at the same time. Although the solution approaches employed in this study are accurate, discrete event simulation results are also provided for validation of the model similar to the existing attempts [26,27] on queuing analysis of D2D systems.

3. Disaster recovery system under study

The disaster scenario illustrated in Fig. 1 is considered in this study. Since in public safety scenarios, large areas may lose cellular coverage,

D2D communications may be a good way to expand coverage of these sites. In this way, the region of interest can remain at least partially active during the periods in which rescue teams and the public need it the most. In such critical conditions, timely response and network connectivity are important factors for reliable communication. For example, D2D features can enable direct communication between first responders and rescue teams, even if they are outside the coverage areas of the LTE system which may be caused by power failures or damages that the BSs may encounter.

LTE technology, is considered to be the basis for the next-generation public safety broadband networks [18]. LTE comes with certain key features and functionalities to support D2D communications such as direct broadcast. For PSNs, the proximity service (ProSe) of D2D is very useful especially for the cases of safety and emergency situations, since these services have the potential of recognizing use cases and potential requirements for discovery and communications between UEs in proximity. With all these features of LTE, it is possible to specify three main scenarios as possible states of the infrastructure. In the first scenario the whole infrastructure in the region considered can be fully operative providing the UEs all the services. In the second scenario the

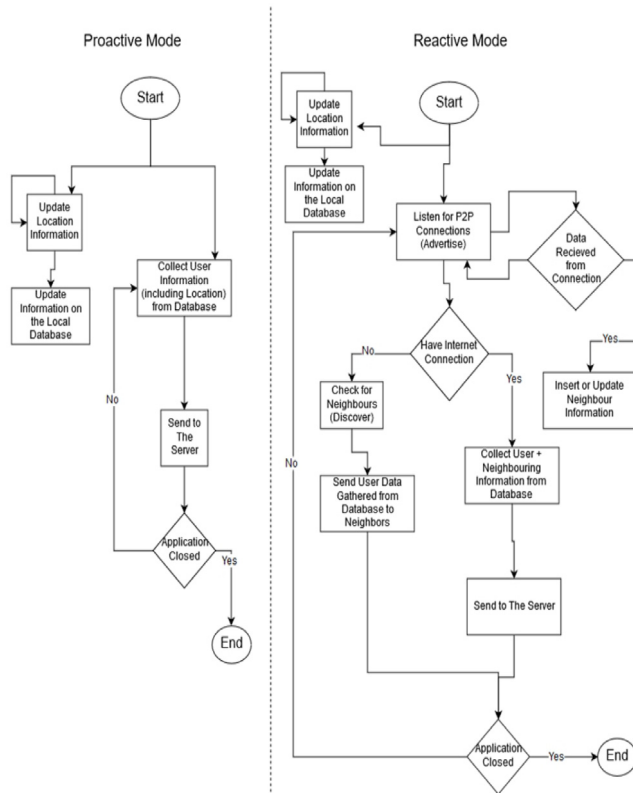


Fig. 3. Flow Chart of the PSN application.

infrastructure is completely damaged and none of the UEs have access to the services. Finally, in the third scenario some of the BSs are heavily damaged while the others are fully or partially functional which means that some UEs can be within the coverage area and some of them are outside. The main focus of this study is the third scenario.

The application considered, collect information from mobile users to aid the rescue teams by locating victims. To this end, the available means of communications are employed. Mobile stations in the coverage area can send information directly to the control center, which is accessible by rescue teams. Fig. 2 provides the perspectives of the central control system and the mobile application. Stations which has no access to the infrastructure start discovering the neighbor stations. Subsequently, if a neighbor which has connection to infrastructure is discovered, it can begin to act as a relay node transmitting the information to the control center. In an attempt to provide the most up-to-date location information to the control center, there are two ways to obtain location information. We can call the first one as the reactive approach which start collecting information after the disaster event, while, in the proactive approach, location related information is collected prior to the disaster. A hybrid approach is proposed in [7], which uses the proactive as well as reactive modes. In proactive mode, the control system can get information from users in specific time periods, or can use a control channel to trigger the transmission of information centrally. On the other hand, in the event of a disaster, the reactive mode of the application is enabled and different roles are assigned to the mobile stations based on their available connections. The flow chart of the system implemented is presented in Fig. 3.

- In case the mobile station has connection to BS, it tries to help nearby stations by acting like a relay node sending the collected information, including its own location to the centralized server.
- In the event that the mobile station does not have connection due to some damage to existing infrastructure, it begins to store information in a local database as if it were in the proactive

mode and transmits the latest data to the nearby devices using D2D communication facilities. If one of the stations can reach one of the relay nodes, this information eventually reaches the centralized database.

In this study, the evaluation of the performance of the interaction between the relay nodes and the BSs is considered, as they may present significant bottlenecks in the event of a relatively large-scale disaster.

4. The performance model for BS and relay node interaction

D2D communication has attained significant amount of attention from researchers in this decade. Thousands of efficient schemes under various D2D research domains have been proposed [28]. Ad Hoc On-Demand Distance Vector (AODV) has been one of the most popular routing algorithms with a significantly high number of varieties introduced in the literature [28,29]. In [29], for the first time, the investigations on performance characteristics of ad-hoc routing algorithms were brought up to 550 nodes. Studies prior to [29], mainly consider simulations of scenarios involving up to 100 nodes (usually 50 nodes) and relaxed (unrealistic) data traffic conditions. In addition, among a large number of varieties of modified versions for AODV, AODV with Route Identification and RREP Capturing (AODV-RIRC) is applied to large scale networks with nodes up to 10000 in [30].

In order to perform a bottleneck analysis of the D2D scenario, it is possible to consider that the D2D communications in ad-hoc fashion are scalable for each relay node. Critical flows are the incoming requests to the relay node and its ability to transmit them to the base station should be investigated. To study these interactions, a tandem queueing system is considered in this study with an analytical modeling approach. The abstract model of the interaction considered is presented in Fig. 4.

Please note that our main objective is to study the scalability of applications similar to the ones presented in studies such as [6–8,18,19], which use D2D communication in conjunction with the use of some mobile stations that can serve as relay nodes between the mobiles in disaster areas and the base stations [19]. In turn, the base station can update the relevant servers (usually cloud application) with the location information for the access of the rescue teams. In our model:

- Ad hoc communication between mobile nodes is not considered. The existing studies on the evaluation of large-scale routing protocols are quite advanced, so the main focus is on the bottleneck analysis which may occur at the relay node and the base station. For the framework and the application considered, the use of the relay node is one of the new contributions.
- The superposition of incoming traffic from the mobile nodes will be used to represent the scale of the users that only one relay node can cope with. In this study exponential distribution is employed for inter arrival and service times similar to [26,27], and [31]. In case a single node can generate on average σ messages per second and there are K nodes in disaster areas, the superposition of all the incoming arrival streams would become $K \times \sigma$ messages per second. For the performance analysis of BSs and relay nodes, it is possible to study the blocking probability, response time and similar performance measures for various K values. In other words, it is possible to present a comprehensive study of scalability.
- The only traffic transmitted to the associated BS resources will come from the relay node. In this sense, the resulting continuous time Markov chain (CTMC) is quite interesting. The only type of arrival to BS is from relay.
- The analytical modeling approach is validated by simulations.

The queueing system at the left-hand side of Fig. 4 represents the relay node which is a UE within the coverage area of a base station assisting the users outside the coverage area. Therefore, the arrivals to the first stage of the tandem system are from the users that do not have any coverage since they are within the radius of an affected base

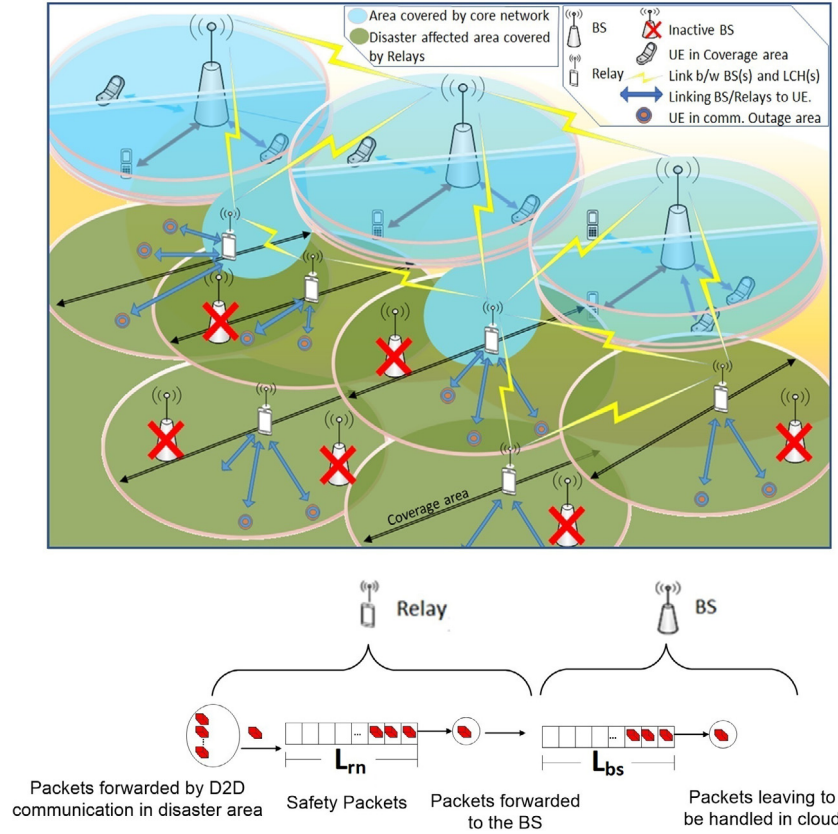


Fig. 4. Queuing model for interaction between the relay node and the BS.

station. These users try to reach to the backbone through the relay node. Incoming requests from the users outside the coverage area join the queue of the relay node, and once they are at the front of the queue they are forwarded to the base station (BS) which is functional. Since there will be dedicated resource allocation in the BS for safety-related applications, the possible arrival transitions to this queuing system (right-hand side of Fig. 4) are caused by the messages forwarded from the relay node. The two-dimensional continuous time Markov chain for this process can be given as in Fig. 5. Here σ is the arrival rate of packets from the mobile stations which are in the connectionless disaster areas, $1/\mu_{rn}$ is the time it takes to process incoming packets to the relay node and send them to BS, and finally $1/\mu_{bs}$ is the time it takes to process the incoming requests on the base station and forward them to the cloud for the authorities and rescue teams to access.

5. The analytical solution approach

The Fig. 5 shows the two dimensional Markov process on a finite lattice strip which can be used in order to represent an abstraction for the interactions between the relay node and the base station. Two integer valued state variables, $I(t)$ and $J(t)$, are used to describe the state of the system considered at time t . $I(t)$ is used to represent the number of packets in the relay node, and $J(t)$ specifies the number of packets in the base station at time t . The minimum and maximum values of $I(t)$ are 0 and L_{rn} respectively. For the number of packets in the base station (state variable $J(t)$), the minimum and maximum values are 0 and L_{bs} respectively. The total number of packets that can be accommodated in the base station at time t , includes the one(s) in service. The system considered is modeled using a Markov process that can be denoted by $Z = \{[I(t), J(t)]; t \geq 0\}$ and the model is used for performance evaluation of the interaction under study. We assume that Z is irreducible with a state space of $\{0, 1, \dots, L_{rn}\} \times \{0, 1, \dots, L_{bs}\}$. It is also assumed that the number of packets in the relay node ($I(t)$), is

represented in the lateral or horizontal axis and the total number of packets in the base station ($J(t)$) is represented in the vertical axis of a finite lattice strip. For the model Z there are three types of possible transitions. The first type are purely lateral from state (i, j) to state (k, j) . The second type is one-step upward transitions from state (i, j) to state $(k, j + 1)$. The final type are one-step downward transitions from state (i, j) to state $(k, j - 1)$.

5.1. Spectral expansion solution

The performance modeling of multi-server systems with multiple queues usually leads to multi-dimensional models. In particular, the analysis of Markov processes whose state space is the N-dimensional set of lattice points [32–34]. The functional equations arising in the analysis of N-dimensional processes usually present analytic difficulties. Because of this, various analytic-algorithmic methods have been developed to solve the multidimensional state space representation of various systems. Once a quasi-birth–death (QBD) Markov model such as the one presented in Fig. 5 is obtained, it can be solved for its steady state probabilities by using several different methods. These methods are Seelen’s method, Matrix-geometric solution, Gauss–Seidel iterative method, and the Spectral Expansion method.

Seelen’s method gives an approximate solution for QBD and Quasi Simultaneous-Multiple Birth and Death (QBD-M) systems. The Markov Chain is truncated to a finite state, which is an approximation of the original process. Then, it is used together with a dynamically adjusted relaxation factor in an efficient iterative solution algorithm [32]. The main drawback of this approach is the lack of a definite method to determine the optimal value of the relaxation parameter which is important to obtain accurate results.

Block Gauss–Seidel iterative method can be used for solving all kinds of simultaneous equations iteratively [32]. The possible infinite-state problem is reduced to a linear equation involving vector generating functions and some unknown probabilities. The main drawback of

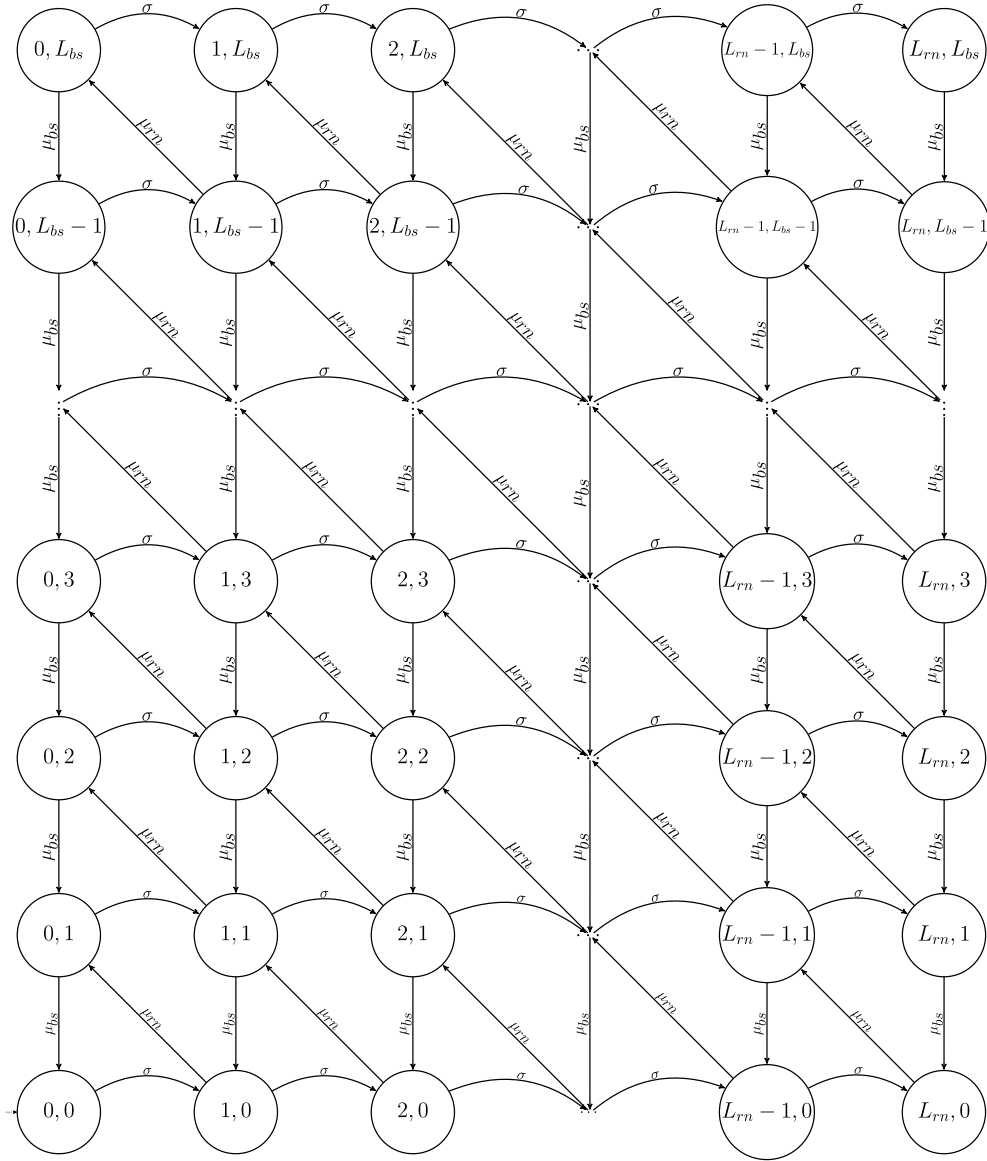


Fig. 5. Two dimensional state space representation of the system.

this method is the serial computations in which each component of the new iterate depends upon previously computed components. Because of this, the updates cannot be performed simultaneously.

The most important methods we can use to solve the system considered in this study are well known matrix geometric and spectral expansion methods [32,35]. In the matrix-geometric solution method first, a non-linear matrix equation is formed from the system parameters. Then the minimal non-negative solution R is computed by using an iterative algorithm. The main drawback of this method is that the number of iterations for computing R cannot be predetermined and there is a great computational requirement to obtain R . Instead, the spectral expansion method offers considerable advantages in terms of efficiency, with no penalties in terms of numerical stability. The speed gains of spectral expansion are demonstrated in [35] especially for the cases where the system approaches saturation.

In this study, the spectral expansion approach is used for the steady state solution of the two-dimensional Markov chain. Matrix A is the matrix of purely lateral transitions with zeros on the main diagonal, where the transitions one step forward and one down are represented in matrices B and C respectively. In the spectral expansion method, we

assume that the process has a threshold M ($M \geq 1$), which has an integer value [32–35] such that the transition rate matrices, A , B , and C , do not depend on j for $j \geq M$.

A , B and C are square matrices each of size $(L_{rn} + 1) \times (L_{rn} + 1)$. The elements of matrix A depend only on the arrival rates of the packets to the relay node, σ . The transition rate matrices A , B and C are given in the following equations. The matrix C represents the departure of the packets from the base station. If there are no requests in the base station, there will be no downward transitions (Fig. 5). Therefore, C_j matrix is the same as C for $j = 1, \dots, L_{bs}$. In other words, the threshold M is taken as $M = 1$.

$$A = A_j = \begin{pmatrix} 0 & \sigma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (1)$$

$$B = B_j = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mu_{rn} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \mu_{rn} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \mu_{rn} & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \mu_{rn} & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu_{rn} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu_{rn} & 0 \end{pmatrix} \quad (2)$$

$$C = \begin{pmatrix} \mu_{bs} & 0 & 0 & 0 & 0 \\ 0 & \mu_{bs} & 0 & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & \mu_{bs} \end{pmatrix} \quad (3)$$

$$C_0 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (4)$$

Following spectral expansion solution, the steady-state probabilities of the states presented in Fig. 5 can be expressed as:

$$P_{i,j} = \lim_{t \rightarrow \infty} P(I(t) = i, J(t) = j), 0 \leq i \leq L_{rn}, 0 \leq j \leq L_{bs}$$

It is then possible to obtain all state probabilities in the form of:

$$P_{i,j} = \sum_{l=0}^{L_{rn}} (a_l \psi_l(i) \lambda_l^{j-M+1} + b_l \phi_l(i) \beta_l^{L_{bs}-j}), M-1 \leq j \leq L_{bs}$$

where, λ and ψ are eigenvalues and left-eigenvectors of $Q(\lambda)$ respectively, and ψ is a row-vector defined as:

$$\psi = \psi_0, \psi_1, \dots, \psi_{L_{rn}}, \lambda = \lambda_0, \lambda_1, \dots, \lambda_{L_{rn}}, \\ \psi Q(\lambda) = 0, |Q(\lambda)| = 0$$

β and ϕ are eigenvalues and left-eigenvectors of $\bar{Q}(\beta)$ respectively and ϕ is a vector defined as:

$$\phi = \phi_0, \phi_1, \dots, \phi_{L_{rn}}, \beta = \beta_0, \beta_1, \dots, \beta_{L_{rn}}$$

Let us define certain diagonal matrices of size $(L_{rn} + 1) \times (L_{rn} + 1)$ as follows:

$$D_j^A(i, i) = \sum_{l=0}^{L_{rn}} A_j(i, l); D^A(i, i) = \sum_{l=0}^{L_{rn}} A(i, l) \\ D_j^B(i, i) = \sum_{l=0}^{L_{rn}} B_j(i, l); D^B(i, i) = \sum_{l=0}^{L_{rn}} B(i, l) \\ D_j^C(i, i) = \sum_{l=0}^{L_{rn}} C_j(i, l); D^C(i, i) = \sum_{l=0}^{L_{rn}} C(i, l)$$

and $Q_0 = B$, $Q_1 = A - D^A - D^B - D^C$, $Q_2 = C$. Then, the state probabilities in a row, can be defined as:

$$v_j = (P_{0,j}, P_{1,j}, \dots, P_{L_{rn},j}), j = 0, 1, \dots, L_{bs}$$

For $0 \leq j \leq L_{bs}$, the balance equations are:

$$v_0[D_0^A + D_0^B] = v_0 A_0 + v_1 C_1 \quad (5)$$

$$v_j[D_j^A + D_j^B + D_j^C] = v_{j-1} B_{j-1} + v_j A_j + v_{j+1} C_{j+1}; 1 \leq j \leq M-1 \quad (6)$$

$$v_j[D^A + D^B + D^C] = v_{j-1} B + v_j A + v_{j+1} C; M \leq j < L_{bs} \quad (7)$$

$$v_{L_{bs}}[D^A + D^C] = v_{L_{bs}} B + v_{L_{bs}} A \quad (8)$$

The normalization equation is given as:

$$\sum_{j=0}^{L_{bs}} v_j e = \sum_{j=0}^{L_{bs}} \sum_{i=0}^{L_{rn}} P_{i,j} = 1$$

From Eq. (7)

$$v_j Q_0 + v_{j+1} Q_1 + v_{j+2} Q_2 = 0; (M-1) \leq j \leq (L_{bs}-2)$$

and the characteristic matrix polynomials can be expressed as [32]:

$$Q(\lambda) = Q_0 + Q_1 \lambda + Q_2 \lambda^2; \quad \bar{Q}(\beta) = Q_2 + Q_1 \beta + Q_0 \beta^2$$

where

$$\psi Q(\lambda) = 0; |Q(\lambda)| = 0; \phi \bar{Q}(\beta) = 0; |\bar{Q}(\beta)| = 0$$

Furthermore,

$$v_j = \sum_{l=0}^{L_{rn}} (a_l \psi_l \lambda_l^{j-M+1} + b_l \phi_l \beta_l^{L_{bs}-j}), M-1 \leq j \leq L_{bs}$$

$\lambda_l (l = 0, 1, \dots, L_{rn})$ and $\beta_l (l = 0, 1, \dots, L_{rn})$ are $L_{rn} + 1$ eigenvalues, each that are strictly inside the unit circle, and $a_l (l = 0, 1, \dots, L_{rn})$, $b_l (l = 0, 1, \dots, L_{rn})$ are arbitrary constants which can be scalar or complex-conjugate. v_j vectors can be obtained using the process in [32]. The state probabilities can be used to compute important performance measures, such as the mean queue length for relay node ($MQ_{L_{rn}}$), the mean queue length for base station ($MQ_{L_{bs}}$), throughput for relay node (γ_{rn}), throughput for base station (γ_{bs}), response time for relay node (RT_{rn}) and the response time for the base station (RT_{bs}).

$$MQ_{L_{rn}} = \sum_{j=0}^{L_{bs}} j \sum_{i=0}^{L_{rn}} P_{i,j} \quad (9)$$

$$MQ_{L_{bs}} = \sum_{i=0}^{L_{rn}} i \sum_{j=0}^{L_{bs}} P_{i,j} \quad (10)$$

$$\gamma_{rn} = \sum_{j=0}^{L_{bs}} \sum_{i=0}^{L_{rn}} i \mu_{rn} P_{i,j} \quad (11)$$

$$\gamma_{bs} = \sum_{i=0}^{L_{rn}} \sum_{j=0}^{L_{bs}} j \mu_{bs} P_{i,j} \quad (12)$$

$$RT_{rn} = \frac{\gamma_{rn}}{MQ_{L_{rn}}} \quad (13)$$

$$RT_{bs} = \frac{\gamma_{bs}}{MQ_{L_{bs}}} \quad (14)$$

5.2. Simulation

Simulation modeling is used in this study to validate the analytical model in terms of accuracy. For this purpose, a simulation software is developed in C++ language and validated to simulate the real system. The results obtained from the analytical model are in turn presented comparatively with the results of the simulation software.

The program developed is a discrete event simulation program, where an event-based scheduling approach is used which depends on the events and their effects to the system state. As the stopping criterion, the relative precision which is known to be one of the most commonly used approaches is employed for the simulation. At the first checkpoint where the condition $\delta \leq \delta_{max}$ is satisfied, the simulation is stopped. Here δ_{max} is the maximum acceptable value of the relative precision of confidence intervals at the 100(1 - α) % significance level, and $0 < \delta_{max} < 1$.

The default values for α and δ are set to 0.05 to make sure the results obtained from the simulation program are within the 5% confidence

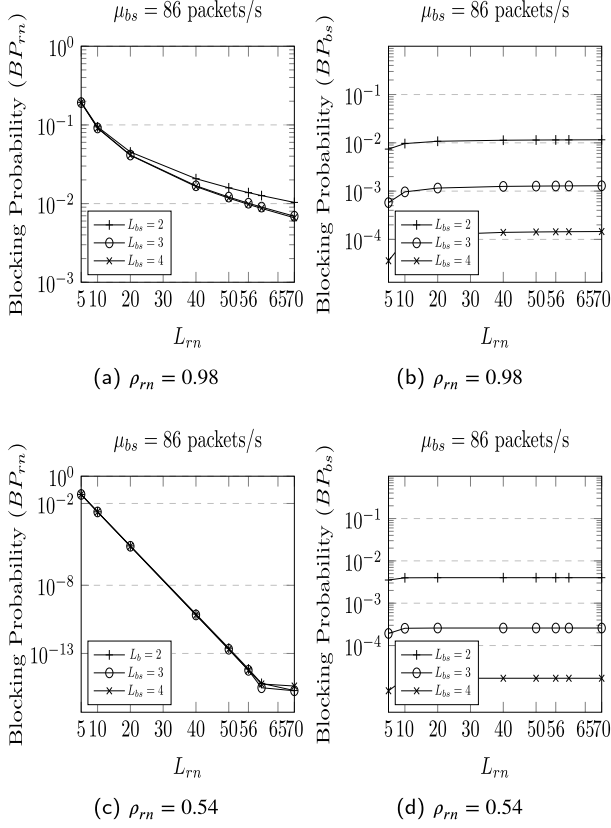


Fig. 6. Queueing size estimation for L_{rn} and L_{bs} for optimum BP_{rn} and BP_{bs} .

Table 2

Realistic LTE Throughput Measurements [38].

Throughput LTE	5MHz	10MHz	20 MHz
Measurement	(2 × 2 MIMO)	(2 × 2 MIMO)	(2 × 2 MIMO)
Realistic Median	0.5–4.0	2.0–7.5	2.0–12.5
Mini-Maxi Subscriber			
Data Rate (Mbps)			

Table 3

Summary of parameters used.

Parameter	Value
μ_{rn}	from 10 packets/s to 100 packets/s
μ_{bs}	86 packets/s for 1 Mbps 205 packets/s for 2.4 Mbps 402 packets/s for 4.7 Mbps 616 packets/s for 7.2 Mbps 702 packets/s for 8.2 Mbps 813 packets/s for 9.2 Mbps
ρ_{rn}	[0.1 – 0.99]
σ	from 1 packets/s to 10 packets/s
L_{rn}	from 10 packets to 70 packets
L_{bs}	from 2 packets to 4 packets

interval with a 95% confidence level. These confidence levels and intervals are quite commonly used for discrete event simulation [32–34,36,37]. The developed simulation program is also validated using well-known queueing theory models such as $M/M/1$, and $M/M/c$ as well as results from the literature [36,37].

6. The accuracy of the analytical approach

The numerical results are presented in this section to evaluate the interaction between the mobile station which can act like a relay node and the base station. The parameters used for computations are carefully chosen to reflect the characteristics of the real systems. The

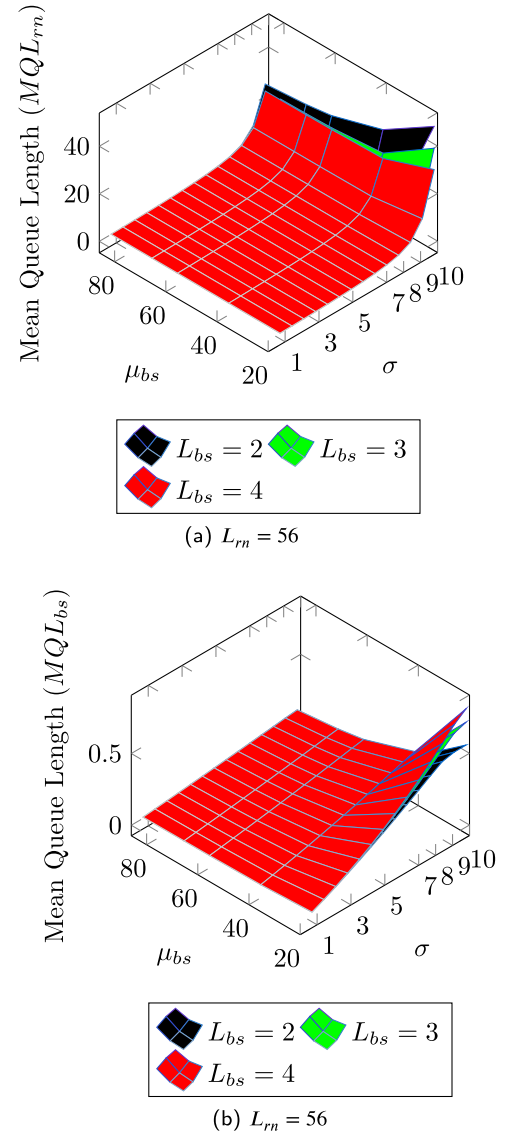


Fig. 7. Mean queue length results for real node and base station as a function of ρ_{rn} and subscribe data rates.

results of our simulation are also presented comparatively for accuracy verification.

6.1. Computation of system specific parameters

This section presents the system parameters and assumptions used for LTE cellular networks. Average realistic data rates of LTE is selected as 1 and 2.4 Mbps for 5 MHz bandwidth, 4.7 and 7.2 Mbps for 10 MHz bandwidth and 8.2 and 9.5 Mbps for 15 MHz from Table 2 for numerical calculations. The analytical model and solution approaches are flexible and can be used for the analysis of systems with various data rates and bandwidth related characteristics.

For 1 Mbps, the system can support up to about 38 users and up to 450 data packets, with each packet size totaling 1460 bytes. The number of users can be increased up to 800 in case 10 MHz is used and only 1 Mbps is provided per user, which can be an acceptable rate, especially in case of a disaster since location related information will be the main communication. The servers are used in terms of Radio Blocks (RB), where 25 RB can be considered as 1 server for 1 Mbps realistic throughput rate. Therefore μ_{bs} can be calculated using subscriber data rate and packet size. This is given in Eq. (15).

$$\mu_{bs} = \text{Data Rate}_{\text{subscriber}} / \text{Packet Size}_{\text{subscriber}} \quad (15)$$

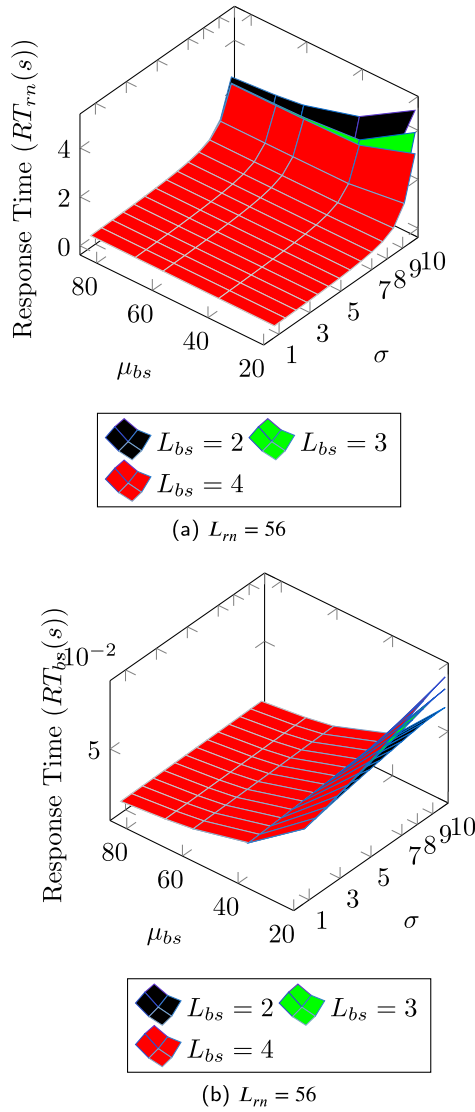


Fig. 8. Response time results for real node and base station as a function of ρ_{rn} and subscriber data rates.

Following this computation, it is possible to specify the parameters used for the evaluation of the considered systems as presented in Table 3. Note that ρ_{rn} represents the traffic intensity of the relay node, which is also equal to the utilization for a single server system.

6.2. Results and discussions

Fig. 6 shows the effects of L_{rn} and L_{bs} on blocking probabilities of the relay node and the base station (BP_{rn} and BP_{bs}) for different ρ_{rn} values. In Fig. 6(a) and Fig. 6(c), the results show a decrease in BP_{rn} as L_{rn} increases for different L_{bs} values, when $\mu_{rn} = 10$ packets/s and $\mu_{bs} = 86$ packets/s. Increasing the L_{rn} value up to 10 does not affect BP_{bs} significantly. Figs. 6(a) and 6(c) also show that the L_{bs} value does not affect the BP_{rn} significantly for queue sizes more than 2. Although the relay node stops sending to the BS when the buffer of the BS is full, the main factors affecting the blocking of the relay node are the arrival rate and the queue capacity of the relay node L_{rn} . When L_{rn} is increased further than 10, BP_{bs} does not change anymore for both $\rho_{rn} = 0.98$ and $\rho_{rn} = 0.56$ values as shown in Figs. 6(b) and 6(d). On the other hand, BP_{bs} decreases as L_{bs} increases in Figs. 6(b) and 6(d). However, the effect of L_{bs} on BP_{rn} can change depending on the system load. While in Fig. 6(a) for $\rho_{rn} = 0.98$, increasing L_{bs} up-to three has

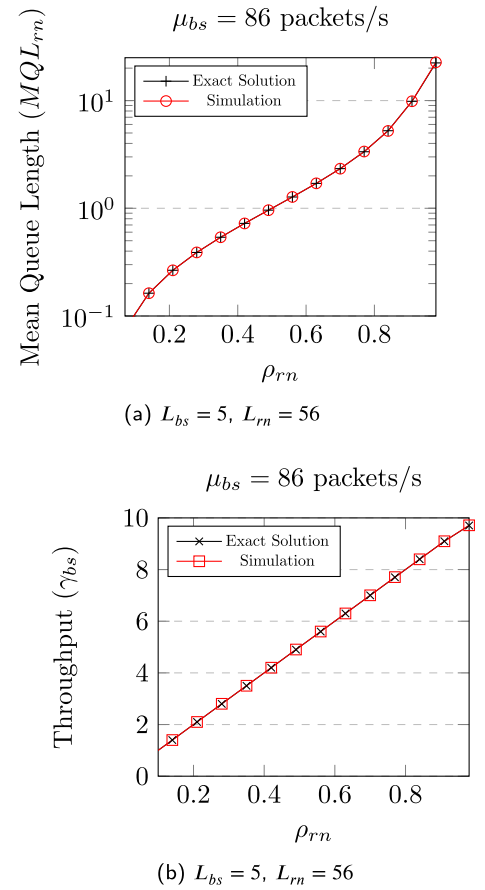


Fig. 9. MQL_{rn} and γ_{bs} results for different traffic loads.

a significant effect on BP_{rn} for high traffic load, for the system where $\rho_{rn} = 0.56$, BP_{rn} does not change significantly for different L_{bs} values as shown in Fig. 6(c). Therefore, keeping L_{bs} relatively small ($L_{bs}=4$) for higher L_{rn} ($L_{rn} = 56$) reduces both BP_{rn} and BP_{bs} to reasonable values where blocking probabilities for both systems are less than 0.01 even for relatively high traffic loads.

MQL_{rn} and MQL_{bs} results are given as a function of ρ_{rn} and subscriber data rates for different L_{bs} values in Fig. 7. MQL_{rn} and MQL_{bs} increase together with ρ_{rn} as shown in Figs. 7(a) and 7(b). However, there is a sharp increase in MQL_{rn} when $\rho_{rn} > 0.8$ in Fig. 7(a). Even though both MQL_{rn} and MQL_{bs} decreases as subscriber data rate increases, increasing subscriber data rate further than 4.7 Mbps does not affect the system performance for MQL_{rn} while $L_{bs} = 3$ and $L_{bs} = 4$. It is evident that increasing L_{bs} up-to four reduces the MQL_{rn} and has a significant effect on system performance, especially when the system is highly utilized. This is mainly because the relay node does not send the messages to the BS in case the buffer of BS is full.

Fig. 8 is given for different ρ_{rn} and subscriber data rate values but this time for RT_{rn} and RT_{bs} , taking into account different L_{bs} values. As ρ_{rn} increases, the RT_{rn} and RT_{bs} in Figs. 8(a) and 8(b) increase as well. Therefore, RT_{rn} and RT_{bs} increase up-to around 5 s and 0.078 s respectively for highly utilized systems while the subscriber data rate is 2.4 Mbps. These results clearly show that the buffer capacities of relay node and base station play a significant role for the optimization of the interaction. Furthermore, there is a trade-off between the buffer capacities of two systems in terms of response times. For example, although the RT_{bs} increases as L_{bs} increases for highly utilized systems, increasing L_{bs} up-to four significantly reduces the RT_{rn} to around 2.30 s for 9.5 Mbps subscriber data rate.

In Fig. 9, MQL_{rn} and throughput of the base station (γ_{bs}) are given as a functions of traffic loads. The numerical results are validated

with the simulation results considering optimum L_{rn} and L_{bs} values obtained from the previous results in Figs. 9(a) and 9(b). Increases in the traffic load are expected especially for emergency situations with large numbers of victims. In turn, this can significantly affect both MQL_{rn} and γ_{bs} . However, there is no linear correlation between MQL_{rn} and γ_{bs} . The main reason for this is different system constraints especially in terms of service times and queueing capacities.

The numerical results presented in this section clearly show the importance of correct configuration for the relay node and BS based on the potential numbers of victims in an event of a disaster which directly affects the expected traffic loads on the infrastructure. The major trends of the results presented can be summarized as follows:

- Based on the analysis of the buffer management, it is evident that retaining a small amount of buffer for the base station, around $L_{bs} = 4$, reduces the blocking probability to an acceptable value for a larger buffer capacity of the mobile node ($L_{rn} = 56$).
- These results clearly show that the relay node can become the main bottleneck for heavily loaded systems rather than the base station.
- The bottleneck also affects the response time and reduces it to about 0.078 s and 2.30 s for RT_{bs} and RT_{rn} respectively, where the subscription data rate is about 9.5 Mbps.

7. Conclusions

This paper presents a modeling study that takes into account queuing issues for applications developed for D2D PSN services. It is always preferable from the point of view of network engineers and emergency teams, to avoid dropping data packets with reasonable latency, especially in the event of a disaster. In addition, resource optimization efforts considering different performance metrics (MQL, BP and RT for the base station and the mobile node) such as the one in this study are important for seamless communication.

In this study, a two-dimensional Markov chain model is developed and the results of the exact solution approach are validated by the simulation results. The models and solution approaches presented in this paper are useful for the bottleneck analysis of similar applications. Models can be used for the analysis of various performance-related issues and, more importantly, the scalability of relay node-base station interactions that can indeed become essential for the first responders in the event of a disaster. At the same time, the analytical model and simulation results presented can provide a solid basis for the network operators for better planning and organization before catastrophic events occur.

This study can be used to specify system characteristics of PSNs for disaster cases, as it can provide the necessary guidance for analyzing network capacity in detail alongside location-related issues. In future studies, the model presented for detailed performance analysis of relay node at the BS interaction can also be used in larger-scale modeling attempts where similar interactions are expected.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Enver Ever: Conceptualization, Methodology, Software, Validation, Writing - original draft, Writing - review & editing. **Eser Gemikonakli:** Methodology, Software, Writing original draft preparation, Writing - reviewing & editing. **Huan X. Nguyen:** Conceptualization, Investigation, Funding acquisition. **Fadi Al-Turjman:** Conceptualization, Project administration, Supervision, Writing - review & editing. **Adnan Yazici:** Conceptualization, Project administration, Funding acquisition, Writing - original draft, Writing - review and editing.

Acknowledgment

This work was supported by the Newton Fund Institutional Links Grant under Grant 216429427 through the U.K. Department of Business, Energy and Industrial Strategy and managed by the British Council.

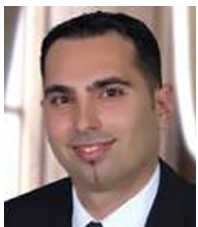
References

- [1] I. Al Ridhawi, M. Aloqaily, Y. Kotb, Y. Jaraweh, T. Baker, A profitable and energy-efficient cooperative fog solution for IoT services, *IEEE Trans. Ind. Inf.* (2019).
- [2] S. Liu, C. Guo, F. Al-Turjman, K. Muhammadd, V.H. C de Albuquerque, Reliability of response region: a novel mechanism in visual tracking by edge computing for IIoT environments, *Mech. Syst. Signal Process.* (2020) 1.
- [3] Z. Lu, G. Cao, T.L. Porta, Teamphone: networking smartphones for disaster recovery, *IEEE Trans. Mob. Comput.* 16 (12) (2017) 3554–3567, <http://dx.doi.org/10.1109/TMC.2017.2695452>.
- [4] K.R. Malik, M. Ahmad, S. Khalid, H. Ahmad, F. Al-Turjman, S. Jabbar, Image and command hybrid model for vehicle control using Internet of Vehicles, *Trans. Emerg. Telecommun. Technol.*
- [5] P.P. Ray, M. Mukherjee, L. Shu, Internet of things for disaster management: state-of-the-art and prospects, *IEEE Access* 5 (2017) 18818–18835.
- [6] M. Usman, A.A. Gebremariam, U. Raza, F. Granelli, A software-defined device-to-device communication architecture for public safety applications in 5G networks, *IEEE Access* 3 (2015) 1649–1654.
- [7] Y. Yatzbaz, B. Cinar, A. Gokdemir, E. Ever, F. Al-Turjman, H. Nguyen, A. Yazici, Hybrid approach for disaster recovery using P2P communications in android, in: *IEEE Proceedings of the 43rd IEEE Conference on Local Computer Networks (LCN)*, IEEE Computer Society, 2018, pp. 1–6.
- [8] Z. Chu, T.A. Le, H.X. Nguyen, A. Nallanathan, M. Karamanoglu, A Stackelberg-game approach for disaster-recovery communications utilizing cooperative D2D, *IEEE Access* 6 (2018) 10733–10742.
- [9] M.N. Nguyen, N.H. Tran, M.A. Islam, C. Pham, S. Ren, C.S. Hong, Fair sharing of backup power supply in multi-operator wireless cellular towers, *IEEE Trans. Wireless Commun.* 17 (3) (2018) 2080–2093.
- [10] S. Tani, K. Motoyoshi, H. Sano, A. Okamura, H. Nishiyama, N. Kato, Flexibility-enhanced HTS system for disaster management: responding to communication demand explosion in a disaster, *IEEE Trans. Emerg. Top. Comput.* (2017).
- [11] J. Horowitz, In aftermath of greek fires, suspicion combines with grief and recrimination, 2018, <https://www.nytimes.com/2018/07/25/world/europe/greece-wildfires-arson.html>.
- [12] G. Shao, X. Li, C. Ji, T. Maeda, Focal mechanism and slip history of the 2011 mw 9.1 off the pacific coast of tohoku earthquake, constrained with teleseismic body and surface waves, *Earth Planets Space* 63 (7) (2011) 559–564, <http://dx.doi.org/10.5047/eps.2011.06.028>.
- [13] D. Yates, S. Paquette, Emergency knowledge management and social media technologies: a case study of the 2010 Haitian earthquake, *Int. J. Inf. Manage.* 31 (1) (2011) 6–13, <http://dx.doi.org/10.1016/j.ijinfomgt.2010.10.001>.
- [14] G. Baldini, S. Karanasios, D. Allen, F. Vergari, Survey of wireless communication technologies for public safety, *IEEE Commun. Surv. Tutor.* 16 (2) (2014) 619–641.
- [15] A. Kumbhar, F. Koohifar, I. Güvenç, B. Mueller, A survey on legacy and emerging technologies for public safety communications, *IEEE Commun. Surv. Tutor.* 19 (1) (2017) 97–124.
- [16] D. Guha-Sapir, P. Hoyois, P. Wallemacq, R. Below, Annual disaster statistical review 2016 the numbers and trends, Centre for Research on the Epidemiology of Disasters, 2017.
- [17] D. Marabissi, R. Fantacci, Heterogeneous public safety network architecture based on RAN slicing, *IEEE Access* (2017).
- [18] R. Favraud, A. Apostolaras, N. Nikaein, T. Korakis, Toward moving public safety networks, *IEEE Commun. Mag.* 54 (3) (2016) 14–20.
- [19] Z. Chu, H.X. Nguyen, T.A. Le, M. Karamanoglu, E. Ever, A. Yazici, Secure wireless powered and cooperative jamming D2D communications, *IEEE Trans. Green Commun. Netw.* 2 (1) (2018) 1–13.
- [20] G. Fodor, S. Parkvall, S. Sorrentino, P. Wallentin, Q. Lu, N. Brahmi, Device-to-device communications for national security and public safety, *IEEE Access* 2 (2014) 1510–1520.
- [21] M. Usman, A.A. Gebremariam, F. Granelli, D. Kliazovich, Software-defined architecture for mobile cloud in device-to-device communication, in: *Computer Aided Modelling and Design of Communication Links and Networks (CAMAD)*, 2015 IEEE 20th International Workshop on, IEEE, 2015, pp. 75–79.
- [22] S. Haider, G. Abbas, Z.H. Abbas, T. Baker, DABFS: a robust routing protocol for warning messages dissemination in VANets, *Comput. Commun.* 147 (2019) 21–34.
- [23] F. Maly, P. Kriz, An ad hoc mobile cloud and its dynamic loading of modules into a mobile device running google android, in: D. Barbucha, N.T. Nguyen, J. Batubara (Eds.), *New Trends in Intelligent Information and Database Systems*, Springer International Publishing, Cham, 2015, pp. 191–198.

- [24] K.M. Rahman, T. Alam, M. Chowdhury, Location based early disaster warning and evacuation system on mobile phones using openstreetmap, in: Open Systems (ICOS), 2012 IEEE Conference on, IEEE, 2012, pp. 1–6.
- [25] J.T.B. Fajardo, C.M. Oppus, A mobile disaster management system using the android technology, WSEAS Trans. Commun. 9 (6) (2010) 343–353.
- [26] L. Lei, X. Shen, M. Dohler, C. Lin, Z. Zhong, et al., Queuing models with applications to mode selection in device-to-device communications underlying cellular networks., IEEE Trans. Wireless Commun. 13 (12) (2014) 6697–6715.
- [27] R. Ma, Y.-J. Chang, H.-H. Chen, C.-Y. Chiu, On relay selection schemes for relay-assisted D2D communications in LTE-A systems, IEEE Trans. Veh. Technol. 66 (9) (2017) 8303–8314.
- [28] F.S. Shaikh, R. Wismüller, Routing in multi-hop cellular device-to-device (D2D) networks: a survey, IEEE Commun. Surv. Tutor. (2018).
- [29] V. Naumov, T. Gross, Scalability of routing methods in ad hoc networks, Perform. Eval. 62 (1–4) (2005) 193–209.
- [30] X. Cai, J. Li, L. Zhu, Performance of routing protocols in very large scale wireless sensor networks, J. Netw. 7 (12) (2012) 1996–2002.
- [31] X. Chen, X. Li, D. Guo, J. Grosspietsch, Resource allocation in public safety broadband networks with rapid-deployment access points, IEEE Trans. Veh. Technol. 67 (2) (2018) 1660–1671.
- [32] R. Chakka, Spectral expansion solution for some finite capacity queues, Ann. Oper. Res. 79 (1998) 27–44.
- [33] E. Ever, Fault-tolerant two-stage open queueing systems with server failures at both stages, IEEE Commun. Lett. 18 (9) (2014) 1523–1526.
- [34] E. Ever, F.M. Al-Turjman, H. Zahmatkesh, M. Riza, Modelling green HetNets in dynamic ultra large-scale applications: a case-study for femtocells in smart-cities, Comput. Netw. 128 (2017) 78–93.
- [35] I. Mitrani, R. Chakka, Spectral expansion solution for a class of Markov models: application and comparison with the matrix-geometric method, Perform. Eval. 23 (3) (1995) 241–260.
- [36] J. Banks, J.S. Carson, B.L. Nelson, D.M. Nicol, Discrete-event System Simulation, Prentice Hall, 2010.
- [37] A.M. Law, Statistical analysis of simulation output data: the practical state of the art, in: Proceedings of the 2015 Winter Simulation Conference, IEEE Press, 2015, pp. 1810–1819.
- [38] MOTOROLA, Realistic lte performance from peak rate to subscriber experience, Tech.rep., MOTOROLA and Stylized M Logo, 2009, xiv, 110.



Enver Ever is an Associate Professor in Middle East Technical University Northern Cyprus Campus. He received B.Sc. degree from the Department of Computer Engineering, Eastern Mediterranean University, Cyprus, in 2002, and the M.Sc. degree in computer networks as well as the Ph.D. degree in performance evaluation of computer networks and communication systems from Middlesex University in 2004 and 2008, respectively. He was with Bradford University as a Post-Doctoral Research Associate for a year. He also served as a Lecturer/Senior Lecturer in the Computer and Communications Engineering Department, Middlesex University from 2008 to 2013. His current research interests include computer networks, wireless communication systems, cloud computing, wireless sensor networks, wireless multimedia sensor networks, integrated circuits, and performance/reliability modeling. He serves on various program committees and received the Exemplary Reviewer Award for his contributions as a reviewer.



Eser Gemikonakli received his B.Sc. Degree in Math and Computer Science and M.Ed. degree in Mathematics and Computer Teaching from Eastern Mediterranean University (EMU), Cyprus in 2004 and 2007 respectively. He then continued his studies at Middlesex University where he obtained his Ph.D. in Multi-Service Traffic Modeling for Wireless Communication Systems. Currently he is an Associate Professor, working as the Acting Dean of Faculty of Engineering in University of Kyrenia. His current research interests include neural networks, petri nets, computer networks and developing performance and performability models of integrated services for wireless network communication systems.



HUAN X. NGUYEN received the B.Sc. degree with the Hanoi University of Science and Technology, Vietnam, in 2000, and the Ph.D. degree from the University of New South Wales, Australia, in 2007. He has been with several universities in the U.K. He was a Research Officer with Swansea University, U.K., from 2007 to 2008, and a Lecturer with Glasgow Caledonian University, U.K., from 2008 to 2010. He is currently an Associate Professor of communication networks with the Faculty of Science and Technology, Middlesex University, London, U.K. He has published over 90 research papers, mainly in the IEEE journals and conferences. His research interests include 5G enabling technologies, PHY security, energy harvesting, and communication systems for critical applications. He was a recipient of a grant from the Newton Fund/British Council Institutional Links Program (2016–2018) for disaster communication and management systems using 5G networks. He currently serves as an Editor for the KSII Transactions on Internet and Information Systems. He was the Co-Chair of the 2017 International Workshop on 5G Networks for Public Safety and Disaster Management.



Fadi Al-Turjman received his Ph.D. degree in computer science from Queen's University, Canada, in 2011. He is a Professor with Near East University, North Cyprus. He is a leading authority in the areas of smart/cognitive, wireless and mobile networks' architectures, protocols, deployments, and performance evaluation. His record spans over 200 publications in journals, conferences, patents, books, and book chapters, in addition to numerous keynotes and plenary talks at flagship venues. He has authored/edited more than 20 published books about cognition, security, and wireless sensor networks' deployments in smart environments with Taylor & Francis, and the Springer (Top tier publishers in the area). He was a recipient of several recognitions and best papers' awards at top international conferences. He also received the prestigious Best Research Paper Award from Elsevier COMCOM Journal for the last three years prior to 2018, in addition to the Top Researcher Award for 2018 at Antalya Bilim University, Turkey. He led a number of international symposia and workshops in flagship IEEE ComSoc conferences. He is serving as the Lead Guest Editor in several journals, including the IET Wireless Sensor Systems, Springer EURASIP, MONET, MDPI sensors, Wiley&Hindawi WCM, and the Elsevier COMCOM, SCS, and Internet of Things.



Adnan Yazici received the Ph.D. degree in Computer Science from Tulane University, USA, in 1991. He is currently a full professor and Chair of the Department of Computer Science in Nazarbayev University in Nur-Sultan, Kazakhstan and a full professor at the Department of Computer Engineering, Middle East Technical University, Ankara, Turkey. He has published over 200 international technical papers and co-authored a book entitled Fuzzy Database Modeling (Springer). His current research interests include wireless multimedia sensor networks, intelligent database systems, multimedia and video databases and information retrieval, data science, and fuzzy database modeling. He was a recipient of the IBM Faculty Award in 2011 and the Parlar Foundations Young Investigator Award in 2001. He was the Conference Co-Chair of the 23rd IEEE International Conference on Data Engineering in 2007, the 38th Very Large Data Bases in 2012, and the 23rd IEEE International Conference on Fuzzy Systems in 2015. He is currently an Associate Editor of the IEEE Transactions on Fuzzy Systems and a member of the Fuzzy Systems Technical Committee of IEEE Computational Intelligence.