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Modeling Emergency Traffic Using a Continuous-Time Markov Chain

Ahmad Hani El Fawal [1,2], Ali Mansour [1,*], Hussein El Ghor [2], Nuha A. Ismail [3] and Sally Shamaa [4]

1 Lab-STICC, UMR 6285—CNRS, ENSTA Bretagne, 29806 Brest, France; elfawal@ieee.org
2 CS Department, Modern University for Business & Science, Beirut P.O. Box 14-6495, Lebanon; hussein.elghor@ul.edu.lb
3 Information Technology Center, University of Technology, Baghdad P.O. Box 3071, Iraq; nuha_alali@yahoo.com
4 Center for Research in Applied Mathematics and Statistics (CRAMS), Beirut P.O. Box 14-6495, Lebanon
* Correspondence: mansour@ieee.org

Abstract: This paper aims to propose a novel call for help traffic (SOS) and study its impact over Machine-to-Machine (M2M) and Human-to-Human (H2H) traffic in Internet of Things environments, specifically during disaster events. During such events (e.g., the spread COVID-19), SOS traffic, with its predicted exponential increase, will significantly influence all mobile networks. SOS traffic tends to cause many congestion overload problems that significantly affect the performance of M2M and H2H traffic. In our project, we developed a new Continuous-Time Markov Chain (CTMC) model to analyze and measure radio access performance in terms of massive SOS traffic that influences M2M and H2H traffic. Afterwards, we validate the proposed CTMC model through extensive Monte Carlo simulations. By analyzing the traffic during an emergency case, we can spot a huge impact over the three traffic types of M2M, H2H and SOS traffic. To solve the congestion problems while keeping the SOS traffic without any influence, we propose to grant the SOS traffic the highest priority over the M2M and H2H traffic. However, by implementing this solution in different proposed scenarios, the system becomes able to serve all SOS requests, while only 20% of M2M and H2H traffic could be served in the worst-case scenario. Consequently, we can alleviate the expected shortage of SOS requests during critical events, which might save many humans and rescue them from being isolated.

Keywords: machine-to-machine; human-to-human; Internet of Things; Markov chains

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1. Introduction

The Internet of Things (IoT) has revolutionized daily life by enabling Machine-to-Machine (M2M) communication, connecting devices to the Internet to exchange information without human intervention [1,2]. Unlike Human-to-Human (H2H) devices, M2M devices submit small data packets in IoT networks [3,4]. On one hand, Long-Term Evolution Advanced (LTE-A) networks support H2H services like Voice over IP (VoIP), File Transfer Protocol (FTP) and video streaming. However, on the other hand, Low Power Wide-Area Networks (LPWANs) were coined to provide low-energy, wide-range connectivity for IoT devices [5]. In fact, ABI Research, which is a technology solution provider, projects that the number of IoT devices that use LPWAN technology will significantly increase to reach 5.3 billion connected devices by 2030 [6]. Under the umbrella of the 3rd Generation Partnership Project (3GPP), LPWAN technologies are categorized into non-3GPP technologies (e.g., Long-Range (LoRa) and Sigfox) and 3GPP-based technologies (e.g., Long-Term Evolution for Machines (LTE-M) and the Narrow Band Internet of Things (NB-IoT)) [7].

To coexist with LTE-A networks, 3GPP technologies introduced LTE-M and the NB-IoT, with a limited bandwidth to accommodate the M2M requirements [8]. Non-3GPP technologies (like LoRa or SigFox) are vital for smart cities, supporting large-scale device connections [9–11]. In this context, NB-IoT networks and LTE-M networks were developed specifically for M2M communications to fulfill their requirements, such as long battery life, low device cost, extended coverage, and supporting a large number of devices [12,13].

Before delving into the core of our contribution, we review some research that helped us to propose our contribution.

In [14], the authors addressed the challenge of integrating M2M and H2H communications in LTE networks. They proposed a delay-aware time-slotted resource allocation model with priority-based queuing, giving H2H users the highest priority. To prevent M2M traffic starvation, the model reallocates some resources to M2M without affecting the H2H quality. Their simulation results showed that the model improves M2M resource efficiency and reduces the waiting time while maintaining the H2H service quality. Meanwhile, the researchers in [15] examined the impact of the increased healthcare sensor (HCS) traffic during the coronavirus disease 2019 (COVID-19) pandemic on congested LTE networks, particularly focusing on the need to prioritize critical e-healthcare data during pandemics. They proposed three solutions to manage the congestion and ensure Quality of Service (QoS) for the HCS traffic: doubling the bandwidth, integrating the LTE-A and LTE-M networks, and request queuing. The conducted simulations show that request queuing provided the best performance in ensuring HCS traffic was not compromised during the pandemic. In another paper [16], a smart healthcare monitoring system was developed using wireless sensors to collect patient data like heart rate and blood pressure. These sensors communicate with a monitoring station via 5G networks, enabling immediate treatment. The system also utilizes machine learning for better detection of critical conditions, reducing hospital visits and improving healthcare quality. In [17], the authors explored the integration of M2M communication into LTE-A networks using a Relay Node (RN) solution. They simulated a M2M scenario with both e-healthcare and logistic devices alongside normal LTE-A users using the Optimized Network Engineering Tool (OPNET) modeler. The results showed that the LTE-A network performance improves when a RN is employed for multiplexing and aggregating the M2M traffic, which typically involves the infrequent transmission of small data amounts. In a previous project [18], we proposed the Adaptive eNodeB (A-eNB) to manage network overload in the NB-IoT during emergency scenarios, ensuring H2H traffic is minimally affected. By dynamically reserving NB-IoT bandwidth, the system can increase M2M connections and reduce congestion. A Continuous-Time Markov Chain (CTMC) was used to enhance the H2H/M2M coexistence, especially during disasters. The results showed that leasing 18 resource blocks for the NB-IoT traffic achieved a 98% completion rate for the M2M traffic during emergencies. In [19], the authors proposed a CTMC traffic model to address the dynamic QoS demands of IoT networks. The model helps to optimize spectrum sharing by deriving the optimal access probabilities for the different service classes. A centralized scheduler with a service-prioritized queuing system is introduced, and the proposed scheme is compared with the mixed critical scheduling and max–min methods. The simulation results showed improved spectrum utilization and reduced queuing delay, while maintaining fairness compared to the max–min.

Based on the mentioned previous works, we are motivated to propose a novel call for help traffic (SOS) to improve rescue calls during emergencies.

The main contributions of this paper can be summarized as follows:

- Developing a CTMC model to characterize H2H and M2M traffic mathematically.
- Using the CTMC model, analyzing and studying the massive number of IoT devices attempting to access a LTE network becomes achievable.
- Studying and evaluating the impact of SOS traffic on M2M and H2H traffic during a pandemic disease such as the coronavirus disease.
- To confirm our mathematical results, the CTMC solution is illustrated using extensive Monte Carlo simulations for different scenarios.

The rest of the paper is organized as follows: In Section 2, we introduce the SOS traffic. The third section explains our CTMC model. In Section 4, we solve the linear system and obtain the mathematical results. In Section 5, we develop a simulation model and we obtain the empirical results. Finally, the conclusion and the future work are provided in the last section.

2. SOS Traffic

Traditionally, the M2M communication system consists of three domains:

1. Physical or Device Domain, where devices capture events (e.g., temperature, heartbeat, blood pressure, etc.) and transmit data via different networks;
2. Network Domain, which conveys the generated data from the device domain to the application domain (e.g., ZigBee, Bluetooth, Wi-Fi, LTE-M, NB-IoT, LoRa, SigFox, etc.);
3. Application Domain, where the data is processed. M2M applications span areas such as security and public safety, e-health, intelligent transportation and smart environments [7].

The three domains are shown in Figure 1.

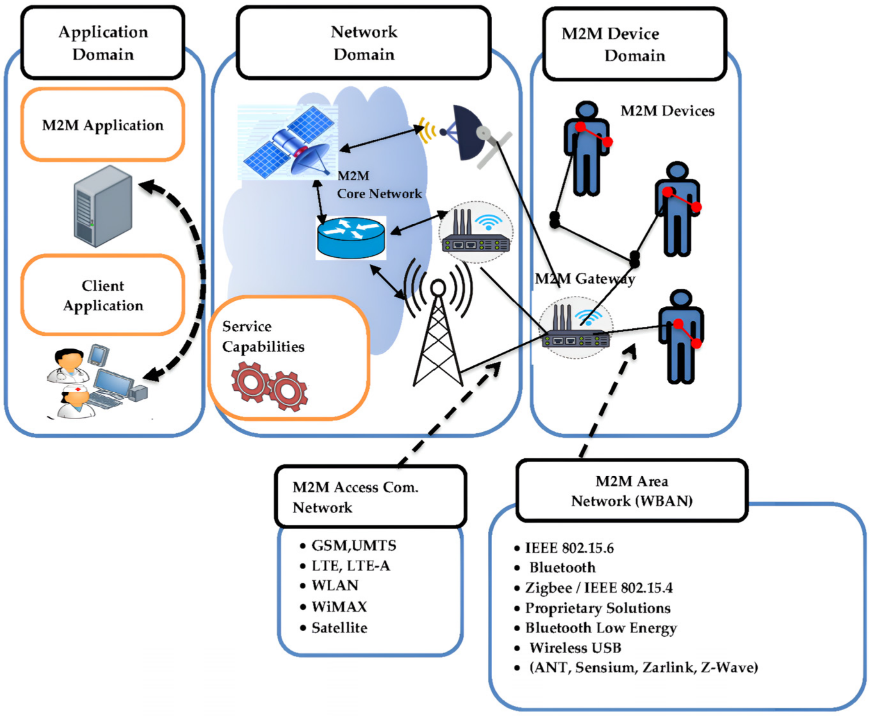

Figure 1. SOS traffic in M2M domains.

M2M domains face many challenges, such as access problems, burst traffic, resource efficiency, diverse data formats, and traffic prioritization, leading to congestion. Effective solutions are needed to manage the growing M2M traffic across networks like LTE-A, LTE-M, and NB-IoT, ensuring they meet IoT standards and support M2M and H2H demands [20,21].

When an emergency incident occurs, M2M and H2H traffic increase exponentially, due to the number of devices and people connected at same time trying to dispatch critical information regarding their safety and rescue calls. For example, during the spread of COVID-19, the World Health Organization sounded the emergency alarm, which we consider as SOS traffic in our paper. COVID-19's main symptoms are coughs, fever and breathing difficulties. COVID-19 has been propagated via the direct contact of humans. Therefore, suspected or infected people should be kept physically isolated when needed, but at the same time, they should be well and wirelessly monitored to reduce the percentage of infection. With M2M devices connected via a wireless telecommunication network, we can maintain the healthcare of suspected patients. Meanwhile, with H2H traffic (such as VoIP and video traffic), health authorities should be able to communicate, give instructions and help suspected patients. Since any infected patient requires both M2M and H2H traffic, we suggest a new traffic called SOS traffic, which contains both traffics, with one request of M2M traffic and one request from H2H traffic arriving simultaneously to the system. Consequently, in this paper, any communication involving a suspected critical case is treated as SOS traffic. Additionally, we propose a model of this new traffic based on a CTMC to study and analyze its impact over the network, as explained in the next section.

3. The Analytical Model

The LTE-A network was initially designed for H2H services, but the rise of M2M has made it necessary to manage connected devices. Researchers estimate that by 2030, there will be around 3.2 billion unavoidable coexistences between M2M and H2H in a single LTE-A network [14]. This section focuses on analyzing the performance characteristics of SOS, H2H and M2M traffic in a LTE network and proposing a novel methodology based on a CTMC. The CTMC prioritizes radio resource allocation, achieving a balance between all traffic for a more efficient system performance.

After exploring different models, the Markov chain model is chosen as one of the best models to analyze telecommunication systems and optimize network performance.

3.1. Markov Chain

Markov chains are systems where elements transition between states over time following certain probabilities. These chains are used to model real-world processes [20]. Markov chains are useful for forecasting the probability of future events and simulating complex scenarios. Several potential catastrophes, including earthquakes, tsunamis and even the spread of disease, were predicted using Markov chains [22]. Events have recently been predicted using Markov chains. In fact, they have effectively been used to prevent or lessen the effects of disasters in a variety of fields, including engineering, physics, meteorology and medicine [23]. In this work, Markov chains and queuing theory are applied to analyze and optimize network performance.

To study SOS, H2H and M2M coexistence in LTE-A networks, a CTMC is chosen due to the continuous arrival of requests and the need to analyze the QoS for all traffic types [20].

3.2. CTMC Model

The CTMC analytical model involves four steps:

- Defining states using Markov chains.
- Generating equilibrium equations.
- Solving the linear system and obtaining the mathematical performance results.
- Developing a model to mimic SOS traffic functionality on M2M and H2H traffic.

3.2.1. Defining States Using Markov Chains

In the first step, we use the Markov chain to define the sequence of possible events for different applications (H2H, M2M and SOS requests) by turning any possible incident into different states and probabilities that identify this incident.

Figure 2 illustrates the CTMC with ten states, divided into four phases: the Empty, Occupied, Full and Queue Phases.

By analyzing Figure 2, we can realize that the system falls into one of four phases:

1. Empty Phase: It contains only one state, S (0,0), which represents the Empty state. This means that none of the resources are allocated because no requests have arrived yet.
2. Occupied Phase: S (1,0), S (0,1), S (1,1), S (2,0) and S (0,2) represent the five states of the Occupied Phase. The system falls into the Occupied Phase when several resource blocks are occupied only (but not all resource blocks). Additionally, the number of ongoing H2H and M2M requests is more than zero and less than the number of resources used in the network (C).
3. Full Phase: It includes four states, S (2,1), S (1,2), S (3,0) and S (0,3). The system reaches this phase when the three resource blocks are serving certain requests.

4. Queue Phase: When the three resource blocks are busy and the system receives a new M2M or H2H request, the system moves to the Queue Phase.

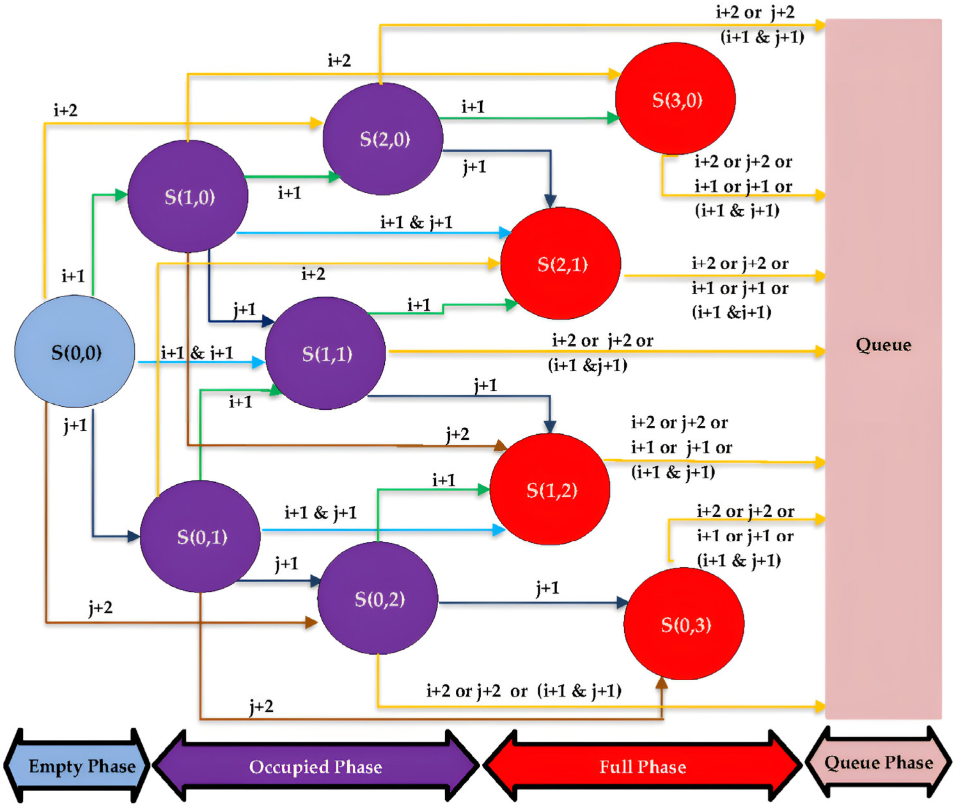

Figure 2. The CTMC model for C = 3, where "C" is the number of resource blocks available in the network, "S (i,j)" are the states in each phase, "i" represents the number of ongoing M2M services, and "j" represents the number of ongoing H2H services.

It should be noted that in our previous work [3], we presented a simplified model considering a short observation period, such that during any observation period, we may only have had one M2M or H2H request. However, after reaching 52 k devices connected simultaneously, the server reached its full capacity, since it could not afford this huge number of requests. In this case, the arrival could have been one of four options:

1. One M2M request arrival ($i + 1$).
2. One H2H request arrival ($j + 1$).
3. One M2M request terminated ($i - 1$).
4. One H2H request terminated ($j - 1$).

Meanwhile, in this paper, we develop a more realistic model that can handle two different requests per time interval. In this case, the arrival could be one of ten options:

1. One M2M request arrival ($i + 1$).
2. One H2H request arrival ($j + 1$).
3. Two M2M request arrivals ($i + 2$).
4. Two H2H request arrivals ($j + 2$).
5. One H2H request and one M2M request arrivals ($i + 1$ & $j + 1$).
6. One M2M request terminated ($i - 1$).
7. One H2H request terminated ($j - 1$).
8. Two M2M requests terminated ($i - 2$).
9. Two H2H requests terminated ($i - 2$).
10. One H2H request and one M2M request terminated ($i - 1$ & $j - 1$).

3.2.2. Generating the Equilibrium Equations

Since we have many notations in the following equations, we summarize them in Table 1.

Table 1. Symbols, notations, values and descriptions.

Symbol	Value	Description
C	3	Number of resource blocks available in network
i		Number of ongoing M2M services
j		Number of ongoing H2H services
λ_{M2M}	+1 or +2	M2M Average arrival rate
λ_{H2H}	+1 or +2	H2H Average arrival rate
λ_{SOS}	+1 & +1	One M2M request and one H2H request (i + 1 & j + 1)
μ_{M2M}	−1 or −2	M2M service rate
μ_{H2H}	−1 or −2	H2H service rate
μ_{SOS}	−1 & −1	Completion of one M2M request and one H2H request (i − 1 & j − 1)
S (i,j)		State with certain i&j requests
$\pi_{(i,j)}$		Steady-state probability
π		Steady-state probability vector

We will generate the equilibrium equations by considering the new arrival events with an arrival rate "λ" and a service rate "μ".

As explained in the previous paragraph, the system might be in one of the following four phases:

1. Empty Phase, represented by S (0,0), as shown in Figure 3.

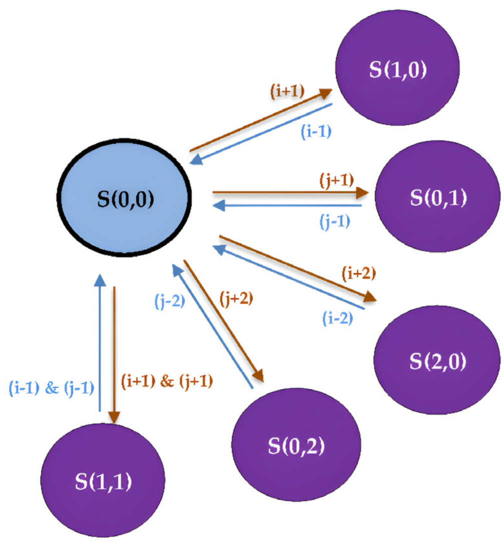

Figure 3. The transitioning example from S (0,0) in the "Empty Phase" to the different states in the "Occupied Phase"; "S (i,j)" represents the different states, where "i" is the number of ongoing M2M services and "j" is the number of ongoing H2H services.

The balance equation for the state S (0,0) can be written as follows:

$$(2\lambda_{M2M} + 2\lambda_{H2H} + \lambda_{SOS})\pi_{(0,0)} = \mu_{M2M}\pi_{(1,0)} + \mu_{H2H}\pi_{(0,1)} + \mu_{M2M}\pi_{(2,0)} + \mu_{H2H}\pi_{(0,2)} + \mu_{SOS}\pi_{(1,1)}$$

2. Occupied Phase: It contains five states, S (1,0), S (0,1), S (1,1), S (2,0) and S (0,2).

In Figure 4, we only represent the transitions from and to the state S (1,0).

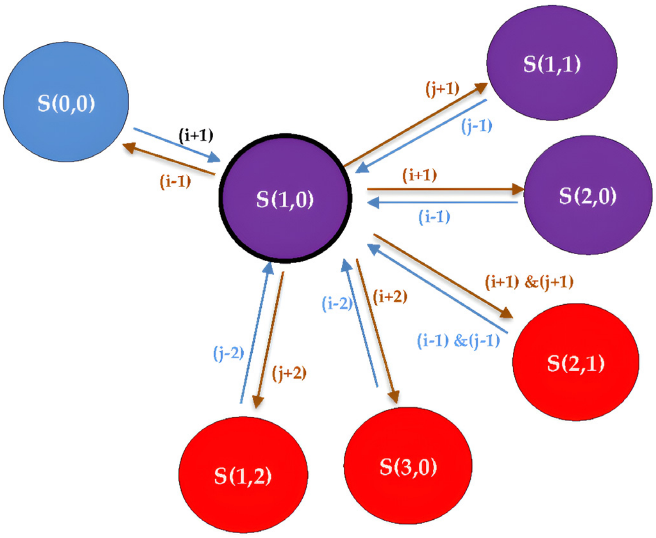

Figure 4. The transitioning example from S (1,0) in the "Occupied Phase" to the different states in the "Empty Phase" and the "Full Phase"; "S (i,j)" represents different states where "i" is the number of ongoing M2M services and "j" is the number of ongoing H2H services.

The balance equation for state S (1,0) can be written as follows:

$$(2\lambda_{\mathrm{M2M}} + 2\lambda_{\mathrm{H2H}} + \lambda_{SOS} + \mu_{\mathrm{M2M}})\pi_{(1,0)} = \lambda_{\mathrm{M2M}}\pi_{(0,0)} + \mu_{\mathrm{M2M}}\pi_{(2,0)} + \mu_{H2H}\pi_{(1,1)} + \mu_{\mathrm{M2M}}\pi_{(3,0)} + \mu_{\mathrm{H2H}}\pi_{(1,2)} + \mu_{\mathrm{SOS}}\pi_{(2,1)}$$

3. Full Phase: It includes four states: S (2,1), S (1,2), S (3,0) and S (0,3).

The transitions from/to state S (1,2) are represented in Figure 5.

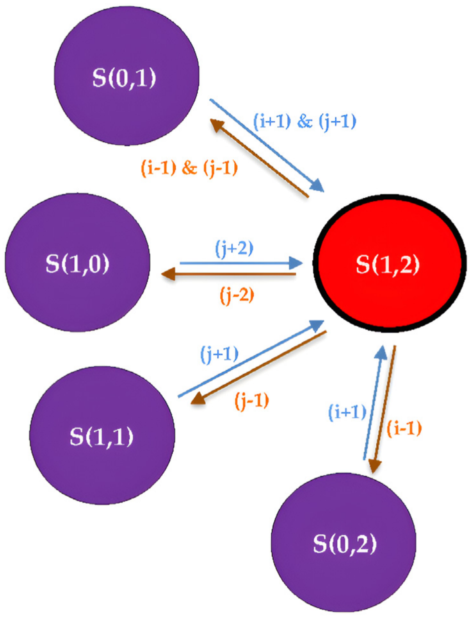

Figure 5. The transitioning example from S (1,2) in the "Full Phase" to the different states in the "Occupied Phase"; "S (i,j)" represents different states where "i" is the number of ongoing M2M services and "j" is the number of ongoing H2H services.

The balance equation for the state S (1,2) can be written as follows:

$$(\mu_{\mathrm{M2M}} + 2\mu_{H2H} + \mu_{\mathrm{SOS}})\pi_{(1,2)} = \lambda_{\mathrm{M2M}}\pi_{(0,2)} + \lambda_{H2H}\pi_{(1,1)} + \lambda_{H2H}\pi_{(1,0)} + \lambda_{SOS}\pi_{(0,1)}$$

4. Queue Phase: When the three resource blocks are busy and the system receives a new M2M or H2H request, the system moves to the "Queue Phase". In this paper, to clarify the main idea of our modeling, we have put aside the Queue Phase. Discussing the potential latency caused by the limitation of the queue and the excessive number of requests will be the most crucial challenge that we will tackle in our future work.

Similar to the way of generating the balance equations for the states S (0,0), S (1,0) and S (1,2), we generate the remaining seven states. Therefore, we end up with seven balance equations that rule seven states:

1. Balance Equation (1) for S (2,0) in the "Occupied Phase":

$$(2\mu_{\mathrm{M2M}} + \lambda_{\mathrm{M2M}} + \lambda_{\mathrm{H2H}})\pi_{(2,0)} = \lambda_{\mathrm{M2M}}\pi_{(1,0)} + \lambda_{\mathrm{M2M}}\pi_{(0,0)} + \mu_{H2H}\pi_{(2,1)} + \mu_{\mathrm{M2M}}\pi_{(3,0)} \quad (1)$$

2. Balance Equation (2) for S (0,2) in the "Occupied Phase":

$$(2\mu_{\mathrm{H2H}} + \lambda_{\mathrm{M2M}} + \lambda_{\mathrm{H2H}})\pi_{(0,2)} = \lambda_{\mathrm{H2H}}\pi_{(0,0)} + \lambda_{\mathrm{H2H}}\pi_{(0,1)} + \mu_{H2H}\pi_{(0,3)} + \mu_{\mathrm{M2M}}\pi_{(1,2)} \quad (2)$$

3. Balance Equation (3) for S (1,1) in the "Occupied Phase":

$$(\mu_{SOS} + \mu_{\mathrm{M2M}} + \mu_{\mathrm{H2H}} + \lambda_{\mathrm{M2M}} + \lambda_{\mathrm{H2H}})\pi_{(1,1)} = \lambda_{\mathrm{H2H}}\pi_{(1,0)} + \lambda_{\mathrm{M2M}}\pi_{(0,1)} + \lambda_{SOS}\pi_{(0,0)} + \mu_{\mathrm{H2H}}\pi_{(1,2)} + \mu_{\mathrm{M2M}}\pi_{(2,1)} \quad (3)$$

4. Balance Equation (4) for S (1,2) in the "Full Phase":

$$(\mu_{\mathrm{M2M}} + 2\mu_{\mathrm{H2H}} + \mu_{SOS})\pi_{(1,2)} = \lambda_{\mathrm{M2M}}\pi_{(0,2)} + \lambda_{\mathrm{H2H}}\pi_{(1,1)} + \lambda_{\mathrm{H2H}}\pi_{(1,0)} + \lambda_{SOS}\pi_{(0,1)} \quad (4)$$

5. Balance Equation (5) for S (2,1) in the "Full Phase":

$$(2\mu_{\mathrm{M2M}} + \mu_{\mathrm{H2H}} + \mu_{SOS})\pi_{(2,1)} = \lambda_{\mathrm{M2M}}\pi_{(1,1)} + \lambda_{\mathrm{H2H}}\pi_{(2,0)} + \lambda_{\mathrm{M2M}}\pi_{(0,1)} + \lambda_{SOS}\pi_{(1,0)} \quad (5)$$

6. Balance Equation (6) for S (0,3) in the "Full Phase":

$$2\mu_{\mathrm{H2H}}\pi_{(0,3)} = \lambda_{\mathrm{H2H}}\pi_{(0,2)} + \lambda_{\mathrm{H2H}}\pi_{(0,1)} \quad (6)$$

7. Balance Equation (7) for S (3,0) in the "Full Phase":

$$2\mu_{\mathrm{M2M}}\pi_{(3,0)} = \lambda_{\mathrm{M2M}}\pi_{(2,0)} + \lambda_{\mathrm{M2M}}\pi_{(1,0)} \quad (7)$$

4. Solving the Linear System, Analytical Results and Discussion

Based on the above ten linear equations containing the ten variables $\pi_{(i,j)}$, where (i,) denotes the number of ongoing services for H2H, M2M and SOS, we can build our linear system.

To recall, the system moves from one state to another when a service is accomplished or a new request arrives (by increasing or decreasing i or j) with a steady-state probability (i,) that should respect the following two constraints:

$$\sum_{i=0}^{c} \sum_{j=0}^{c-i} \pi_{(i,j)} = 1 \quad (8)$$

$$0 \leq \pi_{(i,j)} \leq 1 \quad (9)$$

The ten equilibrium equations can be written in a linear form, AΠ = 0, where the square matrix A represents the coefficients of a linear system, and Π represents the steady-state probability vector:

$$\Pi = \begin{pmatrix} \pi_{(0,0)} & \pi_{(1,0)} & \pi_{(0,1)} & \pi_{(1,1)} & \pi_{(0,2)} & \pi_{(2,0)} & \pi_{(1,2)} & \pi_{(2,1)} & \pi_{(3,0)} & \pi_{(0,3)} \end{pmatrix}^{\mathrm{T}} \quad (10)$$

$$A\,\Pi = (0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0)^{\mathrm{T}} \quad (11)$$

In the matrix A, we use the following notations:

- a = $(2\lambda_{M2M} + 2\lambda_{H2H} + \lambda_{SOS})$
- b = $(2\mu_{H2H} + \lambda_{M2M} + \lambda_{H2H})$
- c =$(\mu_{SOS} + \mu_{M2M} + \mu_{H2H} + \lambda_{M2M} + \lambda_{H2H})$

- d = $(2\mu_{M2M} + \lambda_{M2M} + \lambda_{H2H})$
- e = $(\mu_{M2M} + 2\mu_{H2H} + \mu_{SOS})$
- f = $(2\mu_{M2M} + \mu_{H2H} + \mu_{SOS})$

By using the previous notations in the matrix A, Equation (14) becomes Equation (15) as follows:

$$\begin{bmatrix} -a & \mu_{M2M} & \mu_{H2H} & \mu_{SOS} & \mu_{H2H} & \mu_{M2M} & 0 & 0 & 0 & 0 \\ \lambda_{M2M} & -(a+\mu_{M2M}) & 0 & \mu_{H2H} & 0 & \mu_{M2M} & \mu_{H2H} & \mu_{SOS} & \mu_{M2M} & 0 \\ \lambda_{H2H} & 0 & -(a+\mu_{H2H}) & \mu_{M2M} & \mu_{H2H} & 0 & \mu_{SOS} & \mu_{M2M} & 0 & \mu_{H2H} \\ \lambda_{SOS} & \lambda_{H2H} & \lambda_{M2M} & -c & 0 & 0 & \mu_{H2H} & \mu_{M2M} & 0 & 0 \\ \lambda_{H2H} & 0 & \lambda_{H2H} & 0 & -b & 0 & \mu_{M2M} & 0 & 0 & \mu_{H2H} \\ \lambda_{M2M} & \lambda_{M2M} & 0 & 0 & 0 & -d & 0 & \mu_{H2H} & \mu_{M2M} & 0 \\ 0 & \lambda_{H2H} & \lambda_{SOS} & \lambda_{H2H} & \lambda_{M2M} & 0 & -e & 0 & 0 & 0 \\ 0 & \lambda_{SOS} & \lambda_{M2M} & \lambda_{M2M} & 0 & \lambda_{H2H} & 0 & -f & 0 & 0 \\ 0 & \lambda_{M2M} & 0 & 0 & 0 & \lambda_{M2M} & 0 & 0 & -2\mu_{M2M} & 0 \\ 0 & 0 & \lambda_{H2H} & 0 & \lambda_{H2H} & 0 & 0 & 0 & 0 & -2\mu_{M2M} \end{bmatrix} \quad (12)$$

$$\times \begin{bmatrix} \pi_{(0,0)} \\ \pi_{(1,0)} \\ \pi_{(0,1)} \\ \pi_{(1,1)} \\ \pi_{(0,2)} \\ \pi_{(2,0)} \\ \pi_{(1,2)} \\ \pi_{(2,1)} \\ \pi_{(3,0)} \\ \pi_{(0,3)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where A is a (10 × 10) matrix but not full-rank; consequently, we cannot solve the linear system using this matrix. By replacing the first row of the matrix A with the coefficients of (11), we obtain the following modified system:

$$B\Pi = (1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0)^{T} \quad (13)$$

where B is a full-rank 10 × 10 matrix and the linear system of (15) becomes:

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \lambda_{M2M} & -(a+\mu_{M2M}) & 0 & \mu_{H2H} & 0 & \mu_{M2M} & \mu_{H2H} & \mu_{SOS} & \mu_{M2M} & 0 \\ \lambda_{H2H} & 0 & -(a+\mu_{H2H}) & \mu_{M2M} & \mu_{H2H} & 0 & \mu_{SOS} & \mu_{M2M} & 0 & \mu_{H2H} \\ \lambda_{SOS} & \lambda_{H2H} & \lambda_{M2M} & -c & 0 & 0 & \mu_{H2H} & \mu_{M2M} & 0 & 0 \\ \lambda_{H2H} & 0 & \lambda_{H2H} & 0 & -b & 0 & \mu_{M2M} & 0 & 0 & \mu_{H2H} \\ \lambda_{M2M} & \lambda_{M2M} & 0 & 0 & 0 & -d & 0 & \mu_{H2H} & \mu_{M2M} & 0 \\ 0 & \lambda_{H2H} & \lambda_{SOS} & \lambda_{H2H} & \lambda_{M2M} & 0 & -e & 0 & 0 & 0 \\ 0 & \lambda_{SOS} & \lambda_{M2M} & \lambda_{M2M} & 0 & \lambda_{H2H} & 0 & -f & 0 & 0 \\ 0 & \lambda_{M2M} & 0 & 0 & 0 & \lambda_{M2M} & 0 & 0 & -2\mu_{M2M} & 0 \\ 0 & 0 & \lambda_{H2H} & 0 & \lambda_{H2H} & 0 & 0 & 0 & 0 & -2\mu_{H2H} \end{bmatrix} \times \begin{bmatrix} \pi_{(0,0)} \\ \pi_{(1,0)} \\ \pi_{(0,1)} \\ \pi_{(1,1)} \\ \pi_{(0,2)} \\ \pi_{(2,0)} \\ \pi_{(1,2)} \\ \pi_{(2,1)} \\ \pi_{(3,0)} \\ \pi_{(0,3)} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (14)$$

Using our code in [24], we generated H2H, M2M and SOS traffic to study the mutual impact of SOS traffic on H2H and M2M traffic.

In all scenarios, we consider a regular LTE-A network with a fixed number of resources (C = 3). As for the traffic, we are going to model the three traffic types: M2M, H2H and SOS traffic. We characterize the three traffic types with different average arrival rates, λ_{H2H}, λ_{M2M} and λ_{SOS}, and different service rates, μ_{H2H}, μ_{M2M} and μ_{SOS}.

4.1. Normal-Cycle Scenario

This scenario represents the normal cycle (e.g., non-peak hours) in which there is no emergency case, and consequently, no SOS traffic.

We assume that the three traffic characteristics are as follows:

- For H2H traffic: λ_{H2H} = 2 and μ_{H2H} = 2.
- For M2M traffic: λ_{M2M} = 1 and μ_{M2M} = 1.
- For SOS traffic: λ_{SOS} = 0 and μ_{SOS} = 0.

The mathematical results of the normal scenario are as follows:

$$\pi_{(0,0)} = 3/19 = 16\%$$

$$\pi_{(0,1)} = 3/19 = 16\%$$

$$\pi_{(0,2)} = 3/38 = 8\%$$

$$\pi_{(0,3)} = 1/38 = 2\%$$

$$\pi_{(1,0)} = 3/19 = 16\%$$

$$\pi_{(1,1)} = 3/19 = 16\%$$

$$\pi_{(1,2)} = 3/38 = 8\%$$

$$\pi_{(2,0)} = 3/38 = 8\%$$

$$\pi_{(2,1)} = 3/38 = 8\%$$

$$\pi_{(3,0)} = 1/38 = 2\%$$

The mathematical results of the normal scenario are represented in Figure 6.

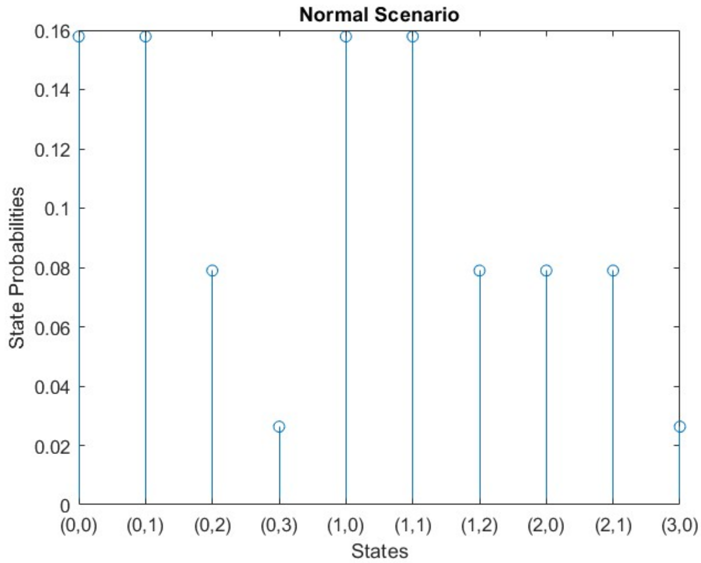

Figure 6. Normal-cycle scenario results, where: S (0,0) represent the initial state, S (0,1) represents one H2H request only, S (0,2) is the state with two H2H requests, and S (0,3) represents three H2H requests, while S (1,0) represents one M2M request only, S (2,0) is the state with two M2M requests, and S (3,0) represents three M2M requests. Moreover, S (1,1) is the state that contains one M2M request and one H2H request, S (1,2) represents the arrival of one M2M request and two H2H requests, and S (2,1) represents the arrival of two M2M requests and one H2H reque.

4.2. Dense-Area Scenario

This scenario represents the dense-area (e.g., crowded city) cycle in which there is no emergency case, and consequently, no SOS traffic.

We assume that the three traffic characteristics are as follows:

- For H2H traffic: $\lambda_{H2H} = 2$ and $\mu_{H2H} = 1$.
- For M2M traffic: $\lambda_{M2M} = 1$ and $\mu_{M2M} = 1$.
- For SOS traffic: $\lambda_{SOS} = 0$ and $\mu_{SOS} = 0$.

The mathematical results of the dense-area scenario are given below:

$$\pi_{(0,0)} = 1/13 = 7.6\%$$

$$\pi_{(0,1)} = 1/13 = 7.6\%$$

$$\pi_{(0,2)} = 1/26 = 3.85\%$$

$$\pi_{(0,3)} = 1/78 = 1.2\%$$

$$\pi_{(1,0)} = 2/13 = 15.3\%$$

$$\pi_{(1,1)} = 2/13 = 15.3\%$$

$$\pi_{(1,2)} = 1/13 = 7.6\%$$

$$\pi_{(2,0)} = 2/13 = 15.3\%$$

$$\pi_{(2,1)} = 2/13 = 15.3\%$$

$$\pi_{(3,0)} = 4/39 = 10\%$$

The mathematical results of the dense-area scenario are represented in Figure 7.

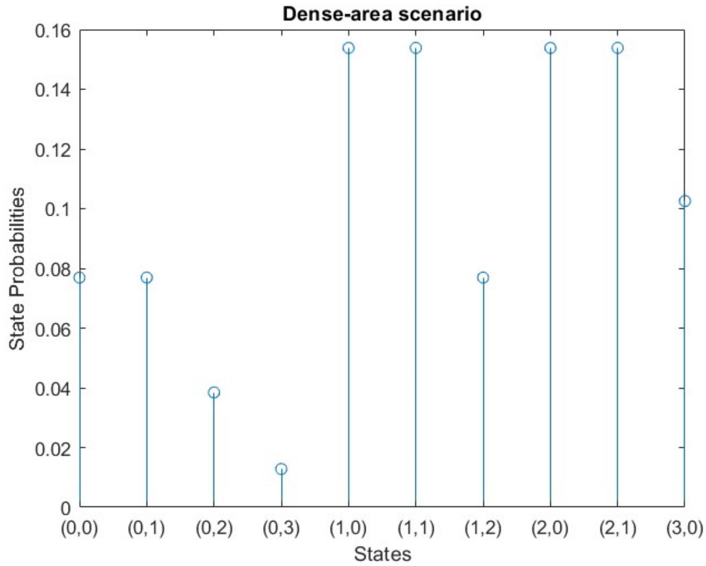

Figure 7. The dense-area scenario results, where S (0,0) represents the initial state, S (0,1) represents one H2H request only, S (0,2) is the state with two H2H requests, and S (0,3) represents three H2H requests, while S (1,0) represents one M2M request only, S (2,0) is the state with two M2M requests, and S (3,0) represents three M2M requests. Moreover, S (1,1) is the state that contains one M2M request and one H2H request, S (1,2) represents the arrival of one M2M request and two H2H requests, and S (2,1) represents the arrival of two M2M requests and one H2H request.

4.3. Worst-Case Scenario

This scenario represents the worst-case cycle, in which we have huge traffic accompanied with SOS traffic.

Assuming that the three traffic characteristics are as follows:

- For H2H traffic: $\lambda_{H2H} = 2$ and $\mu_{H2H} = 1$.
- For M2M traffic: $\lambda_{M2M} = 2$ and $\mu_{M2M} = 1$.
- For SOS traffic: $\lambda_{SOS} = 2$ and $\mu_{SOS} = 1$.

The mathematical results of the worst-case scenario are given below:

$$\pi_{(0,0)} = 23/609 = 3.7\%$$

$$\pi_{(0,1)} = 38/609 = 6.2\%$$

$$\pi_{(0,2)} = 38/609 = 6.2\%$$

$$\pi_{(0,3)} = 18/203 = 8.8\%$$

$$\pi_{(1,0)} = 50/609 = 8.2\%$$

$$\pi_{(1,1)} = 50/609 = 8.2\%$$

$$\pi_{(1,2)} = 30/203 = 14.7\%$$

$$\pi_{(2,0)} = 30/203 = 14.7\%$$

$$\pi_{(2,1)} = 88/609 = 14.4\%$$

$$\pi_{(3,0)} = 88/609 = 14.4\%$$

The mathematical results of the worst-case scenario are represented in Figure 8.

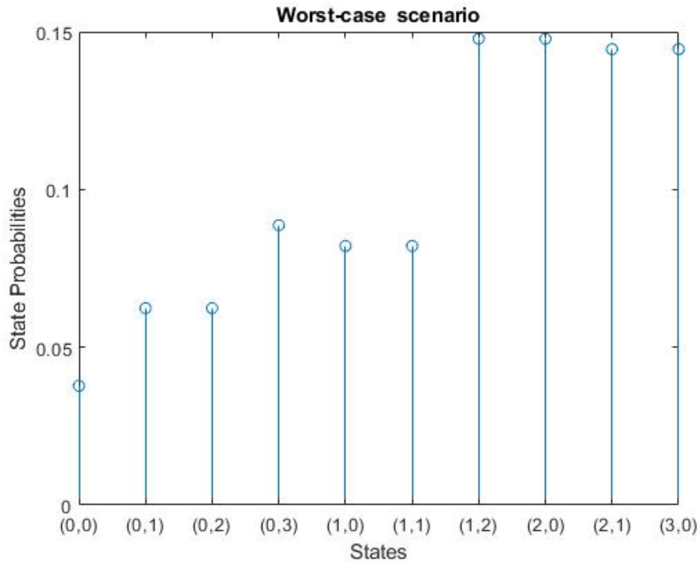

Figure 8. The worst-case scenario results, where S (0,0) represents the initial state, S (0,1) represents one H2H request only, S (0,2) is the state with two H2H requests, and S (0,3) represents three H2H requests, while S (1,0) represents one M2M request only, S (2,0) is the state with two M2M requests, and S (3,0) represents three M2M requests. Moreover, S (1,1) is the state that contains one M2M request and one H2H request, S (1,2) represents the arrival of one M2M request and two H2H requests, and S (2,1) represents the arrival of two M2M requests and one H2H request.

In this section, we developed analytical results corresponding to different scenarios. In the coming section, we simulate these scenarios using the Simulink simulator.

5. Simulink Model, Empirical Results and Discussion

We employ a user-friendly Matrix Laboratory (MATLAB) tool called Simulink. Simulink is used to design and test various models and time-based and multi-rate systems. It provides a more readable model representation through graphics, making simulations easier.

To recall, in emergencies (e.g., the spread of a pandemic disease like COVID-19, tsunamis, terrorist attacks like the September 11 attack, etc.), M2M and H2H communications significantly increase network traffic due to the simultaneous connection of numerous devices and people. This led to the development of the SOS traffic. In this paper, any communication involving a suspected critical case is treated as SOS traffic. We assume, in this case, the reception of one M2M request and one H2H request simultaneously.

5.1. Model Parameters

We developed a model based on our previous work [9]. The system is modeled as an M/M/1 queue, where the arrivals follow a Poisson process and the service times follow an exponential distribution.

Our model consists of three types of traffic:

- M2M traffic, which represents only the arrival of M2M communications (e.g., sensors and actuators) with an average arrival rate of λ_{M2M} (i + 1 or i + 2) and a service rate of μ_{M2M} (i − 1 or i − 2).
- H2H traffic, which includes the arrival of H2H communications only (e.g., VoIP, File Transfer and video traffic) with an average arrival rate of λ_{H2H} (j + 1 or j + 2) and a service rate of μ_{H2H} (j + 1 or j + 2).
- SOS traffic, which involves both traffic types, one request of M2M traffic and one request of H2H traffic, arriving simultaneously to the system with an average arrival rate of λ_{SOS} (i + 1 and j + 1) and a service rate of μ_{H2H} (i − 1 and j − 1).
- We assume that H2H and M2M traffic have the same priority, while SOS traffic has the highest priority.

- A priority queue type is used with an infinite capacity size.
- In a single LTE network with a 5 MHz bandwidth, C = 25 Physical Resource Blocks (PRBs); a PRB represents the minimal unit that can be scheduled for user equipment to send or receive data [18].
- The simulation duration = 1000 s.

To benchmark our model, we use two metrics:

- Service Completion Rate (SCR): It gives the number of completed requests per time interval, and it is based on the service rate and the average arrival requests for certain traffic [25].

To calculate the SCR, we should apply the following equation:

$$SCR = 100\frac{\sum Number\ of\ arrived\ entities}{\sum Number\ of\ departed\ entities} \tag{15}$$

- Server utilization (SU): This metric gives the probability of the system to be busy serving arrivals in terms of the number of utilized resource blocks in each state, compared to the total number of PRBs used in the network (C).

The server utilization of the system is defined as follows:

$$\mathrm{SU} = 100\frac{\sum Number\ of\ departed\ entities}{c} \tag{16}$$

5.2. Studying the Impact of M2M and SOS Traffics over H2H Traffic

To study the impact of M2M and SOS traffic on H2H traffic, we designed four scenarios:

5.2.1. Normal-Cycle Scenario

This scenario represents the normal traffic during non-peak day hours or in rural areas. The parameters for this scenario are:

- An arrival rate of M2M requests, λ_{M2M} = 10.
- The fixed H2H arrival rate is represented by λ_{H2H} = 5.
- An incremental arrival rate of SOS requests, λ_{SOS} = 10.

Meanwhile, μ_{M2M} = 1, μ_{H2H} = 1 and μ_{SOS} = 1.
The results of the normal-cycle scenario are shown in Table 2.

Table 2. SCR of H2H, M2M and SOS during normal-cycle scenario.

Traffic	Departed	Arrived	SCR
M2M	10,000	10,000	100%
H2H	5000	5000	100%
SOS	10,000	10,000	100%

When $\lambda_{\mathrm{M2M}} \leq 10$ and $\lambda_{\mathrm{SOS}} \leq 10$, the system is able to serve all M2M and H2H requests, because the H2H arrivals, with λ_{H2H} = 5 and a service rate of μ_{H2H} = 1, occupy an average of 5 resources from the 25 total resources; the M2M arrivals, with a service rate of μ_{M2M} = 1, occupy 10 resources from the 25 total resources; and the M2M and H2H arrivals, with a service rate of μ_{SOS} = 1, occupy the remaining 10 resources from the PRBs.

5.2.2. Dense-Area Scenario

This scenario represents the heavy traffic during peak day hours or in the dense areas. The parameters for this scenario are given below:

- An arrival rate of M2M requests, λ_{M2M} = 12
- A fixed H2H arrival rate, represented by λ_{H2H} = 5
- An incremental arrival rate of SOS requests, λ_{SOS} = 12

while $\mu_{\text{M2M}} = 1$, $\mu_{\text{H2H}} = 1$ and $\mu_{\text{SOS}} = 1$.

The results of the dense-area scenario are shown in Table 3.

Table 3. SCR of H2H, SOS and M2M for dense-area scenario.

Traffic	Departed	Arrived	SCR
M2M	12,000	95,000	80%
H2H	5000	4000	80%
SOS	12,000	12,000	100%

5.2.3. Emergency-Case Scenario

An emergency-case scenario refers to an urgent situation that requires immediate action, such as a tsunami, a pandemic like COVID-19 or a terrorist attack.

The parameters for this scenario are as follows:

- An arrival rate of M2M requests, $\lambda_{\text{M2M}} = 16$.
- A fixed H2H arrival rate, represented by $\lambda_{\text{H2H}} = 5$.
- An incremental arrival rate of SOS requests, $\lambda_{\text{SOS}} = 16$.

Meanwhile, $\mu_{\text{M2M}} = 1$, $\mu_{\text{H2H}} = 1$ and $\mu_{\text{SOS}} = 1$.

The results of the emergency-case scenario are shown in Table 4.

Table 4. SCR of H2H, SOS and M2M for emergency-case scenario.

Traffic	Departed	Arrived	SCR
M2M	16,000	68,000	44%
H2H	5000	22,000	44%
SOS	16,000	16,000	100%

5.2.4. Worst-Case Scenario

In this scenario, many M2M and H2H requests are synchronized in such a way that they form a huge traffic storm.

The parameters for this scenario are as follows:

- An arrival rate of M2M requests, $\lambda_{\text{M2M}} = 20$.
- A fixed H2H arrival rate, represented by $\lambda_{\text{H2H}} = 5$.
- An incremental arrival rate of SOS requests, $\lambda_{\text{SOS}} = 20$.

Meanwhile $\mu_{\text{M2M}} = 1$, $\mu_{\text{H2H}} = 1$ and $\mu_{\text{SOS}} = 1$.

The results of the worst-case scenario are shown in Table 5.

Table 5. SCR of H2H, SOS and M2M for worst-case scenario.

Traffic	Departed	Arrived	SCR
M2M	20,000	4000	20%
H2H	5000	1000	20%
SOS	20,000	20,000	100%

Figure 9 illustrates the degradation of the SCR across various scenarios.

When $12 \leq \lambda_{\text{M2M}} \leq 16$ and $12 \leq \lambda_{SOS} \leq 16$ with a constant arrival rate of $\lambda_{\text{H2H}} = 5$, a degradation in M2M and H2H service completion rates can be realized, because in our assumption, the total number of requests are more than the available resources of $c = 25$. At the peak ($\lambda_{\text{M2M}} = 12$ and $\lambda_{\text{SOS}} = 12$), H2H requests are served at (80%), (80%) of M2M requests are served, and SOS requests are served with a completion rate equal to 100%, so we can conclude that 20% of the arrival rates of SOS were not served. When ($\lambda_{\text{M2M}} = 16$ and $\lambda_{\text{SOS}} = 16$), H2H requests are served at (44%), and (44%) of M2M requests and (100%) of SOS requests are served. When reaching the worst-case scenario, with $\lambda_{\text{M2M}} = \lambda_{\text{SOS}} = 20$ and $\lambda_{\text{H2H}} = 5$, a huge degradation in the arrival rates of M2M and H2H requests was detected.

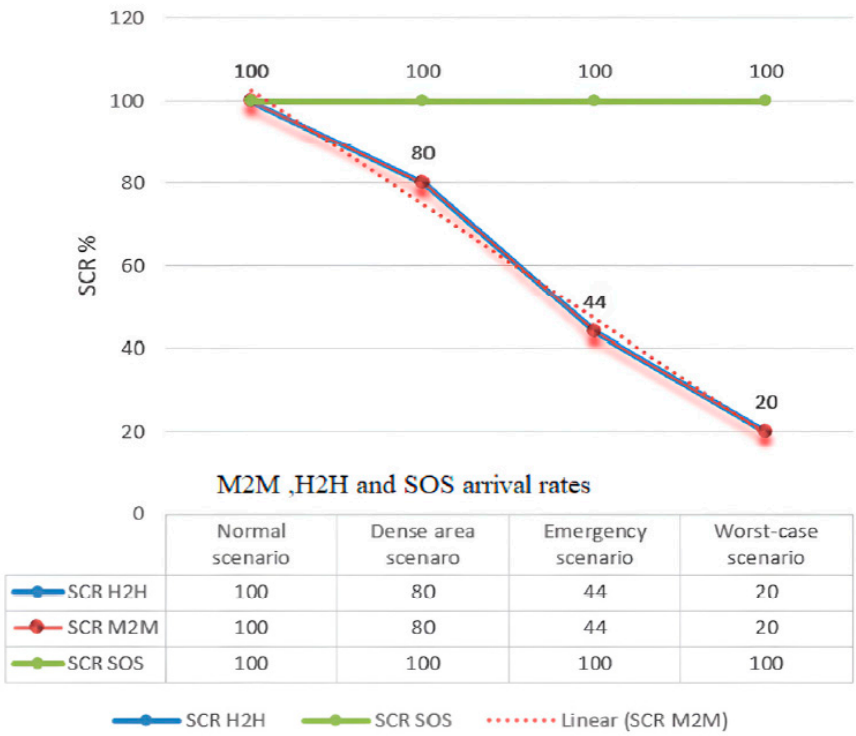

Figure 9. The impact of the M2M and SOS traffic on the H2H traffic in the different scenarios.

5.3. Studying the Impact of H2H and SOS Traffic on M2M Traffic

To study the impact of H2H and SOS traffic on M2M traffic, we designed four scenarios: We consider a fixed arrival rate for M2M (λ_{M2M} = 5), with an increasing arrival rate for both H2H and SOS.

- A fixed arrival rate of M2M requests, λ_{M2M} = 5.
- An incremental H2H arrival rate, represented by $2 < \lambda_{H2H} < 20$.
- An incremental arrival rate of SOS requests, $2 < \lambda_{SOS} < 20$.

Meanwhile, μ_{M2M} = 1, μ_{H2H} = 1 and μ_{SOS} = 1.

5.3.1. Normal-Cycle Scenario

This scenario represents the normal traffic during non-peak day hours or in the rural areas.

The parameters for this scenario are given below:

- A fixed arrival rate of M2M requests, λ_{M2M} = 5.
- The H2H arrival rate, represented by λ_{H2H} = 10.
- SOS requests at a rate of λ_{SOS} = 10.

Meanwhile, μ_{M2M} = 1, μ_{H2H} = 1 and μ_{SOS} = 1.

The results of the normal-cycle scenario are shown in Table 6.

Table 6. SCR of H2H, SOS and M2M for normal-cycle scenario.

Traffic	Departed	Arrived	SCR
M2M	5000	5000	100%
H2H	10,000	10,000	100%
SOS	10,000	10,000	100%

When $\lambda_{H2H} \leq 10$ and $\lambda_{SOS} \leq 10$, the system is able to serve all M2M and H2H requests, because H2H arrivals, with λ_{M2M} = 5 and a service rate of μ_{M2M} = 1, occupy an average of 5 resources from the 25 total resources; H2H arrivals, with a service rate of μ_{H2H} = 1, occupy 10 resources from the 25 total resources; and SOS arrivals, with a service rate of μ_{SOS} = 1, occupy the remaining 10 resources from the resource blocks.

5.3.2. Dense-Area Scenario

This scenario represents the heavy traffic during peak day hours or in the dense areas. The parameters for this scenario are given below:

- An arrival rate of M2M requests, λ_{M2M} = 5.
- An H2H arrival rate, represented by λ_{H2H} = 16.
- An incremental arrival rate of SOS requests, λ_{SOS} = 16.

Meanwhile, μ_{M2M} = 1, μ_{H2H} = 1 and μ_{SOS} = 1.
The results of the dense-area scenario are shown in Table 7.

Table 7. SCR of H2H, SOS and M2M for dense-area scenario.

Traffic	Departed	Arrived	SCR
M2M	5000	4000	80%
H2H	12,000	9500	80%
SOS	12,000	12,000	100%

5.3.3. Emergency-Case Scenario

An emergency-case scenario refers to an urgent situation that requires immediate action, such as a tsunami, a pandemic like COVID-19 or a terrorist attack.

The parameters for this scenario are as follows:

- An arrival rate of M2M requests, λ_{M2M} = 5.
- An H2H arrival rate, represented by λ_{H2H} = 16.
- An incremental arrival rate of SOS requests, λ_{SOS} = 16.

Meanwhile, μ_{M2M} = 1, μ_{H2H} = 1 and μ_{SOS} = 1.
The results of the emergency-case scenario are shown in Table 8.

Table 8. SCR of H2H, SOS and M2M for emergency-case scenario.

Traffic	Departed	Arrived	SCR
M2M	5000	2000	44%
H2H	16,000	7000	44%
SOS	16,000	16,000	100%

5.3.4. Worst-Case Scenario

In this scenario, many M2M and H2H requests are synchronized in such a way that they form a huge traffic storm.

The parameters for this scenario are given below:

- An arrival rate of M2M requests, λ_{M2M} = 5
- An H2H arrival rate, represented by λ_{H2H} = 20
- An incremental arrival rate of SOS requests, λ_{SOS} = 20

Meanwhile, μ_{M2M} = 1, μ_{H2H} = 1 and μ_{SOS} = 1.
The results of the worst-case scenario are shown in Table 9.

Table 9. SCR of H2H, SOS and M2M for worst-case scenario.

Traffic	Departed	Arrived	SCR
M2M	5000	1000	20%
H2H	20,000	4000	20%
SOS	20,000	20,000	100%

Figure 10 illustrates the degradation of SCR across various scenarios.

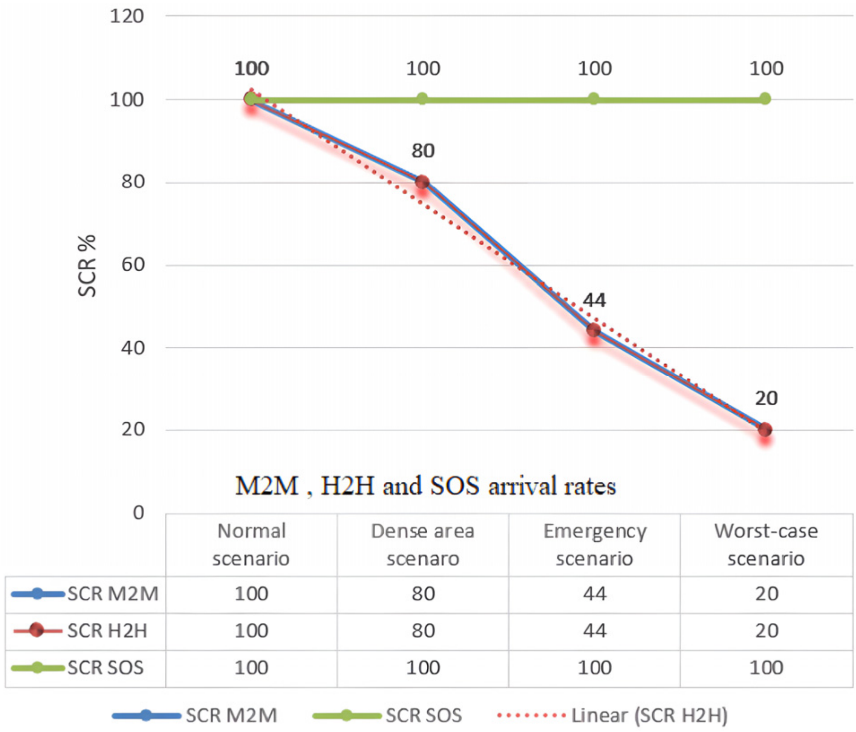

Figure 10. Impact of H2H and SOS traffic on M2M traffic in different scenarios.

When $12 \leq \lambda_{H2H} \leq 16$ and $12 \leq \lambda_{SOS} \leq 16$ with a constant arrival rate of $\lambda_{M2M} = 5$, a degradation in M2M and H2H service completion rates can be realized, because in our assumption, the total number of requests are more than the available resources of $c = 25$. At the peak ($\lambda_{H2H} = 12$ and $\lambda_{SOS} = 12$), H2H requests are served at (80%), (80%) of M2M requests are served and SOS requests are served with a completion rate equal to 100%, so we can conclude that 20% of the arrival rates of M2M and H2H were not served. When ($\lambda_{H2H} = 16$ and $\lambda_{SOS} = 16$), H2H requests are served at (44%), and (44%) of M2M and (100%) of SOS requests are served. When reaching the worst-case scenario, where $\lambda_{H2H} = \lambda_{SOS} = 20$ and $\lambda_{M2M} = 5$, a huge degradation in the arrival rates for M2M and H2H was detected.

6. Conclusions

In this paper, we began to research LPWAN and LTE technologies while spotting on their challenges, especially during disaster events. We showed that a huge degradation in M2M and H2H traffic will cause many people to be endangered because of the lack of connectivity with rescue centers. Therefore, we proposed an SOS traffic that bridges this critical gap. We created a CTMC to characterize H2H, M2M and SOS traffic. After applying many scenarios, we ended up with analytical results. Then, we simulated similar scenarios using Simulink while presenting many empirical results. In both the mathematical and empirical results, we realized that the H2H and M2M traffic was being affected badly by the increased number of SOS requests. To solve this problem, we applied the highest priority to the SOS traffic over the M2M and H2H traffic. In the worst-case situation, only 20% of the M2M and H2H traffic might be handled using this approach; however, 100% of the SOS traffic is served. As a result, we can prevent the anticipated shortage of SOS alerts during crucial events, saving many lives and preventing people from being abandoned.

In our future work, we intend to improve the QoS for the H2H and M2M traffic while maintaining the best quality for the SOS traffic by assigning the appropriate priorities to all traffic. Additionally, in this study, the Queue Phase has been set aside in order to clarify and simplify the core idea of our modeling. In our future work, we will discuss the possible latency caused by the scalability and the excessive number of connected devices.

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