Disseminating Shared Information in Disaster Relief Efforts: A Communication Computable Model

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***Abstract*—VHF radio systems commonly used to support search and rescue activities after disasters limit the flow of information among response teams deployed in the field. It generates islands of information that jeopardizes the coordination and effectiveness of the response activities. This article proposes a communication model that uses opportunistic networks and real-time messages delivery to help address such limitation. Since the communication model is computable, it is possible to diagnose the flow of information expected for a particular work scenario. The diagnose results allow identifying elements that could help improve the information flow in such scenario. This proposal allows first responders to address the stated problem during the phases of preparedness, response and recovery from a disaster.**

Keywords–communication computable model; opportunistic network; coordination activities; disaster relief efforts.

I. INTRODUCTION

The response process to extreme events affecting urban areas (e.g. earthquakes, hurricanes or tsunamis) involve several types of first responders, such as firefighters, police officers, medical personnel, and military task forces. All of them work in teams dispersed along the affected area. In an ideal situation, these teams are coordinated by disaster managers (i.e. decision makers) located in a command center. However in a real scenario, the improvisation is the common denominator during at least the first 48-72hs, and therefore every team in the field has to make their own decisions based on the information they have.

This lack of coordination is caused by two main reasons: (1) the typical delay in taking the control of the situation [12], (2) the lack of shared information to make local decisions and keep the coordination with other teams [10]. Although sometimes relevant shared information (e.g. maps of the affected area) is known and used by some response teams, such information does not flow naturally among them. It occurs because of the communication limitations of VHF radio systems used by the first responders to support interactions among them [2, 19]. This situation generates islands of knowledge with a few or no flow among them, which jeopardizes any attempt to coordinate the first response process. Increasing the information flow in the field should help make better and fast local decisions, and mainly to rescue a more important number of people during the first 72hs after an extreme event.

Trying to deal with the stated challenge this paper presents a communication computable model that uses opportunistic networks and real-time communication to help increase the flow of shared information among response teams. Initially the model considers response efforts performed in a small area; e.g. a town or a large neighborhood. Since proposed model is computable, it can be systematically used to design and diagnose the communication setting to deploy in the field. The model computability also makes these processes fast and cheap. These features become the proposed model into a interesting tool to use during preparedness, response and recovery from an extreme event.

Next section introduces several key aspects of the search and rescue process that are relevant to understand and validate the communication proposal. Section III presents and discusses the related work. Section IV formalizes the main structure of the communication computable model. Section V describes, through a formal representation, the information delivery using a couple of well-known routing strategies on the proposed model. Section VI shows how to calculate the Worst Case Time to Absorption (WCTA) for the model. The WCTA represents the longest expected time for a message delivery among two response teams. Section VII discusses strengths and weaknesses of the two analyzed routing strategies. Section VIII presents the conclusions and the future work.

II. ADDRESSING THE RESPONSE PROCESS

The *response* process to an extreme event involves a short time period (around to 72 hours) and it is focused mainly on performing search and rescue (SAR) activities [16]. Such period is also known as the "golden relief time". After that period the response process turn to the *recovery* of the affected areas and assistance of injured people, since the probability to find survivors is very low [4]. In means that SAR activities must be as fast and effective as possible, because the number of rescued people will depend on it. The coordination level of these activities affects directly their effectiveness.

Typically SAR activities involve teams dispersed in a small area (Figure 1). The communication capabilities among them is poor or null due to the typical messages overwrite or the lack of access to the communication channel [14]. In the best case, these teams are coordinated by an incident commander (IC) located in a command post.

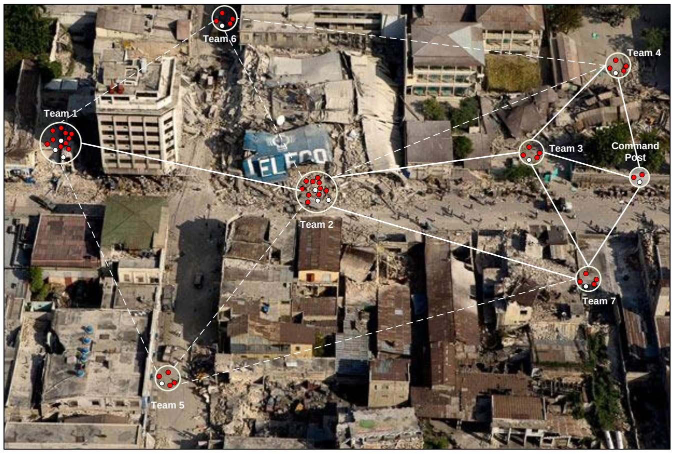

Figure 1. Search and Rescue Teams in the Field

SAR teams use VHF radio devices to support interactions among them, because the infrastructure-based communication systems are typically damaged or collapsed. Although radio systems are reliable, many teams remain isolated because of the limitation imposed by communication link [10, 14]. The isolated teams receive few or no information; therefore they have to improvise for reaching the teams' goals. The improvisation reduces the coordination and the effectiveness of the response process.

The authors hypothesize that *opportunistic networks and real-time communication can contribute to increase the flow of shared information among the SAR teams in the field*. Opportunistic Networks (oppnets) use the mobile devices' communication capabilities to build a network that transfers data from a source node to a destination one without knowing the path or route to follow [7]. An oppnet can be seen as a subset of Delay-Tolerant Networks where communication opportunities are intermittent, so an end-to-end path between source and destination may never exist. The nodes of an oppnet can be cell phones, PDAs, netbooks, or any other mobile computing device with wireless communication capability.

By real-time communication we mean a process in which the messages generated at the source node should arrive to the destination one before a certain instant (i.e. deadline) without errors. It is important to notice that real-time communication is neither live nor fast. Being real-time is just related to the satisfaction of temporal constraints.

The communication model proposed in this paper adheres to real-time concept for the messages delivery, and uses an opportunistic network as communication support. Each node of the oppnet provides three main services:

1. *Recording the local information:* The node acts as a sensor that allows to record information provided by the local SAR team. Just shareable information (i.e. relevant for more than one team) is input into the system.
2. *Discovering neighbor nodes:* Using this function a node recognizes other nodes in the neighborhood, which are able to hold and transmit messages through the oppnet.
3. *Exchanging one-hop messages:* Since the network topology is unknown, each node should transfer a message to its neighbors.

Considering these three basic services, the proposed communication model should act as a wireless sensor network (WSN) with routing capabilities that allows delivering messages with the restrictions of a real-time system. Each node of WSN is potentially a consumer/provider of shared information, and also responsible for the messages delivery.

III. RELATED WORK

The typical communication limitations during disaster relief efforts are still under study by the scientific community [2, 10, 12, 14, 19]. Although it is still an open problem, there are some interesting proposals that try to deal with this challenge. For example McCarthy et al. [11] proposed an autonomous communication infrastructure to support SAR activities after avalanches in a mountain. Braunstein et al. [3] present a hybrid distributed wireless networking architecture to support medical emergency responses. Although these solutions were not designed to support SAR activities after a disaster, they could contribute to increase the flow of shared information in the field.

Aldunate et al. [1] and also Rodriguez-Covilli et al. [17] propose a wireless communication infrastructure based on Mobile Ad hoc Networks (MANETs) to support SAR teams in the field. Although these solutions have shown interesting results they do not consider real-time communication; i.e. they do not guarantee the message delivery before a deadline. Similarly, Gomes-Bello et al. [5] propose m-ARCE; an ubiquitous mobile office for disaster management, where users can send and receive information anywhere and anytime. The proposal is just a design, and it assumes that a reliable MANET will be always available to support the messages exchange.

Schöning et al. [18] propose a system that runs on a handheld device and uses augmented reality to support the communication of spatial information during an emergency response process. Although this proposal seems to be useful to deliver blueprint or sketches, it does not help increase the flow of information among first response teams in the field. There are also many other communication initiatives that involve novel communication infrastructure (e.g. WiMax mobile) and usually satellite communication. Although they provide strong communication support in the affected area, they require expensive mobile devices and supporting infrastructure (e.g., mobile antennas deployed on communication trucks), which make them unfeasible for most countries [2].

On the other hand, the research activities in opportunistic networks have increased during the last year, due to the spread of new handheld devices embedding important communication interfaces (e.g. Wi-Fi or Bluetooth). Most research works are related to specific applications, and do not address key design issues such as message delay or network overload. In [7] the authors introduce the concept of oppnet as an application-oriented network to support several mobile work scenarios. Then, they describe an oppnet as a peer-to-peer network [8], which can be used to improve effectiveness and efficiency of emergency preparedness and response activities [9]. However such research works do not analyze the efficiency or effectiveness of the proposal.

Huang et al. presents in interesting introductory survey on opportunistic networks [6]. Then, Nguyen et al. [15] review different routing strategies available in oppnets. These authors discuss the main strategies without considering real-time issues, which are relevant to support search and rescue activities.

Trying to deal with the stated problem this article proposes to use opportunistic networks and real-time communication to increase the flow of information among SAR teams deployed in the field, and thus to improve the coordination and effectiveness of such activities. Under the assumption that there is no stable path between source and destination nodes, the message delay or network latency is analyzed. Two well-known routing strategies are also analyzed and compared. Next section describes communication computable model that represents the proposal.

IV. The Communication Computable Model

A general model for an opportunistic network is very complex to build because there are many factors that should be considered, such as the node mobility pattern, transmission range or communication interferences. All these variables are almost impossible to combine in just one mathematical representation, therefore it is assumed a stochastic behavior for these systems. Basically, the probability of one node (i.e. SAR team) meets another one is modeled as a Poisson process. Using such simplification the network behavior can be captured in a single parameter λ, that represents the probability of two nodes meeting in a certain interval of time. Then, the time between two successive meetings can be modeled as a random variable with exponential distribution with parameter $1/\lambda$. Under these assumptions, the behavior of the oppnet can be seen as a Markov chain with an absorbing state. The source node is represented as the first state in the Markov chain and the destination node as the absorbing one. Each time a message is copied from one node to another, the process moves to a new state. In this way, the Markov chain is built on the number of messages' copies present at some instant in the system.

Formally, let $0 \leq t_{ij}(1) \leq t_{ij}(2) \leq \ldots$ be the successive meeting times between nodes i and j. The difference between two of them is $\delta_{ij}(n) = t_{ij}(n) - t_{ij}(n-1)$. It is assumed that $\{t_{ij}(n), n \geq 1\}$, $1 \leq i,j \leq N + 1$, $i \neq j$ are mutually independent and homogeneous Poisson processes with rate λ. In addition, $\{\delta_{ij}(n)\}$ are mutually independent and exponentially distributed with mean $1/\lambda$.

A transmission will occur if two nodes are within communication range. It is assumed the transmission is instantaneous and deterministic; it means there is no delay in transferring information from one node to other. Moreover, in case of being within communication range, the transmission is completed for sure.

An stochastic process, whose states X can take a discrete set of values and depend on time t, can be modeled as a function $X(t)$. Such function, that represents the state of the process at time t, is said to be a Markov chain if the following property is satisfied:

$$P\,[X(t_n) = x(t_n) \mid X(t_{n-1}) = x(t_{n-1}), \ldots, X(t_1) = x(t_1)] =$$
$$P\,[X(t_n) = x(t_n) \mid X(t_{n-1}) = x(t_n)]$$

where $t_1 < t_2 < \ldots < t_n$

A Markov process can be discrete time-based or continuous time-based depending on the way in which the process evolves in time. In particular, Continuous Time Markov Chains (CTMC) are used to model birth/death process, queuing systems, and systems reliability. The continuous time Markov process embedded in the chain has, for each particular state, a sojourn time that follows an exponential distribution. However, the succession of visited states follows a discrete time Markov chain. If a process is for example in state i, the holding time in that state will be exponentially distributed with some parameter $1/\lambda_i$, where i represents the population size (e.g. the amount of people infected with a virus). The holding time is a measure of how quick the process changes from one state to the next one. An absorbing state in a CTMC is a state to which the process will eventually arrive and cannot leave after.

In a CTMC, the transition probability function from a state i to a state j, with t > 0, can be described as follows:

$P_{ij}[t] = P[X(t+s) = j \mid X(t) = i]$ is independent of $s \geq 0$.

Summarizing, an opportunistic network can be modeled as a CTMC, where each state represents the number of message copies in the network. The first node in the chain represents the source node (e.g. the SAR team sharing information) and the absorbing node the destination one or sink (e.g. teams consuming such information). The sojourn times follow an exponential law having the required memory-less property of a Markov process. The transient state probabilities for each state may be computed following well-known CTMC theory. The following set of differential equations provides the transient probability distribution for each state, taking $\pi(0)$ as the starting probability of each state.

$$\frac{d\pi(t)}{dt} = \pi(t)\mathbf{Q} \quad (1)$$

where **Q** is the infinitesimal matrix generator given by the rate of transition from one state to the next one. It should be noted that in **Q**, the absorbing state is not included. The set of differential equations can be solved by different methods, e.g. using the Laplace Transform (**LT**).

The transient state probability provides information about the way in which the message is transmitted from node to node by computing the probability of being in each state at a particular instant. However, this is not the main concern in a real-time opportunistic network. In fact, what is more important in this case is to compute how much time is required for a message to reach the destination node (e.g. a consumer). It can be obtained by determining the time required by the CTMC to get into the absorbing state. The cumulative probability for each state is given by:

$$\mathbf{L}(t) = \int_0^t \pi(u)du \quad (2)$$

The above expression can be rewritten in terms of a set of differential equations:

$$\frac{d\mathbf{L}(t)}{dt} = \mathbf{L}(t)\mathbf{Q} + \pi(0) \quad (3)$$

with $\mathbf{L}(0) = 0$

The time spent before absorption can be calculated by taking the limit $lim_{t\to\infty}\mathbf{L}(t)$. As the equations are restricted to the non-absorbing states, the limit can be applied on both sides of (3) to obtain the following set of linear equations:

$$\mathbf{L}(\infty)\mathbf{Q} = -\pi(0) \quad (4)$$

From (4) the Mean Time To Absorption (MTTA) can be computed as:

$$\mathtt{MTTA} = \sum_{i=1}^{N} L_i(\infty) \quad (5)$$

Another interesting parameter to evaluate is the expected number of copies present in the network at time *t*, *m(t)*. This can be computed from the solution to equation (1).

$$m(t) = \sum_{i=1}^{N} i\pi_i(t) \quad (6)$$

V. Message Routing in Oppnets

In order to understand the flow of information in these oppnets, this section presents and compares the particular solutions for couple of well-known routing strategies: *epidemic routing* and *spray and wait.*

The epidemic routing is based on the dissemination of a virus in biology. Basically, a node with a message copy transfers such message to every neighbor node. In contrast with the previous one, in spray and wait there are two phases. In the first one the source node passes the message up to R neighbor nodes. During the second phase all the (R+1) nodes holding the message are in condition to deliver it to the destination one.

A. Epidemic routing

Epidemic routing uses the maximum amount of resources available in the network. As has been already mentioned, each node receiving the message becomes a vector able to propagate it to other network nodes. In this way, a message copy may be present in every node, consuming thus memory and bandwidth. In epidemic routing, messages are delivered with maximum throughput, which may be desirable in an oppnet operating with time restrictions.

Using the Inverse Laplace Transform (LT^{-1}) we can calculate the transient probability function. Therefore the MTTA for epidemic routing can be defined as follows:

$$\mathtt{MTTA} = \frac{1}{N\lambda}\sum_{i=1}^{N}\frac{1}{i} \quad (7)$$

As can be seen, the MTTA is inversely proportional to the number of nodes in the network and the rate at which the nodes meet. A highly connected network, that is one in which the nodes have an important rate of meeting each other, is significant to achieve a good throughput.

The expected number of copies can be computed from (6). Since there is no general expression for the $\pi_i(t)$, the solution to equation (6) depends on the number of nodes in the network.

B. Spray and Wait

The construction of the CTMC model is a bit tricky since the general behavior of the network is not changed. Particularly, the rate at which the nodes meet each other and the mobility are still the same. However, only a reduced number of nodes ***R*** hold a copy of the message.

The transient probability function for the different states can be computed as in the previous case with the help of the Laplace Transform. Therefore, the MTTA for stray and wait can be defined as follows:

$$\mathtt{MTTA} = \frac{1}{\lambda}\left[\frac{1}{N} + \sum_{i=2}^{R}\frac{(N-1)!}{(N-i)!N^i} + \sum_{i=R+1}^{N}\frac{(N-k+R-1)!}{(N-i)!N^R}\right] \quad (8)$$

The average number of message copies in the system before the message reaches the sink (e.g. consumer node) can be computed with equation (6). However, as the CTMC in this case catches the movement of the source and not strictly the number of copies, the equation should be modified:

$$m(t) = \sum_{i=1}^{R} i\pi_i(t) + \sum_{i=R+1}^{N} R\pi_i(t) \quad (9)$$

Similar to the previous strategy, there is no close form for every term, therefore it should be computed for each particular case.

C. Epidemic routing vs. Spray and Wait

In what follows an example is given for an oppnet with seven nodes, six of them are relays and the seventh is the sink. Both routing strategies are compared using the MTTA and *m(t)* values.

The first thing that should be constructed is the infinitesimal matrix generator ***Q*** for each routing strategy (Figures 2 and 3). For easing the presentation we consider λ=1.

$$\begin{matrix} -6 & 5 & 0 & 0 & 0 & 0 \\ 0 & -6 & 10 & 0 & 0 & 0 \\ 0 & 0 & -6 & 12 & 0 & 0 \\ 0 & 0 & 0 & -6 & 12 & 0 \\ 0 & 0 & 0 & 0 & -6 & 10 \\ 0 & 0 & 0 & 0 & 0 & -6 \end{matrix}$$

Figure 2. ***Q*** for the Epidemic routing

$$\begin{matrix} -6 & 5 & 0 & 0 & 0 & 0 \\ 0 & -6 & 4 & 0 & 0 & 0 \\ 0 & 0 & -6 & 3 & 0 & 0 \\ 0 & 0 & 0 & -5 & 2 & 0 \\ 0 & 0 & 0 & 0 & -4 & 1 \\ 0 & 0 & 0 & 0 & 0 & -3 \end{matrix}$$

Figure 3. ***Q*** for the Spray and Wait routing, with ***R*** = 3

The computation of the MTTA is done from equations (7) and (8), for the epidemic and the spray and wait strategies respectively.

$MTTA_e = 0.4083$

$MTTA_{s\&w} = 0.4907$

The average number of copies present in the system at the moment of delivering the message to the destination node is the following one:

$m(MTTA) = 1.4620$ (for epidemic routing)
$m(MTTA) = 0.9730$ (for spray and wait)

The obtained results show what was expected. Epidemic routing is almost a 25% faster in delivering the message than spray and wait. However epidemic demands more network resources since it copies the message to every neighbor node. Moreover, once the message has arrived to the destination the epidemic routing keeps propagating the message among the nodes that do not have it yet. Eventually, a copy of the message is in the buffer of every node in the network. In the spray and wait instead, the delay in the network is higher, but the amount of copies required is low, basically because it is limited to $\boldsymbol{R}$. In several work scenarios (such as disaster relief efforts) it could be important to reduce the network load.

VI. Opportunistic Networks and Worst Case Behavior

The network throughput is based on a best effort. As has been shown in the previous sections, the number of nodes in the network and the mobility of them determine the average performance. For real-time applications it is necessary to keep within bounds the message delay, therefore worst case assumptions can be made. It is clear that working on worst case assumptions eliminates the stochastic nature of the oppnet making it work in a deterministic way. Even if the CTMC model is not used in this case, the idea of a process moving from one state to the next one till reaching an absorbing state, is kept. In what follows, the Worst Case Time to Absorption (WCTA) is computed for the previously discussed routing strategies.

For the case of direct-transfer, the message is delivered when the source meets the destination. If the source node knows the location of the destination one and it has a certain mobility pattern (i.e. the time required to get the destination node can be computed), it is possible to determine the worst case transmission time as follows.

$$\mathtt{WCTA} = \frac{distance}{VMG} \tag{10}$$

where *VMG* stands for Velocity Make Good, that is the actual speed towards the objective (it is not the speed of the vehicle). In epidemic routing, a worst case situation may be built considering that only when all nodes but the destination have a message copy, it gets to the destination one. Let us consider a situation in which each node have contact just with the next one (i.e. the network topology is a line). In that case, the situation is similar to the direct-transfer analyzed before. Depending on the number of nodes in the network, this situation can be reflected by the following equation:

$$\mathtt{WCTA} = \sum_{i=1}^{N} \frac{distance_{i,i+1}}{VMG_i} \tag{11}$$

In the spray and wait strategy, the worst case situation is built upon the previous one. Only the last node receiving a message copy from the source will be able to make contact with the destination one. Therefore the WCTA is defined as follows:

$$\mathtt{WCTA} = \sum_{i=1}^{R} \frac{distance_{1,i}}{VMG_{1,i}} + \frac{distance_{R,destiny}}{VMG_{R,destiny}} \tag{12}$$

An interesting message transportation strategy that can be used as a compliment of the routing strategy, is the mobile carrier. A mobile carrier or *mule* is a special node with a certain mobility pattern that is used to connect distant sub-networks (e.g. dispersed SAR teams). It can be a fireman, a fire truck, an ambulance or any other vehicle able to transport a mobile computing device. If these mules are periodic and with known paths, it is also possible to compute the worst case transmission delay between the gateways in the sub-networks. If the message is generated just after the *mule* has passed, there will be a T_p waiting time before it has a possibility of transmitting the message. The transmission delay depends on the time the *mule* needs to get the destination, T_f.

$$WCTA = T_p + T_f \tag{13}$$

Computing an end-to-end WCTA between different sub-networks linked by *mules*, the equations 10 to 13 should be combined conveniently.

VII. Discussion

The behavior of the network will be conditioned by the situation after the extreme event, and the network throughput will depends on the number of network nodes and the parameter λ. In the case of the rescue team, λ will usually have an important value since the SAR teams carry out their work in a particular spot within the disaster area. Determining the value of λ for the general network is difficult because it depends on many factors that are relative to the situation after the event. However the increment in the number of nodes reduces the message delay.

Taking advantage of this situation we can use several vehicles, such as ambulances, police cars, and fire/army trucks, as *mules* that help increase the transfer ratio of the oppnet, by incrementing the nodes' meeting ratio. In a best effort, every possible mule should be used to support message exchanges in the field. However, providing real-time guarantees requires determining the worst case scenario in order to keep within bounds the message delay.

In the worst case scenario the transmission of information between the command post and the SAR teams requires predictability. Since the oppnet providing the communication link has a stochastic behavior, it is not possible to provide a guarantee or a bound for the network throughput. This situation can be addressed if the SAR operations incorporate periodic mules with known paths and possible "*alarm mules*" for emergency calls.

The network delay in "*normal operation*" can then be analyzed based on a Round Robin policy. Thus, the worst case occurs when a message is ready to be sent just after the mule has passed by the gateway. In that case, the message will have to wait for a period. If the mule has a fixed path, then depending on the position of the source/destination nodes, there will be a transmission time that is equal to the time necessary to go from one place to the other one. The transfer times between the hand-held devices used by SAR teams can be ignored, since they are at least one order smaller. Equation 13 gives us the upper bound message delay T_d for a message to go from one node to the destination one, where T_p is the period of the mule, and T_f is the maximum travel distance time between any two nodes.

$$T_d = T_p + T_f \qquad (14)$$

In the case of using an "*emergency mule*" in (14), $T_p = 0$. This situation is completely extraordinary and should be used only in cases in which it is impossible to wait for the ordinary mule.

VIII. Conclusions and Future Work

This article proposes a communication computable model that combines the use of opportunistic networks and real-time concepts to help increase the flow of shared information among SAR teams deployed in a disaster scenario. Two well-known routing algorithms are analyzed and compared on such communication model: *epidemic* and *spray and wait*. Although the throughput in epidemic routing is higher than in spray and wait, both seem to be suitable to increase the information flow in the work scenario. The use of mules can also contribute to increase considerably the network throughput.

Since real-time delivery is considered, the paper defines a formula to calculate Worst Case Time to Absorption. This indicator determines the maximum delay that must be considered in messages transportation. The article also shows how to calculate the Mean Time To Absorption, which represents the expected average time for messages delivery.

These two indicators allow us understand how the information would flow in the field, and based on that, to determine if mules will be required to improve the network throughput. A large throughput helps to disseminate the shared information and thus, to increase the availability of shared information to make decisions and coordinate the SAR activities the field.

Since the proposed model is computable, it can be used during the *preparedness* phase [13] to plan how to disseminate the shared information during an eventual response process. Provided the use of the model is easy and fast, it can be also used during *response* phase to identify weaknesses in the communication flow, and eventually to determine how much and which mules are being required in a specific area. During the *recovery* phase the model can be used to design the communication support that will be required by the first responders to keep the coordination among them.

The next step in this research work considers evaluating the proposal into a simulated scenario, but using real-world communication networks. Such evaluation allows us to determine the accuracy of the proposed model, and eventually to identify improvement issues.

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