A Real-Time Analysis Approach in Opportunistic Networks

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***Abstract*—There are several mobile work scenarios requiring real-time messages. Examples of these scenarios are disaster relief or mobile work in isolated areas. Although opportunistic networks are not intended for real-time messages, under certain conditions the communication could be feasible. This paper presents the schedulability analysis of an opportunistic network for real-time traffic. It includes a stochastic and deterministic analysis of the network performance. Moreover, a scheduling policy is also proposed.**

I. Motivation

In several areas, such as disaster relief efforts, mining operations and health campaigns in rural areas, the work requires real-time communication. However, opportunistic networks (oppnets) are the main communication infrastructure that is feasible implemented to support information exchange among mobile workers. Although opportunistic networks were not proposedF for real-time communication, under certain conditions they can do it and thus, they could provide a communication solution to various work areas.

Oppnets is a rather new concept born around 6 years ago [1]. The key idea behind this kind of networks is to use mobile devices to build a network to transfer data from a source node to a destination one without knowing the path or route to follow. An oppnet can be seen as a subset of Delay-Tolerant Networks where communication opportunities are intermittent, so an end-to-end path between the source and the destination may never exist [2]. A source node passes its message to a nearby node. Nodes move around and while being near to others pass the messages they have to them and at some point the destiny node is eventually reached. The basic characteristic is that the nodes may enter and leave the oppnet at any time, they can move and take with them the messages. Usual elements to become part of an oppnet are cell phones, netbooks, or any electronic device with communication capacity. The oppnet may be based on any kind of communication technology such as WI-FI, Bluetooth, ZigBee.

In work scenarios like disaster relief efforts, oppnets provide an important alternative to support the information exchange among first responders. After a natural disaster (e.g. earthquakes, tsunamis or hurricanes) most traditional communication systems are collapsed or damaged. Search and rescue teams deployed in the field use a VHF radio system to communicate and coordinate the activities among them. Although this system has shown to be useful and robust. It also has several limitations that have been broadly discussed in the literature; e.g. the communication based on broadcast and the impossibility to transfer digital information (e.g. maps or pictures) [3]. In these situations, an opportunistic network based on mobile computing devices can help improve the communication support in the field. The network is built upon a multi-hop chain that transfers information from the command center (or command post) all the way down to the teams in the field and back. It has real-time characteristics as the time in which the information should go from one end to the other has to be bounded. The mobile devices may be from smartphones to notebooks. The physical link used to pass messages may be based on IEEE 802.15.X (from Bluetooth to ZigBee) or Wi-Fi ad-hoc networks based on IEEE 802.11".

In oppnets, there is no requirement for the nodes to know the path between source and destination. Current research in opportunistic networks is putting the effort on the construction of application models oriented to environmental monitoring (ZebraNet or SWIM projects [4]), emergency handling applications [5], and social networks [6]. Even if these applications seem completely different they share common principles for the routing strategies. The efficiency measured in terms of throughput, latency or end-to-end message delay is in conflict with other important issues like battery duration (energy consumption), memory usage, bandwidth requirement, etc.

Oppnets are based on a best effort routing strategy. As there is no known path between source and destination, a message delivery relies on cooperative policies in which it is necessary to use intermediate nodes as carriers. The routing strategy is at the core of the oppnet performance. Two main approaches are used. In the first one, direct-transmission, only the source node is capable of transmitting the message to the destination one. In the second approach, epidemic routing, the message is passed from node to node as a virus spreading in a population. This strategy demands much more bandwidth as every node in the network may eventually have a copy of every message generated but the throughput is better. On the contrary, direct-transmission demands very little bandwidth but its throughput is very low. Between both extremes there are many different combinations that try to solve the trade-off.

Contribution: The main contribution of this paper is the introduction of real-time analysis for the realization of opportunistic networks oriented to emergency handling after natural disasters. Under the assumption that there is no stable path between source and destination nodes, the message delay, or network latency will be analyzed and worst case behavior will be computed.

Organization: The rest of the paper is organized in the following way. Section II presents the stochastic model of oppnets and the traditional tools to evaluate its performance. In Section III the real-time schedulability problem is analyzed and a solution is presented. Finally in Section IV conclusions are drawn and future work is presented.

II. System Model

In what follows the system will be analyzed considering only the emergency case situation. A more detailed description of the system model can be found in [7]. A general model for an opportunistic network is very complex to build. There are many factors that should be considered like node mobility pattern, transmission range, interferences, etc. All these variables are almost impossible to combine in just one mathematical representation so what is assumed is a stochastic behavior. Basically, the probability of one node meeting another one is modeled as a Poisson process. With this simplification the behavior of the network can be captured in a single parameter, λ, that measures the probability of two nodes meeting in a certain interval of time. With this, the time between two successive meetings can be modeled as a random variable with exponential distribution with parameter $1/\lambda$. Under these assumptions, the message passing in an 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.

For a transmission to occur it is necessary that two nodes are within communication range. It is assumed that the transmission is instantaneous and deterministic, that means there is no delay in the transfer of information from one node to the other and that in case of being within range, the transfer is completed for sure. With this assumption, the problem of messages scheduling in the nodes is left for Section III.

A. Markov chain model

In what follows, it is assumed that each node has only one message ready to be delivered.

Markov Chains has been adopted for the study of communication systems, reliability models, etc. An opportunistic network can be modeled as a Continuous Time Markov Chain (CTMC). For this case, each state represents the amount of copies of the message in the network. Figure 1 shows an schematic of a $N+1$ nodes network with classic epidemic routing, that is every node holding the message is able to pass it to another node, weather is the destination node or not. The sojourn times follow an exponential law which has the required memoryless property of the Markov Process.

The transient state probabilities for each state may be computed following well known Markov Chain theory. Solving the following set of differential equation provides the transient probability distribution for each state, taking $\pi(0)$ as the starting probability of each state.

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

where $\mathbf{Q}$ is the infinitesimal matrix generator given by the rate of transition from one state to another [1]. $\mathbf{Q}$ is constructed as shown in Figure 2. It should be noted that in $\mathbf{Q}$, the absorbing state is not included.

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 arrive to the destination node or sink. To do this, it is necessary to determine the time needed by the CTMC to get into the absorbing state.

The cumulative probability for each state is given by:

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

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

$$\frac{d\mathbf{L}(t)}{dt} = \mathbf{L}(t)\mathbf{Q} + \pi(0) \tag{2}$$

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 (2) to obtain the following set of linear equations:

$$\mathbf{L}(\infty)\mathbf{Q} = -\pi(0) \tag{3}$$

From (3) the mean time to absorption (MTTA) can be computed as:

$$\mathtt{MTTA} = \sum_{i=1}^{N} L_i(\infty) \tag{4}$$

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.

$$m(t) = \sum_{i=1}^{N} i\pi_i(t) \tag{5}$$

[1]Technically is not a matrix generator as the sink node is not included. For ease of explanation the name has been kept

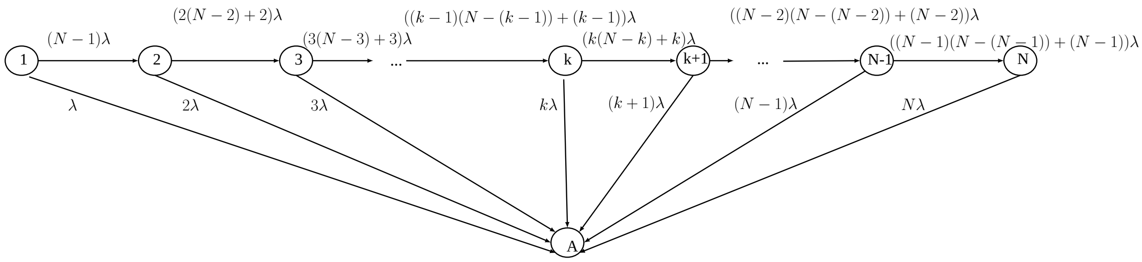

Fig. 1. Markov model for an Opportunistic Network of N+1 nodes with Epidemic Routing

$$
\begin{matrix}
-k(N-k)+k)\lambda & k(N-k)\lambda & 0 & \dots & 0 \\
0 & -(k(N-k)+k)\lambda & k(N-k)\lambda & \dots & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \dots & k(N-k)\lambda \\
0 & 0 & 0 & \dots & -(k(N-k)+k)\lambda
\end{matrix}
$$

Fig. 2. Matrix Infinitesimal Generator. $N+1$ is the number of nodes in the network and k the amount of copies in each state. Epidemic routing.

III. Real-Time and Oppnets - What is possible?

In Section II the communication model for an oppnet has been presented. It is clear that an oppnet works with a best effort approach and that no deadlines can be guaranteed with a routing strategy based on the node's encounters probabilities. For the oppnet to work with real-time parameters, certainty should be added to the routing strategy in order to transform it in deterministic.

Epidemic routing provides a fast propagation of the messages when the node's mobility is high. However, it consumes a lot of resources and for particular situations it turns out to be inefficient. For example, in an emergency handling situation, rescuers may move around a bounded area limiting the probability of encountering nodes outside it. Direct-transmission is not a good solution either. For it to be useful, a node holding a message should traverse the area until it reaches the destination node to pass the message.

It is important to remark that nodes in an oppnet have to perform multiple functions. They may be source and destination but also, as there is no physical and permanent link onto which transmit the messages, they become routers and link themselves. In fact, a node carries in its memory messages of other nodes that it has to transmit to the destination or to other intermediate nodes. With this in mind, the natural way to introduce a deterministic behavior in an oppnet is the use of special carriers or nodes named *mules* to link the rescuers in the field with the headquarters coordinating the actions (hospitals, police stations, military command, etc). The *mules* transform the stochastic communication model presented before in a *token ring*. Figure 3 shows this approach. Rescuers are grouped in cells. Each one, has a special node named *gateway* that collects the messages generated within the cell to be transmitted to other cells and receives the messages coming from outside. Within the cell, messages are transmitted following an epidemic routing strategy.

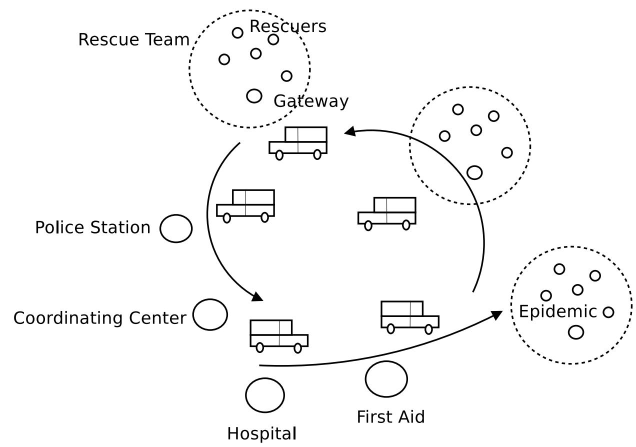

Fig. 3. Mules routing for Emergency Handling

Mules are special nodes that transport the messages among disconnected areas. They may be ambulances, fire trucks, police cars, helicopters, etc. For a real-time behavior, two kind of mules can be distinguish: periodic and sporadic. The first one has an specific trajectory that links predefined cells in a periodic fashion. In this way a worst case analysis can be performed. The second one, are seldom used as they are reserved for very special urgent situations. An sporadic *mule* will act only in an extreme case. It will act following a direct-transmission strategy linking end points.

A. Schedulability analysis

In this section, message scheduling is analyzed from a real-time point of view. It is important to notice here that there is a two level scheduling problem. In the first level, the routing strategy of the network is analyzed. In the second level, the messages ordering within the *nodes* is analyzed. As cells are reduced both in the amount of nodes and the area in which the nodes are disseminated, it is assumed that the epidemic routing within the cell is instantaneous and once the *gateway* transmits a message all nodes received it without additional delays.

a) Routing: As previously mentioned, periodic *mules* transform the routing strategy in a *token ring*. This network topology is well known in real-time communications. Only the node holding the token is able to use the channel. The token is passed from node to node in a round robin fashion. The worst case situation occurs when the message is generated just after the token leaves the node. In that case, it has to wait for a whole token's period before it can regain access to the channel. With the *mules* the situation is isomorph. The *mule* represents the token. When it visits a cell, the *gateway* passes messages generated in the nodes to it and receives the messages coming from outside the cell. Like in the *token ring*, the worst case situation arises when the *gateway* receives a message from one node in the cell that has to be transmitted just after the *mule* leaves. In the case of the *token ring*, the transmission delay in the channel is related to its physical characteristics. In the oppnets and *mules*, the delay is determined by the speed of the mule to move from one point to the other. This speed is not uniform and usually a direct line between two points is not possible. The worst case is determined by the two points farther away in the circuit of the mule. The maximum transmission delay from a routing point of view is then computed from the following equation:

$$T_{delay} = T_p + \frac{\texttt{Max\_Distance}}{\texttt{VMG}} \tag{6}$$

where T_p is the period of the *mule* and VMG stands for Velocity Make Good, that is the actual velocity of the *mule* between the extremes.

b) Node's scheduling: The routing schedulability analysis supposes that once a message is generated it will be delivered. However, this may not always happen in that way. Nodes, *mules* or *gateways* may have an important amount of messages to transmit enqueued. In this case, some scheduling policy has to be implemented to select the correct message to be delivered. Fixed priorities, Earliest Deadline First, Shortest Message First, First In First Out, etc. are possible scheduling policies to follow at the node level. Any of the previous ones can be selected and the whole schedulability analysis can be performed. However, it must be considered two additional aspects. In the first place, node's memory is limited so at some point messages may be eventually turned down. In the second place, it is useless to transfer a message from the *gateway* to the *mule* if there is no chance of arriving to destination before the deadline. A complete analysis of this situation exceeds the purpose of this work-in-progress presentation. Just to present an example, assume a FIFO scheduling of the messages within the *gateway* and that for reasons of limited buffer size, the *mule* can accept just one message from the *gateway*. A message will have to wait as many periods of the *mule* as the length of the messages' queue in the gateway at the moment of being generated. Equation 6 is modified in the following way:

$$T_{delay} = |MQ| T_p + \frac{\texttt{Max\_Distance}}{\texttt{VMG}} \tag{7}$$

where $|MQ|$ is the length of the message queue in the *gateway*.

c) Scheduling condition: From (7) it is possible to state the scheduling condition for an opportunistic network working with a *mule* routing strategy and FIFO ordering in the nodes' buffers.

Lemma 1: A message with deadline D originating at a node with maximum buffer length $|MQ|$ will meet its deadline if and only if:

$$|MQ| T_p + \frac{\texttt{Max\_Distance}}{\texttt{VMG}} \leq D$$

IV. Conclusions and Future Work

In this paper a real-time analysis of opportunistic networks has been presented. Although the opportunistic network paradigm is based on a best effort approach and no guarantees on message delivery are given, in certain cases like emergency handling after natural disasters like hurricanes or earthquakes, they may be used for an effective coordination of the team rescuers in the disaster area. The kind of temporal guarantees a communication model like this is capable of providing has been shown. The model supposes a two level scheduling that has to be further explored to obtain more precise results. In particular as future work a comparative analysis of performance is going to be done among the different scheduling policies.

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