Modeling the NB-IoT Transmission Process with Intermittent Network Availability

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Abstract. Standardized by 3GPP, Narrowband Internet-of-Thing (NB-IoT) technology operating in licensed bands is nowadays widely deployed and utilized for static deployments of IoT communications services. The recent trend to equip large complex inherently nomadic systems such as trains and ships with advanced sensory capabilities call for mobility support in NB-IoT technology. Such systems entering and leaving the NB-IoT coverage periodically could lead to synchronized behavior of sensor nodes resulting in occasional spikes in the number of sensors simultaneously accessing the NB-IoT random access channel. In this study, we develop a model capturing behavior of nomadic systems roaming between coverage of NB-IoT technology. The metrics of interest are mean message transmission delay as well as the message loss probability. Our numerical results illustrate that these metrics are mainly affected by the duration of the outage interval and fraction of time systems spends in outage conditions. At the same time, the loss and delay performance only insignificantly affected by the number of sensors implying that NB-IoT random access procedure may efficiently handle sporadic loads.

Keywords: NB-IoT · massive MTC · random access · mobile sensors.

1 Introduction

Standardized as a part of 3GPP Release 13 Narrowband Internet-of-Things (NB-IoT) technology quickly became the de-facto standard for commercial IoT systems [14]. The NB-IoT technology utilizes much narrower channels of only 200 KHz by enabling the devices having about 10% complexity of that for LTE Cat-1. As a result, it offers unprecedented coverage of up to 30 km with over 50 thousand of networked devices per cell and much longer battery lifetimes [10, 4]. Similarly to its predecessor, LTE-M, NB-IoT is deployed over the LTE infrastructure, which makes it possible to provide enhanced security features as well as deployment options via software updates [6, 13].

NB-IoT technology is designed to mainly target those applications generating data periodically over constant or random time intervals, e.g., environment and medium monitoring services. However, dealing with event driven applications, especially, those that might be triggered by events affecting large territories, e.g., disaster use-cases, public protection and disaster relief (PPDR) applications, may lead to sub-optimal performance of NB-IoT technology as a result of congestion events at the random access stage [18, 17].

Recently, the scope of NB-IoT technology is enhanced to target vehicle mounted sensors [3, 15]. The new use-cases include container tracking systems mounted at large moving systems such as trains or vessels sailing near-the-shore [9]. Featuring thousands of sensors these systems move between the areas with NB-IoT coverage naturally causing random access ”storms” just after entering coverage areas of NB-IoT base stations (BS). To develop efficient access barring schemes accurate models characterizing on-off service process of sensors in such systems are needed.

In this paper, we formulate an accurate model of the service process of sensors deployed at the large object (e.g., train or vessel) moving across the area with intermittent NB-IoT connectivity. Explicitly accounting for both random access and data transmission phases by capturing the essentials of NB-IoT technology we represent the transmission process of data messages from a large number of sensors as a multidimensional Markov chain. The key performance indicators include the mean message transmission delay and message loss probability. The latter include losses as a result random access and data transmission. The developed model can be utilized for developing access barring schemes for novel applications of NB-IoT technology for large nomadic systems.

The paper is organized as follows. The system model is formulated in Section 2. The model of the service process is introduced in Section 3. Numerical results are provided in Section 4. The conclusions are drawn in the last section.

2 System Model

In this section we introduce our system model by specifying its parts. We successively characterize deployment and connectivity, sensor behavior and traffic, NB-IoT random access and data transmission models. Finally, we introduce the considered metrics of interest.

2.1 Deployment and Connectivity

We consider a large complex object such as vessel or train with N NB-IoT sensors deployed on-board moving across a certain area, see Fig. 1. A part of the area is covered with NB-IoT technology. We assume that the coverage and outage duration are geometrically distributed with parameters λ_{ON} and λ_{OFF}. These parameters can be found analyzing a special use-case of interest, see, e.g., [9] for container vessel example.

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2.2 Sensor Behavior and Traffic

We assume that all the sensors operate independently of each other, i.e., their transmissions are not globally synchronized or, alternatively, intentionally de-synchronized. The

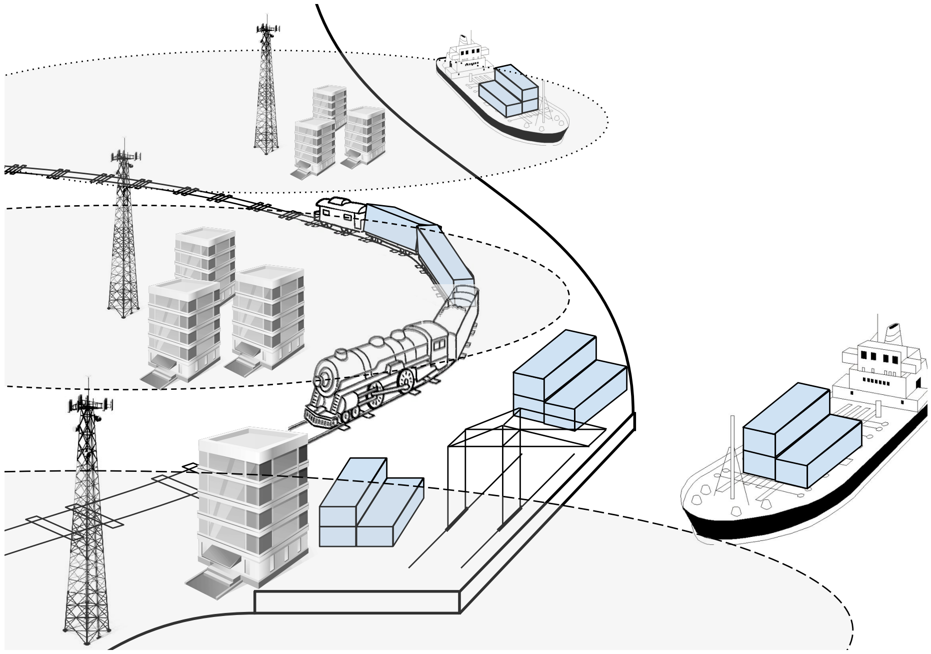

Fig. 1. Potential scenario with intermittent NB-IoT connectivity.

inter-message generation time is assumed to be geometrically distributed with the parameter λ. Once message is generated, the sensor is assumed to test network availability. If there is NB-IoT coverage the message is scheduled for transmission by initiating the NB-IoT random access procedure. If the network is unavailable, sensor enters the waiting phase. During this phase, the network availability is tested or regular time intervals. Once the network becomes available the random access procedure is immediately initiated. The message lifetime is assumed to be limited and geometrically distributed with the parameter T_l.

2.3 The Captured NB-IoT Mechanisms

NB-IoT Random Access Phase Following NB-IoT specification [1] user equipment (UE) is assumed to determine NB-IoT carrier by measuring the power of the received synchronization signals, see Fig. 2 on the downlink direction. The time interval between synchronization information repetition may vary between 24 and 2604 ms [2]. Once synchronized, UE can configure the NPRACH resource so that the number of repetitions and the transmit power is sufficient.

Next, the NPBCH carries the master information block (MIB) for 640 ms transmission time interval (TTI). Also, overhead information about the cell characteristics is transmitted to the SIB1-NB for 2560 ms and other SIB2-NB information from the base station. More details can be found in [11].

After the DL message transmission has been completed, UL transmission on the NPRACH is performed. The number of repetitions can be 1, 2, 4, 8, 16, 32, 64, 128.

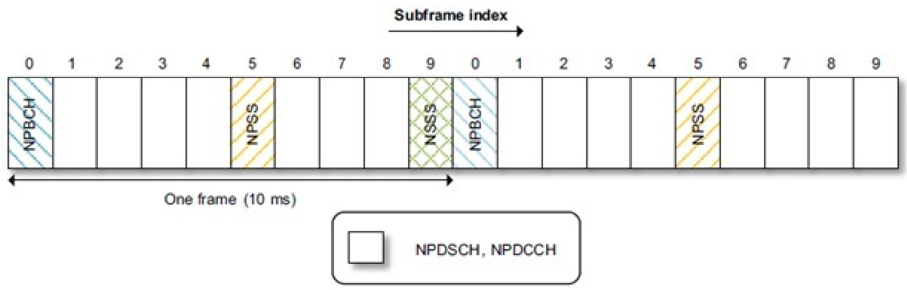

Fig. 2. Downlink physical channels on an NB-IoT anchor carrier [11]

One preamble consists of 4 groups of characters, each of which consists of 5 characters and a circle prefix (66.67 μs or 266.7 μs for 10 or 40 km of distance to the base station, respectively). For this reason, the random access duration is in the range 5.6 ms - 819.2 ms [5]. The base station for estimating TA in the presence of an unknown offset of the residual frequency of the device exists the deterministic tone hopping pattern within a repetition unit. NB-IoT specifies the minimum number of orthogonal preambles to be 12.

NB-IoT Data Transmission Phase The data transfer phase is initiated in NPDCCH channel. Repetitions of this signal can be 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048 times. This is utilized to transmit the Downlink Control Information (DCI).

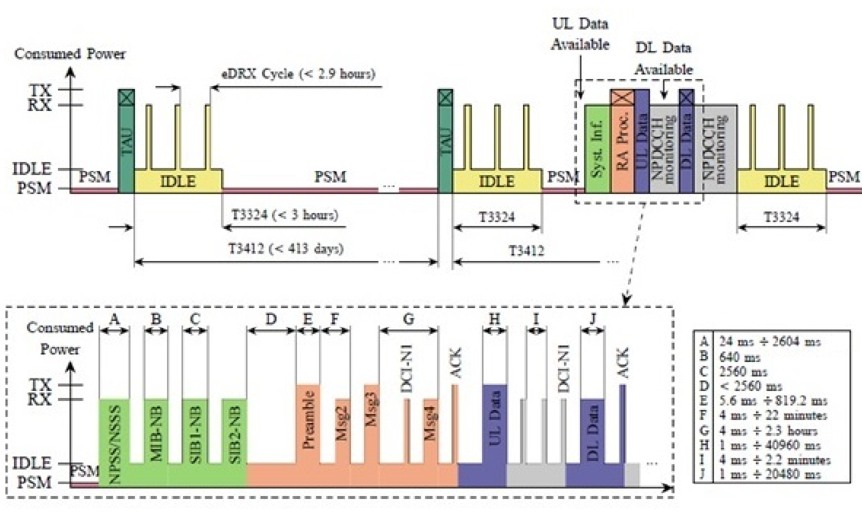

Fig. 3. Life cycle and related power levels of an NB-IoT UE [5, 2].

Fig. 3 illustrates the full PSM cycle without any activity followed by an activation to transmit data is shown. DL signals are represented on the Y axis as RX. DL signals use 15 kHz Subcarrier spacing. The code modulation scheme is provided only by QPSK. NPDSCH serves for transmitting service data in DL including broadcast information for SI transmission. It is possible to use sequentially 1, 2, 3, 4, 5, 6, 8, 10 SF and the same number of repetitions as for NPDCCH. To transmit data to UL, the NPUSCH channel is used. UL typically uses either 3.75 kHz or 15 kHz Subcarrier spacing. For this reason, NPUSCH has two formats and has various combinations of RU duration of 1, 2, 4, 8, 32 ms. A detailed relationship is presented in Table 1.

Table 1. RU values specified by NPUSCH format and subcarrier spacing

NPUSCH format	Subcar. spacing	No. of subcar.	Number of slots	Length of RU	Modulation scheme
format 1	3.75 kHz	1	16	16 ms	BPSK/QPSK
	15 kHz	1	16	8 ms	BPSK/QPSK
		3	8	4 ms	QPSK
		6	4	2 ms	QPSK
		12	2	1 ms	QPSK
format 2	3.75 kHz	1	4	8 ms	BPSK
	15 kHz	1	4	2 ms	BPSK

2.4 Metrics of Interest

The metrics of interest include the mean message delay and message loss probability. In the next section, we proceed analyzing the specified system model.

3 Mathematical Model

In this section, we formalize and solve our mathematical model. First, we outline the basic structure of the model and then proceed specifying the Markov chain framework and then solve it using numerical algorithms.

3.1 Approach at the Glance and Assumptions

The core of the proposed modeling approach is on application of two-dimensional Markov chain, where we explicitly differentiate between two large set of states: connectivity (ON) and outage (OFF) subspaces. Sensor nodes are assumed to follow the same rules message generation rules in both subsets of states with the only exception that transmission is only possible in connectivity subspace. Thus, in the OFF states the number of sensors having a message ready for transmission grow creating the backlog of messages to be transmitted at the beginning of the ON state. However, the lifetime of the message might be expired leading to the loss of messages.

In the connectivity subset of states, UEs are assumed to compete for access to the system according to NB-IoT access rules. We assume that the time is discrete with the time slot duration coinciding with frame duration in NB-IoT technology. The following additional assumptions are accepted:

- **Assumption 1:** The time spent in the ON and OFF states are a random variables T_{ON} and T_{OFF}, that follow geometric distributions with the parameters q_{ON} and q_{OFF}, respectively. One may determine these probabilities using the connectivity and outage sojourn times, see, e.g., [9].
- **Assumption 2:** To simplify formalization we consider the messages arrival process from N sensors as the aggregated one with intensity of $N\lambda$, where λ is the message intensity from a single sensor. With this interpretation each sensor can have at most one message ready for transmission that agrees with our system model assumptions. The sensor remains in the system until its message is successfully transmitted or the maximum number of access and transmission attempts is reached.
- **Assumption 3:** In the *ON* state, the sensor tries to associate with the BS using l preambles. If access attempt is successful, sensor transmits a message. If the message is successfully transmitted, this sensor leaves the system.
- **Assumption 4:** Sensors having the message ready for transmission forms a queue, where all the sensors are considered to be simultaneously active. If the ON (connectivity) state ends, this backlog of sensors are in the active state in the beginning of the next ON period.

3.2 Markov Model

Empowered with the introduced assumptions, the system evolution can be represented using the Markov chain illustrated in Fig. 4. Let $\{S^t, N^t_{act}, t = 0, 1, \dots\}$ be stochastic process, where S^t describes the connectivity state of the system with ON state corresponding to 1 and OFF states denoted by 0, N_{act} is the number of active sensors in the systems having message ready of transmission that have not received access to NB-IoT system yet. Thus, the process is defined over the state space $\mathbb{Z} \in \{0,1\} \times \{0,1,\dots,N\}$, Recalling our assumptions, it is easy to see that the choice of the next state depends only on the current one implying that the process $\{S^t, N^t_{act}, t = 0, 1, \dots\}$ is Markov in nature.

The number of active UEs at the time slot $t+1$ is related to the number of active UE in the time slot t as follows

$$N^{t+1}_{act} = N^t_{act} - T(N^t_{act}, S^t) + V^t(N^t_{act}), \tag{1}$$

where $T(N^t_{act}, S^t)$ is number of successful transmissions when the system is in the state S^t and the system has N^t_{act} active subscribers.

Denote by $V^t(N^t_{act})$ number of sensors that have become active in slot t, provided that N^t_{act} was active subscribers to the beginning of slot t. Since the number of active sensors coincides with the number of messages, we have

$$S^t = \begin{cases} 0 & \text{if the system is in OFF state} \\ 1 & \text{if the system is in ON state} \end{cases}, \tag{2}$$

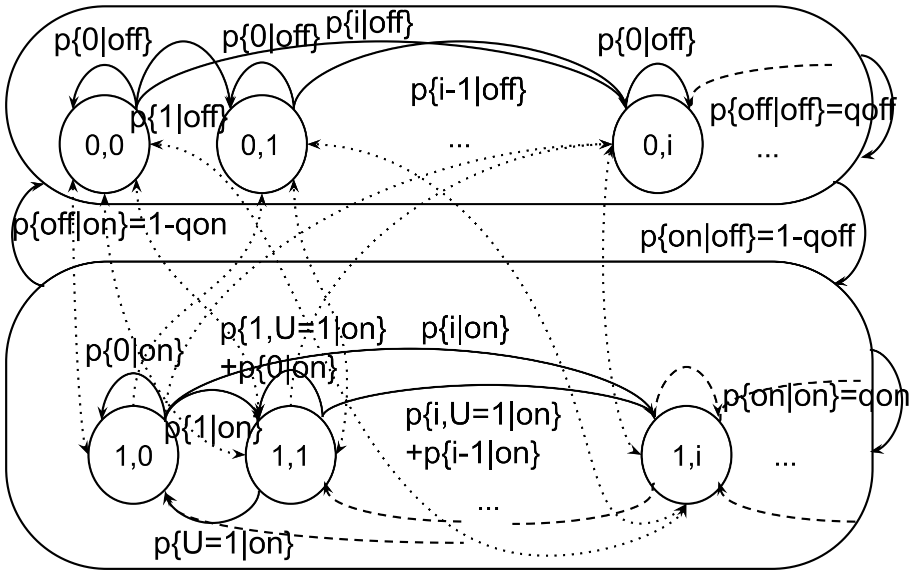

Fig. 4. Markov Chain

Table 2. Principal structure of transition probability matrix.

	0,0	**0,1**	⋯	**0,i**	⋯		**1,0**	**1,1**	⋯	**1,i**	⋯
0,0			⋯		⋯	**0,0**			⋯		⋯
0,1	0		⋯		⋯	**0,1**	0		⋯		⋯
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0,i	0	0	⋯		⋯	**0,i**	0	0	⋯		⋯
1,0			⋯		⋯	**1,0**			⋯		⋯
1,1			⋯		⋯	**1,1**			⋯		⋯
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
1,i			⋯		⋯	**1,i**			⋯		⋯
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

implying that the component S^{t+1} takes the following form

$$S^{t+1} = \begin{cases} 0 & \text{with probability } q_{OFF} \text{ if } S^t = 0 \\ 0 & \text{with probability } 1 - q_{ON} \text{ if } S^t = 1 \\ 1 & \text{with probability } q_{ON} \text{ if } S^t = 1 \\ 1 & \text{with probability } 1 - q_{OFF} \text{ if } S^t = 0 \end{cases} \tag{3}$$

Using (1)-(3), one can calculate the transition probabilities of $\{S^t, N^t_{act}, t = 0, 1, \dots\}$. Fig. 4 illustrates the generic structure of the proposed Markov model. Note that the associated transition probability matrix is sparse with only non-zero values, see Table

2. They are obtained as follows. For $i > j$ we have

$$p\{j,S^{t+1} \mid i,S^t\} = \begin{cases} s\sum_{m=i-j}^{N-j} C_{N-i}^{m-(i-j)} q^{m-(i-j)} \times & S_t = 1 \\ \times(1-q)^{N-j-m} Pr\{T = m \mid i\} & \\ sC_{N-i}^{i-j} q^{i-j}(1-q)^{N-j} & S_t = 0 \end{cases}$$

while for $i \le j$ the following holds

$$p\{j,S^{t+1} \mid i,S^t\} = \begin{cases} s\sum_{m=0}^{N-j} C_{N-i}^{j-i+m} q^{j-i+m} \times & S_t = 1 \\ \times(1-q)^{N-j-m} Pr\{T = m \mid i\} & \\ sC_{N-i}^{j-i} q^{j-i}(1-q)^{N-j} & S_t = 0 \end{cases}$$

where i is N_{act}^t, j is N_{act}^{t+1}, s is the probability of transition from state ON to state OFF accounting for the following

$$s = \begin{cases} q_{on}, & S^t = 1, S^{t+1} = 1 \\ 1 - q_{on}, & S^t = 1, S^{t+1} = 0 \\ q_{off}, & S^t = 0, S^{t+1} = 0 \\ 1 - q_{off}, & S^t = 0, S^{t+1} = 1 \end{cases}, \tag{4}$$

$Pr\{T = m \mid i\}$ is the probability that there are T UEs with message ready for transmission in the system. This quantity takes on on when $S^t = 0$. Otherwise, we have

$$Pr\{T = m \mid i\} = \sum_{k=0}^{i} C_i^k p^k (1-p)^{i-k} P(l,k,m) \tag{5}$$

where p is the probability that the active sensor transmits in the current slot.

$$p = \begin{cases} 0 & \text{if i=0} \\ \min(l/i, 1) & \text{else,} \end{cases} \tag{6}$$

and $P(l,k,m)$ is the probability of the distribution of k messages over l channels, such that m channels are selected by exactly one UE. Following [16] this probability is given by

$$P(l,k,m) = \begin{cases} \frac{(-1)^m l! k!}{l^k m!} \sum_{f=m}^{min(l,k)} \frac{(-1)^f (l-f)^{k-f}}{(f-m)!(l-f)!(k-f)!} & m \leqq k \\ 0 & m > k \end{cases}. \tag{7}$$

3.3 Performance Metrics

Having obtained the transition probability matrix, one can solve it finding stationary probabilities using standard methods, e.g., by solving a system of linear equations [7, 12].

Having the stationary probabilities at our disposal characterizing the number of active UEs in the system in the steady-state we may now derive the metrics of interest. Applying the Little result to a system with a limited number of waiting positions, the average delay is calculated as

$$E[d] = \frac{E[N_{act}]}{\lambda_{out}}, \tag{8}$$

where λ_{out} is the intensity of the output stream, i.e.,

$$\lambda_{out} = (N - E[N_{act}]) \cdot (1 - e^{\frac{-\lambda}{N}}). \tag{9}$$

Combining (8) and (9), the mean delay value is given by

$$E[D] = \frac{E[N_{act}]}{(N - E[N_{act}]) \cdot (1 - e^{\frac{-\lambda}{N}})}, \tag{10}$$

To calculate the message loss probability, we first determine the sensor transmission probability. The latter is given by the ratio of the number of transmitted messages obtained in (9) and the total number of messages λ_{inp},

$$\lambda_{inp} = N \cdot (1 - e^{\frac{-\lambda}{N}}). \tag{11}$$

Now, the transmission probability reads as

$$P_{tran} = 1 - \frac{E[N_{act}]}{N}. \tag{12}$$

immediately leading to the message loss probability in the following form

$$P_{loss} = \frac{E[N_{act}]}{N}. \tag{13}$$

4 Numerical Results

In this section, we elaborate our numerical results. We start assessing accuracy of the developed model and then proceed illustrating the system response to input parameters, including mean delay and message loss probability.

4.1 Accuracy Assessment

We start assessing the accuracy of model developed in the previous section. To this aim, we specifically develop an accurate simulation environment capturing all the details of the system model and specifics of NB-IoT access procedure. The simulation is written in Mathlab using multi-threaded optimization allowing to scale well for realistic values on the number of sensors and ON and OFF period duration. To gather statistics we have utilized the method of replications with sampling technique. To deliver the statistics of interest, each replication consisted of 100 ON and OFF periods. The number of replications was set to 10. For this reason, in what follows, we illustrate the point estimates of considered metrics.

The comparison of model results and the ones obtained using the simulator is illustrated in Fig. 5 for different values of the fraction of time the system in outage, γ.

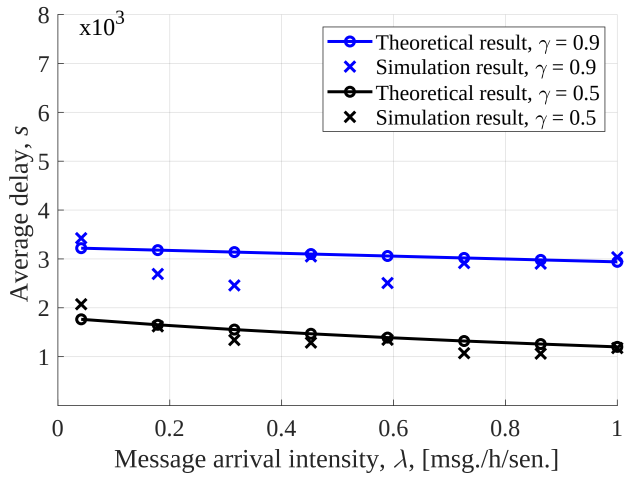

Fig. 5. Comparison with computer simulations.

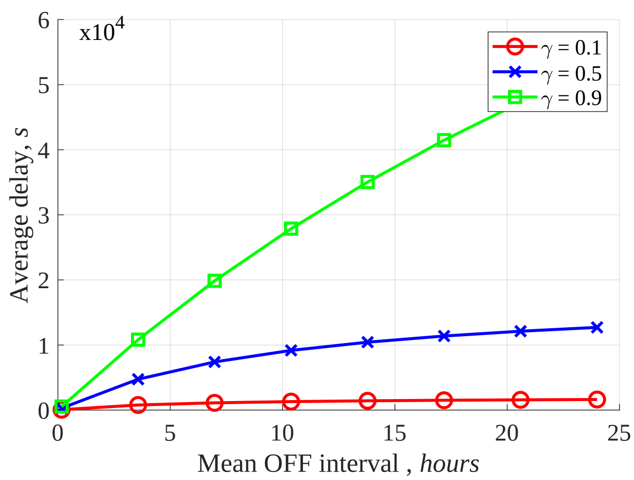

Fig. 6. Mean delay as a function of γ for $\lambda = 0.2$ msg/h.

Furthermore, as one may observe, the analytical data coincides with the simulation ones very well across the considered range of message arrival intensity. Thus, in what follows, to study system response to various input parameters we utilize the developed model. Additionally, we emphasize that for considered range of message arrival intensity the mean delay decreases. We discuss this effect in detail in the rest of this section.

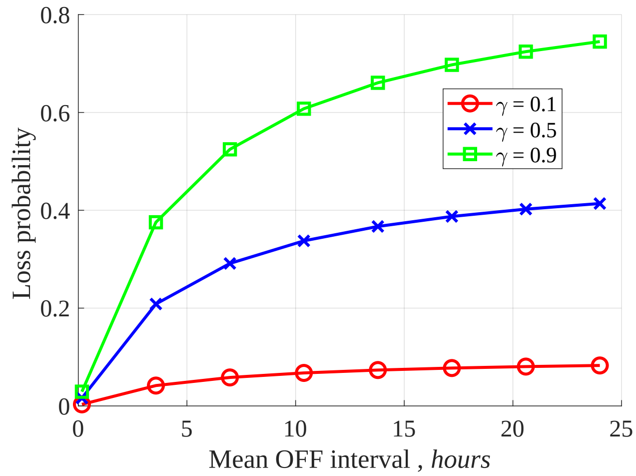

Fig. 7. Message loss probability as a function γ for $\lambda = 0.2$ msg/h

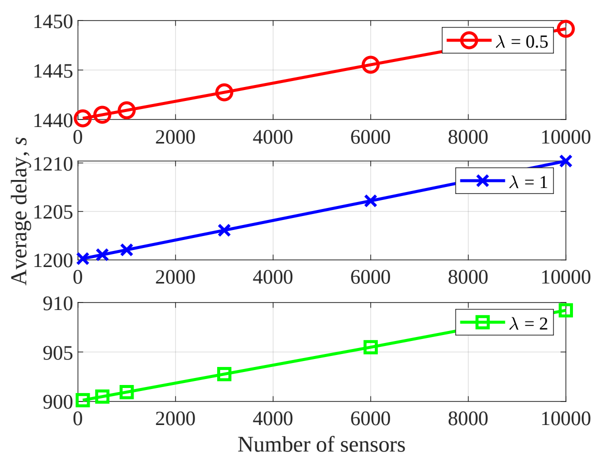

Fig. 8. Mean delay for $\gamma = 0.5$ and $1/\lambda_{OFF} = 1$ hour.

4.2 System Performance

We start studying the system response by considering the mean delay as a function of mean outage period, $1/\lambda_{OFF}$ for different values of the fraction of time in outage, γ, illustrated in Fig. 6. First of all, we stress that in the considered system the message delay may reach extreme values of 3×10^4 s. Still these values might be tolerable in practical use-cases as no real-time communications is expected. This time is mainly induced by the outage interval duration with NB-IoT infrastructure. Expectedly, the increase in

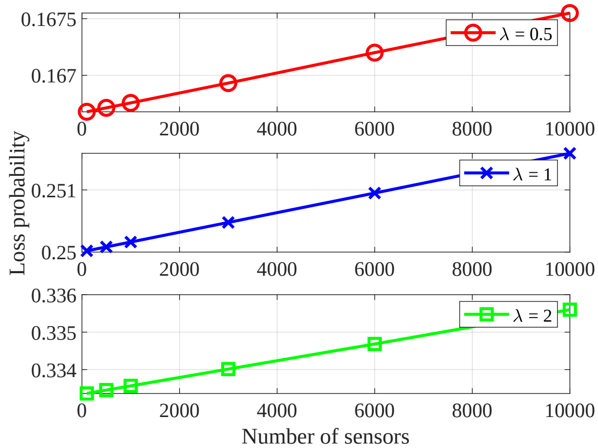

Fig. 9. Message loss probability for $\gamma = 0.5$ and $1/\lambda_{OFF} = 1$ hour.

the fraction of time in outage increases the mean message delay for a given values of $1/\lambda_{OFF}$. Similar effect is also observed when increase the mean outage interval.

The results presented in Fig. 7 shows message loss probability as a function of mean outage period, $1/\lambda_{OFF}$, for the same system parameters. Analyzing the results, one may observe that the main trends remain the same, i.e., the increase in the values of γ as well as in $1/\lambda_{OFF}$ leads to higher loss probabilities. However, it is interesting to observe that for just 10% of time spent in outage the loss probability remains less than 10% for all considered values of $1/\lambda_{OFF}$ implying that the system even satisfies ITU-R M.2412 constraints on the message loss probability [8].

Number of sensors equipped at the considered large nomadic system is expected to drastically affect the performance metric of interest. To assess their effect, Fig. 8 shows the mean delay as a function of the number of sensors for three considered message arrival intensities from a single sensor, $\gamma = 0.5$ and mean outage interval of one hour. As one may observe the mean delay first decrease in response to higher number of equipped sensors. The reason is that for the considered practical values of time out-of-coverage the delay performance is mainly dictated by the outage interval duration. Indeed, during the connectivity intervals, for considered practical values of message arrival intensity per single sensor, sensors experience almost no competition for resources. Thus, increasing the number of sensors the effect of outage intervals dominates.However, when the number of sensors further increases and thus the traffic intensity increases the delay increases as well.

Fig. 9 shows the message loss probability as a function of the number of sensors for the same system parameters. Here, the effect of the number of sensors is much more profound. The increased message loss probability is explained by the fact that sensors having a message ready for transmission tend to accumulate during the outage period and start competing together at the same time when connectivity period begins. Still this effect is not as drastic as one may expect implying that the random access procedure of NB-IoT technology may efficiently handle sporadic loads of up to 2000 UEs. Similarly to delay performance, message loss probability drastically increases when per-sensor load increases.

5 Conclusions

The intermittent connectivity in mobile massive IoT use-cases may lead to various undesirable effects such as sensor synchronization once entering the service area mMTC technology. In this paper, we have proposed an analytical model for NB-IoT technology serving a nomadic system equipped with a large number of sensors, e.g., ship or train, roaming between coverage areas of NB-IoT BSs. The model is based on the Markov chain theory and allows to consider realistic values of outage and non-outage periods as well as message arrival intensities. The metrics of interest are the message loss probability and mean message delay.

Our numerical results demonstrate that the developed model captures the simulation results well across a wide range of message arrival intensities and fraction of time in outage. Further, we have revealed that performance metrics of interest are mainly affected by the outage interval duration and fraction of time system spends in outage state. We have also observed that the even very long outage intervals with the infrastructure do not drastically increase the message loss probability meaning that the capacity of NB-IoT random access channel is sufficient to efficiently handle sporadic loads of up to thousands UEs.

Acknowledgement

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