Supporting Real-Time Message Delivery in Disaster Relief Efforts: an Analytical Approach

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Abstract. Several initiatives propose the use of opportunistic networks and heterogeneous devices to help overcome the communication and coordination limitations evidenced during first response activities in disaster relief scenarios. These solutions tend to create an Internet of Things ecosystem in which most components are mobile, autonomous and interact with other in a loosely-coupled fashion. Regardless the benefits provided by these infrastructures, the message delivery on them does not consider time constraints. This aspect is particularly relevant in this scenario since the time to conduct the first response activities is quite short, therefore they must be done quickly and coordinately. Trying to help address this challenge, this paper proposes a message propagation model for opportunistic networks that considers heterogeneous devices and guarantees the real-time behavior of the network by bounding the maximum delay for messages transmission. The message propagation is modeled using an analytical approach. Two different scheduling policies are used to analyze the model and their feasibility conditions are proved.

Keywords: Opportunistic Networks, Real-Time Message Delivery, Disaster Relief Scenarios, Mobile Computing Ecosystem

1 Introduction

Every year natural disasters hit urban areas and produce dramatic losses in terms of both, human life and damage to property. Example of these extreme events are earthquakes, tsunamis, wild fires, floods and volcano eruptions. Typically, the first 72 hours after the event (known as the "golden relief time") are the most important ones, since after that the probability to find survivors is really low [17]. In order to address the first response, several teams are deployed in the field, which usually involve firemen, police officers, medical personnel, and military units. Each team has a leader that coordinates the activities inside the team, with other team leaders, and also with an incident commander who is in charge of the operations in the field. In this scenario, it is very important to provide communication and coordination capabilities to the first responders.

When disasters strike, traditional communications collapse: telephone lines fall down and cell phone towers if not down are usually overloaded with messages and calls. Rescuers should use alternative communication channels. Usually, the interactions are done with VHF/UHF radio systems since it allows a quick deployment of the communication system, which is a mandatory requirement [10]. However, these systems have several shortcomings, such as limited number of channels, messages being overwritten by more powerful devices or mixed messages as transmitters are not well identified. Moreover, these radio systems are limited to support resilient network protocols and topologies, keep a multi-organizational coordination, and maintain information consistency [10]. Without an appropriate communication support, the decisions made by the incident commander and the team leaders are based only on their own experience, since no or little information is available to support such activity. Moreover, activities coordination becomes a challenge almost impossible to overcome. Given this situation, it is not surprising to see improvisation in the field [17] , which usually impact negatively on the emergency response process, as observed in the Yarnell Hill Fire (2013) [6] and also in World Trade Center (2001) [11].

Many communication infrastructures have also been proposed to try deal with the need of a suitable (digital) communication; most of them are based on mobile ad hoc networks (MANETs) or opportunistic networks(OppNets), and mobile computing devices [1, 5, 7, 16]. Recently, these infrastructures have been evolving toward the Internet of Thing (IoT) scenario, where many heterogeneous devices interconnected via MANETs or OppNets interact to provide information support and also additional communication and coordination capability to first responders [12, 14]. The current availability of IoT-enabled devices can help increase the resilience of the communication in the field, by leveraging their spontaneous wireless networking capabilities while the conventional communication infrastructure is out of service [15].

In [17] the use of an opportunistic network for collaborative applications (like the one needed in the first hours after a natural disaster) is analyzed and the first concepts of time constraints are introduced. In [18] there is an analysis of real-time traffic for the case of FIFO scheduling at the gateway without priorities.

In [2] the authors analyze the stochastic performance of different routing strategies under different inter-meeting times distributions. The authors do not contemplate a real-time behavior as no deterministic guarantee is provided. Additionally,

The use of mules has been proposed in previous works, as a way to keep the network resilient in case of node failures or to transport data in distributed networks that cover wide areas without communications infrastructure (or with limited connections among nodes). In [9] different techniques are proposed to determine the mules paths considering the geographic conditions and the infrastructure present. In [4] a trade-off analysis is presented to minimize the number of mules in the system, while guaranteeing throughput requirements on one side and the optimum path to cover the territory.

Regardless the usefulness of the previous works, they do not consider accomplishing with real-time restrictions for the message delivery. This requirement is mandatory in disaster relief efforts given the time constraints existing to conduct the first response activities during the golden relief time. In this sense, this proposal takes a step forward in order to try deal with a challenge that still remains open. The proposal also opens the door to the participation of IoT world in these solutions, since a wide variety of computing and sensing devices can become part of this ecosystem.

The main contribution of this paper is a bounded message propagation model for OppNets that involves IoT-enabled devices as nodes, and supports communication in the field during first responses. An analytical approach is used to represent the propagation model and the IoT-based communication infrastructure. Although the message delivery in OppNets is based on a best effort approach, it can be used in several real-time environments if certain conditions are met. The paper also introduces two message scheduling policies for these networks and computes the maximum delay for the message delivery. With this information, the feasibility of implementing a real-time OppNet is evaluated.

Next section describes the proposed model emphasizing in its role as facilitator of the message propagation in the disaster area. Section 3 shows the schedulability analysis of the proposed models. Section 4 presents an example, and Section 5 presents the conclusions and future work.

2 System Model

In a disaster relief scenario, the VHF radio systems used by first response teams although easy to use impose several limitations. In [13] some of the most important are explained. These are the impossibility to transmit digital information and the lack of enough channels for all the teams and the general coordination. An alternative to address these limitations is to use mobile phones, but after a disaster typically most infrastructure-based communication systems are damaged or collapsed. Therefore, we follow [1, 5, 7] to use OppNets built upon a multi-hop chain that transfers information from the command post to the teams in the field and back. As there are time restrictions, the transmissions have real-time characteristics. Message end-to-end delay should be predictable.

Fig. 1 shows a general deployment of first response teams and the different actors involved in a disaster relief ecosystem. First response teams are typically coordinated by an incident commander (IC), who is located in the command post (in the field). From there, the IC assigns tasks and coordinates activities of the first responders. Each team has a *gateway*, i.e., a person/device who is in charge of coordinating activities with other teams. This node receives the information from its team members and transfers it to the command post. At the same time, it receives the orders and recommendations from the IC and transmits them to the team members.

Typically, the area in which teams are deployed is large, and the distance among the teams and also between them and the command post is too big

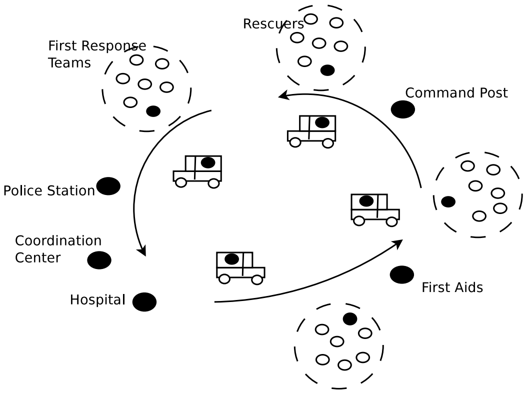

Fig. 1. Mules routing for emergency handling. Gateways are marked in black; small black circles are the gateways of the first response teams

to allow for a direct link. To cope with this problem, *mules* are introduced for transporting the messages in both directions. Mules can be implemented in different ways, for example with drones, motorcycles, cars (autonomous or not), or even bicycles [8]. The information flow in the system has four steps: $N \rightarrow G \rightarrow Mule \rightarrow G \rightarrow N$ Where N denotes a node and G is the gateway related to that node. We assume no gateway failures given that any node can take over the role of the gateway.

From a communications point of view, each team is independent of any other. That is, the communication being held inside a team has no influence on other teams, either because they are working at a different radio frequency channel or because they are so distant that their radios are not interfering with each other. Based on this, we can define the set of *gateways*: $\mathbf{\Gamma} = \{G_1, G_2, \ldots, G_n\}$ Each of the n *Gateways* is responsible for interchanging messages with the *mules* and the nodes. That is, *mules* only communicate with a node through a *gateway.* For each G_i there is a set of n_i nodes: $\mathbf{N}_{G_i} = \{N_{i_1}, N_{i_2}, \ldots, N_{i_n}\}$

In real-time, system predictability is mandatory, as every possible situation should be contemplated to guarantee the deadlines. Although contention based protocols work well in the average, the back off algorithms introduce uncertainties at the transmission moment preventing their use in real-time communication systems. Time Division Multiple Access (TDMA) protocols are suitable for real-time operation as they are able to transmit messages in a predictable (bounded) time, since each node has access to a transmission slot periodically.

In TDMA schemes, time is considered to be slotted and the duration of one slot is considered as the unit of time. The duration of the slot is determined by the system designer and it involves parameters like the speed of the *mule* and the distance both in time and space between two consecutive *mules.*

Each node $N_{j_i} \in G_j$ has a set of μ_i messages to transmit, $M(N_{j_i}) = \{m_{ji1}, m_{j_{i2}}, \ldots, m_{j_{i\mu_i}}\}$. Moreover, three types of messages are considered in the system: periodic, sporadic and aperiodic. They are described by a tuple

$m_{jih}\langle P_{jih}, C_{jih}, D_{jih}\rangle$, where P_{jih} is the period or minimum intergeneration time of the message, C_{jih} is the worst case time for transmitting a message and D_{jih} is the deadline. Both periodic and sporadic messages have to be received before their deadlines, while aperiodic messages have no real-time constraint. That is, deadlines associated with these messages are infinite and they have the lowest priority in the system; they are usually transmitted if there is time. Sporadic messages are aimed to handle emergency calls, such as imminent possible explosions or breakdowns. Once a node generates a periodic or sporadic message, it has to wait for the minimum time (specified by the period) to generate a new one of the same kind.

3 Real-Time Schedulability Analysis

In this section, message scheduling is analyzed from a real-time point of view. We determine that there are four scheduling stages: *nodes-gateways*, *gateways-mules*, *mules-gateways* and *gateways-nodes*. In what follows, for illustration, feasible conditions for each level are determined for two scheduling policies: First In First Out (FIFO) and Rate Monotonic (RM) [3].

The end-to-end worst case transmission time requires the analysis of each stage in the transmission process. Due to the real-time requirements, the scheduling in each stage is analyzed considering the worst case situation. Equation 1 establishes the end-to-end delay for a message m_i originated at *node* $i \in G_j$ and destined to node $h \in G_k$.

$$T_{\texttt{end\_to\_end},i} = T_{NG} + Wait_G + Wait_M + T_{GN} \tag{1}$$

where T_{NG} is the time required for the message to go from the node to the gateway; $Wait_G$ is the time the message spends in the gateway until it is completely uploaded to the mule; $Wait_M$ stands for the time the message is in the mule until it is received by the destination gateway; and T_{GN} is the time required for the message to go from the gateway to the destination node.

In Sections 3.2 and 3.2 we will show how these variables are derived for FIFO and Rate Monotonic scheduling protocols, and shown in Equations 2 and 3.

3.1 Node-Gateway

For real-time messages, TDMA variants have been proposed [19]. TDMA reserves a slot in every frame for each node that needs to transmit. Node's clocks should be synchonized. The first response teams may have between 10 and 30 people [6], plus a set of sensors for a maximum of 40-50 nodes in a team.

Each node transmits in a fixed slot time, τ, in every frame T_f. The worst situation for a message in a node is to be generated just after its time slot. In that case, the node will have to wait for the next frame before being able to start to transmit the message. If message length C is greater than τ, a total of $T_f = \lceil C/\tau \rceil$ frames would be necessary.

If the node has several messages to transmit, different approaches can be considered. The simplest one is to assume a FIFO order; in that case, the worst case situation occurs when the message is the last one in the node's queue, MQ.

Lemma 1. *For a maximum of* $|MQ|$ *messages in a node, the worst case delay for a single node to transmit a message to a gateway with FIFO order is given by:*

$$T_{NG} = T_f \sum_{i=1}^{|MQ|} \left\lceil \frac{C_i}{\tau} \right\rceil \tag{2}$$

Note: we dropped the subindex reflecting the gateway and the node, because we are just analyzing the node delay, which is independent of the others.

In case that rate monotonic (RM) order is used for transmitting, each priority level has its queue, where messages wait for being transmitted. In that case, higher priority messages are always dispatched before lower priority ones. Typically, the number of priority levels is restricted for implementation details.

Lemma 2. *Equation 3 defines the delay to transmit a message from a single node to the gateway with rate monotonic ordering. Where* HP *denotes the set of higher priority messages.*

$$\min t \ \mathtt{s.t} \ t = T_f \sum_{i=1}^{|MQ|} \left\lceil \frac{C_i}{\tau} \right\rceil + \sum_{j \in HP} \left\lceil \frac{t}{T_j} \right\rceil T_f \left\lceil \frac{C_j}{\tau} \right\rceil \tag{3}$$

Within the first response team, the *gateway* is another *node* with its own time slice within the frame. Therefore, the previous analysis is valid for the reverse case in which messages are transmitted from the *gateway* to the *node*. In other words, the GN and NG delays can be analyzed jointly.

3.2 Gateway-Mule-Gateway

Once messages are queued in the gateway for transmission, the following two hops (gateway-mule and mule-gateway) are analyzed together, given their symmetry. The message exchange between the *mule* and the gateway can begin as soon as they get into communication range and continue until they lose contact. When the *mule* and the *gateway* are within transmission range, they will exchange messages in a full-duplex way. The number of messages that they can exchange is then only restricted by the time interval in which they are within range.

The period of the *mule*, P_{mu}, can then be seen as the sum of two time windows, $P_{mu} = B+W$, where B is the duration of the blind window (i.e., when a gateway cannot transmit to the *mule*), and W is the duration of the transmission window. P_{mu} represents the interval of time between two consecutive mules connecting to the gateway.

Let us assume that $\forall i \ C_i = C$, The interval of time in which the *mule* is within transmission range with the *gateway* is the transmission window, noted

W. Thus, the number of messages ω uploaded to the *mule* by the *gateway* in the transmission window can be obtained from equation: $\omega = W/C$

The mules may have a queue for each gateway, so messages with destination nodes in the network of a particular gateway are enqueued there. The queuing capacity of a mule is equal to the number of messages that can be delivered during the transmission window. To guarantee that all the messages in the system are delivered by their deadlines, we have to ensure that enough mules are present for this, either by enlarging the transmission window or by incorporating more mules to the system. The number of mules in the system is notated ξ.

Mules start their trajectory at a certain gateway. This gateway has a privileged situation with respect to the others as it will always find an empty queue, while the following ones will have to wait for the arrival of a mule with an empty queue. This fact has to be considered when computing the set of messages that each gateway has to schedule. While the first gateway in the path only deals with the messages originated in its nodes, downstream gateways will have to consider their own messages and also those from the previous ones. Although these messages are not actually served by the gateway, they interfere with the transmission. The position within the path determines the priority in the same way a "daisy chain" arrangement does it.

The set of messages that gateway G_j has to deal with, is the union of all the messages from its nodes, plus all the messages generated in upstream gateways:

$$M(G_j) = \cup_{h=1}^{j-1} \cup_{i=1}^{n_h} \cup_{x=1}^{\mu_i} m_{hix} \tag{4}$$

where n_j is the number of nodes connected to gateway G_j and μ_i is the number of messages originating in node N_{j_i} of gateway G_j. The bandwidth required by the set of messages associated to gateway G_j is given by:

$$U_{M(G_j)} = \sum_{h=1}^{j} \sum_{i=1}^{n_j} \sum_{x=1}^{\mu_i} \frac{C_{hix}}{P_{hix}} \tag{5}$$

Lemma 3. *For a gateway G_j to be able to transmit its messages, the bandwidth demand for the set of messages associated to it should be:*

$$U_{M(G_j)} \leq \xi \frac{W}{P_{mu}} \tag{6}$$

FIFO: The waiting time for a message in a FIFO queue in the gateway is a function of the number of messages Q, generated in the *gateway* G_j and the interference that upstream gateways G_1 to G_{j-1} may introduce.

Lemma 4. *Provided (6) is satisfied, the worst-case waiting time for a message arriving to the gateway G_j is given by:*

$$Wait_{G_j} = \texttt{minimum}\ t\ \texttt{s.t.}\ t = B + Q \cdot C + \left\lceil \frac{\sum_{h=1}^{j-1} \sum_{i=1}^{n_j} \sum_{x=1}^{\mu_i} \left\lceil \frac{t}{P_{hix}} \right\rceil C_{hix}}{\omega} \right\rceil P_{mu} \tag{7}$$

The time spent by messages in the mule is just the time used by the mule to reach the destination gateway, because once messages are uploaded to the mule, they will be delivered at the destination gateway. $Wait_{mu} = T_{trip}$

Rate Monotonic: The use of rate monotonic priority order in the system is conditioned by the "daisy chain" disposition of the gateways. To avoid priority inversions that could eventually produce starvation in some gateways, the store-and-forward mechanism is used along the way. Like before, the mules queue length is equal to the amount of messages that can be uploaded to the mule while being in the transmission range of the gateway, ω.

Let us assume $\omega = 2$, there are three gateways, each one has a message and they are in reverse order of priority. Therefore, the first message has the lowest priority, but as it is the first in the "daisy chain" it is uploaded to the mule. In the second gateway, the medium priority message is uploaded. When the mule gets to the third gateway, the high priority message has to be uploaded to prevent a priority inversion, and the lowest priority message is exchanged by the highest priority one. To do this, the transmissions between the gateways and the mules are assumed to be full-duplex.

Like in the FIFO case, gateways downstream have to consider the interference of higher priority messages from upstream gateways. Note that the transmission order is not affected by the gateway position; it is only affected by the priority of messages, making the overall system fair.

Lemma 5. *Under Rate Monotonic order and subject to equation (6), a message m of priority π will have the worst case delay (in the gateway-mule-gateway path) given by:*

$$Wait_{G_j} = \texttt{minimum}\ t \ \ \texttt{s.t.}\ \ t = \sum_{\forall m \in \pi} C + B \left\lceil \frac{t}{P_{mu}} \right\rceil + \sum_{\forall \chi \in HP} \left\lceil \frac{t}{P_{\chi}} \right\rceil C \tag{8}$$

Mule transport time. In both cases, FIFO and RM, T_{trip} is the time spent by the message in the mule, which corresponds to the time the mule moves from the gateway where it got the message to the destination node, through its fixed path. Clearly, this is independent of the scheduling algorithm that is chosen and depends only on the technology used for the mules and other optimization criteria (e.g., saving fuel).

3.3 Scheduling Condition

Lemma 6. *An opportunistic network operating with mules and gateways implementing FIFO or RM order is schedulable if:*

$$\forall m_{ijh} \quad D_{ijh} \geq T_{\texttt{end\_to\_end},ijh} \tag{9}$$

4 Example

The following example shows the main characteristics of both FIFO and Rate Monotonic orderings at the *gateway* and how messages are delivered in each case by the *mule*. Let's suppose there are two *mules* in the system and that the round trip is $T_{\mathtt{rt}} = 10$. The distance between the *mules* is 5, that is the period of the *mule* is $T_p = 5$. In the worst case, the blind window is $B = 3$ leaving only 2 slots for the transmission window, $W = 2$. It is assumed that all messages have the same length and that it is equal to the slot. The *gateways* have queue length $|MQ| = 3$. With these parameters, the *gateway* can transfer to the *mule* only two messages in each transmission window, $\omega = 2$. As the *mules* move around the ring in one direction, in the worst case, the destination is just upstream and almost a whole round is needed for the *mule* to reach it. As $W = 2$ and $T_{\mathtt{rt}} = 10$, in the worst case the trip takes $T_{trip} = 8$ slots. Let the set of messages be: $M(G) = \{(6, 1, 40, 1), (6, 1, 40, 1), (15, 1, 100, 2)\}$. For the case of FIFO ordering all messages have the same priority and are put into the queue in order of arrival, for example m_1, m_2 and m_3. With Fixed Priorities, messages m_1 and m_2 have the highest priority in the *gateway* so they are transmitted whenever the *mule* is in range.

For the FIFO ordering, Figure 2 shows the evolution of the message transmission from the *gateway* to the *mule*. Each message is represented in a different row and color while the *mule* is represented in the last one with two colors, grey for the blind window and white for the transmission one. Arrows indicate the instant at which the messages arrive to the *gateway*. As can be seen, messages arrive just after the transmission window finishes. With the arrival of a new *mule*, two messages are uploaded. In this case m_1 and m_2. The boxes in the messages rows indicate that the messages are uploaded to the *mule*. The worst case response time is given by Equation 7.

For the case of RM ordering, there are two queues one for each priority. The worst case waiting time is given by equation 8, for messages (m_1, m_2) and m_3 is $t = 5$ and $t = 24$, respectively. In Fig. 3 the evolution of the messages transmissions are shown. Only at $t = 24$ in accordance with equation 8 message m_3 is able to get into the *mule*.

From the example, it is clear that RM benefits higher priority messages by delivering them first. However, as can be seen in Fig. 2 and 3 in both cases m_3 is dispatched and there is no backlog in the queue at the moment $t = 31$.

The traffic towards the *gateways* is restricted to 20% only for each *mule*. The network configuration and the time required for a *mule* to do a round-trip and the fact that there is only one going through a *gateway* each time, it is deduced that there are a maximum of two *mules*. So the maximum traffic in the network towards any *gateway* should not be greater than 40%. If all the messages in the *gateway* are transmitted towards only one *gateway* and considering that the demand is 36.7%, with the two *mules* mentioned it is enough to satisfy the demand.

Fig. 4 and 5 show how both *mules* deliver the messages in destiny. Each *mule* is represented in a different row. In white, it is shown a previous message that M_1

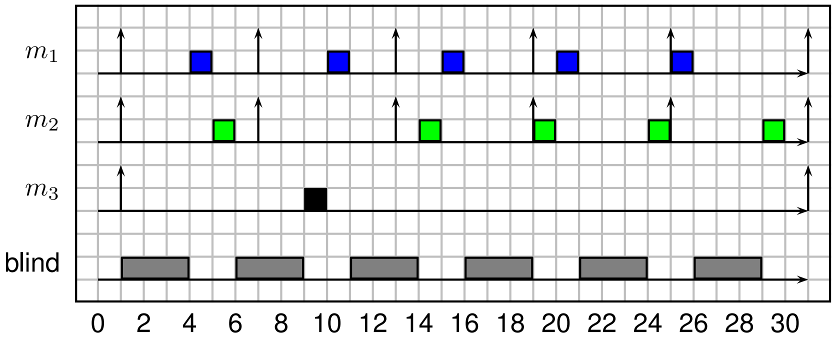

Fig. 2. FIFO ordering, m_1, m_2 and m_3, m_3 is able to get into the *mule* at $t = 9$.

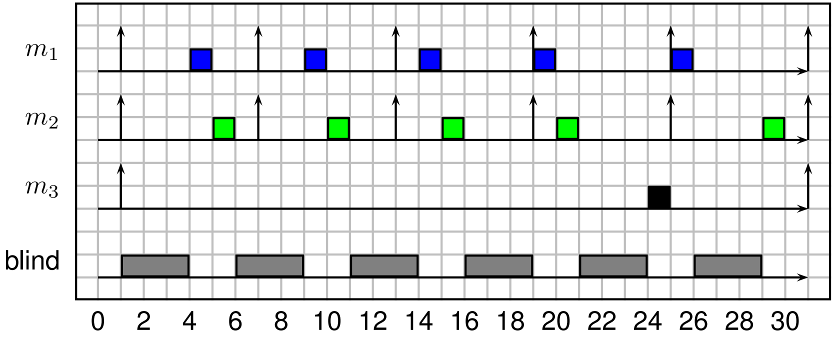

Fig. 3. RM ordering, m_1, m_2 and m_3, m_3 is able to get into the *mule* at $t = 24$

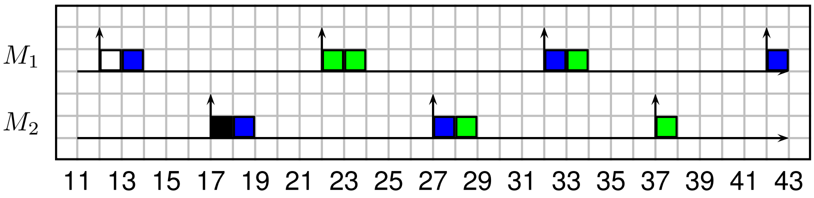

Fig. 4. m_1, m_2 and m_3. FIFO order in the *gateway*

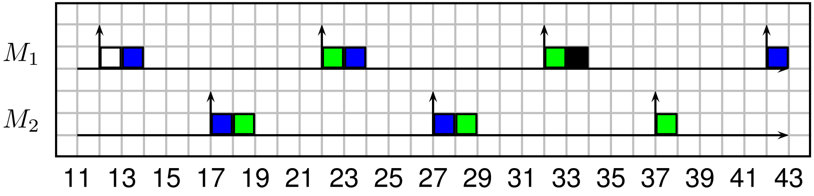

Fig. 5. m_1, m_2 and m_3. RM order in the *gateway*

may have queued before m_1 and m_2. The temporal sequence is correlated with Fig. 2 and 3, as can be seen the destination of messages originated in the *gateway* are just prior to coming back so the *mule* needs to do almost a complete round-trip before delivering the first message. The example shows that it is possible to deliver all the messages with just two *mules.*

It is necessary to compute the schedulability of the network by computing the delays in the gateways by using equations (10) and (11) for the FIFO and RM respectively.

$$T_{\texttt{end\_to\_end}} = NG + 9 + 19 + GN = NG + 28 + GN \tag{10}$$

$$\begin{aligned} T_{\texttt{end\_to\_end},m_1} &= NG + 5 + 19 + GN = NG + 24 + GN \\ T_{\texttt{end\_to\_end},m_2} &= NG + 5 + 19 + GN = NG + 24 + GN \\ T_{\texttt{end\_to\_end},m_3} &= NG + 24 + 19 + GN = NG + 43 + GN \end{aligned} \tag{11}$$

From the previous results it is clear that the system is schedulable if the delay in the transit of messages from the nodes to the *gateway* and the *gateway* to the nodes is less than: $NG + GN \leq D_i - T_{\texttt{end\_to\_end},i}$

5 Conclusions and Future Work

In this paper a model for real-time communications among search and rescue teams and incident commander in disaster relief areas is proposed. A a bounded message propagation model for OppNets that involves IoT-enabled devices as nodes, and supports communication in the field during first responses is introduced. Two scheduling policies were analyzed (FIFO and RM) in this context. While the first one facilitates the unrestricted information flow, the second one introduces priorities that guarantee that important messages arrive first to destination. Particularly, the analytic results show that the RM helps improve the response times of high priority messages, which usually are those that make a difference in disaster relief scenarios. These results provide predictability to real-time message propagation in an OppNet which is the main contribution of the paper.

Next steps in this initiative considers performing a proof-of-concept to verify the analytic results obtained based on the proposed model, and thus determine more accurately the impact of this proposal for both, the research community and the application domain.

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