Analysis of Unslotted IEEE 802.15.4 Networks with Heterogeneous Traffic Classes

J. Ortín, M. Cesana, A. E. C. Redondi, M. Canales, J. R. Gállego

***Abstract*—We propose a modeling framework composed of a Markov chain and the related coupling equations to evaluate the performance of unslotted IEEE 802.15.4 wireless sensor networks based on CSMA/CA Medium Access Control. Different from the related literature, the proposed model is able to capture heterogeneous classes of nodes with class-specific traffic generation rate and includes a more refined calculation of the probability of finding the channel busy during the carrier sensing process. The proposed model is used to derive class-specific performance figures including the probability of a successful transmission and the average delay for a successful/unsuccessful transmission.**

I. Introduction

The diffusion of wireless sensor networks based on the IEEE 802.15.4 standard has stimulated research efforts on the performance evaluation of the utilised Medium Access Control (MAC) scheme. The slotted and unslotted versions of the IEEE 802.15.4 CSMA/CA are modeled in [1], and [4]. Pollin *et al.* propose in [1] a model for slotted, acknowledged 802.15.4 CSMA/CA for saturated and unsaturated nodes. Park *et al.* extends that model in [2], including a retry retransmission limit for collided frames under unsaturated traffic regime. Regarding unslotted 802.15.4 CSMA/CA, a first analysis is performed in [3] assuming unsaturated traffic and unacknowledged frames. Based on [2], the modeling of unslotted CSMA/CA is also carried out in [4] considering a deterministic idle time after every frame transmission.

In all the aforementioned work, the traffic generation process is assumed to be homogeneous, that is, all the nodes generate traffic with the same pattern. While this assumption simplifies the model, it might not reflect realistic wireless sensor networks supporting heterogeneous applications, thus characterized by heterogeneous nodes traffic-wise.

To fill this gap, we propose here a Markovian model to evaluate the performance of heterogeneous 802.15.4 networks with different "classes" of nodes (each class generating traffic according to a class-specific rate). To the best of our knowledge, the only other work modeling heterogeneous traffic in IEEE 802.15.4 networks is [5]. Nonetheless, the main differences/contributions of our work are threefold: first, instead of using a different Markov chain to model each node as in [5], we use a Markov chain for each class of nodes thus decreasing the complexity of the model; secondly, all the aforementioned related work assume that the probability of finding the channel busy during the carrier sensing process does not depend on the backoff stage at the node; although this effect is not relevant when all nodes are saturated, the accuracy of the model is compromised when heterogeneous nodes (e.g., saturated and unsaturated nodes) coexist in the same network; to this extent, we show how to keep track of the backoff stage when deriving the probability of finding the channel busy. Thirdly, we derive a more accurate expression for the collision probability experienced by the nodes. Specifically, we consider that if there is a collision, the probability that any other node performs a CCA must be conditioned by the fact that the channel is not busy.

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II. Proposed Model

We assume a scenario with M classes of nodes, each class l formed by N_l nodes generating frames according to a Poisson process of rate λ_l. All the nodes access the medium according to the unslotted IEEE CSMA/CA 802.15.4 protocol [6]; when a node tries to transmit a new frame, it waits for a random number of backoff slots in the range $[0, 2^{BE} - 1]$, being BE the backoff exponent that is initialized to m_{min}. When the backoff counter is 0, the node performs CCA to determine whether the transmission channel is empty. If not, BE is increased by 1 until it reaches the limiting value m_{max} and the node waits for a new random backoff period generated with the new value of BE. This process is repeated until the number of failed CCAs exceeds the parameter m. In that case, the frame is discarded due to a channel access failure. On the contrary, if the channel is empty, the node switches from the listening mode to the transmitting mode, transmits the frame and waits for the reception of the ACK. If the ACK is not received, then the frame is retransmitted following the CSMA/CA mechanism described above. This process can be repeated up to n times. When this value is exceeded, the frame is discarded due to a collision failure.

To model the backoff, sensing and transmitting states of the nodes, we rely on the Markov chain model shown in Fig. 1. A state in the chain is the tuple (i, j, r), being i the backoff stage, j the backoff counter and r the retransmission counter. The backoff stage and the retransmission counter are limited by the parameters m and n respectively. Similarly, j ranges from 0 to $W_i = 2^{BE_i} - 1$, with BE_i the backoff exponent corresponding to the backoff stage i. In the states with $j = 0$

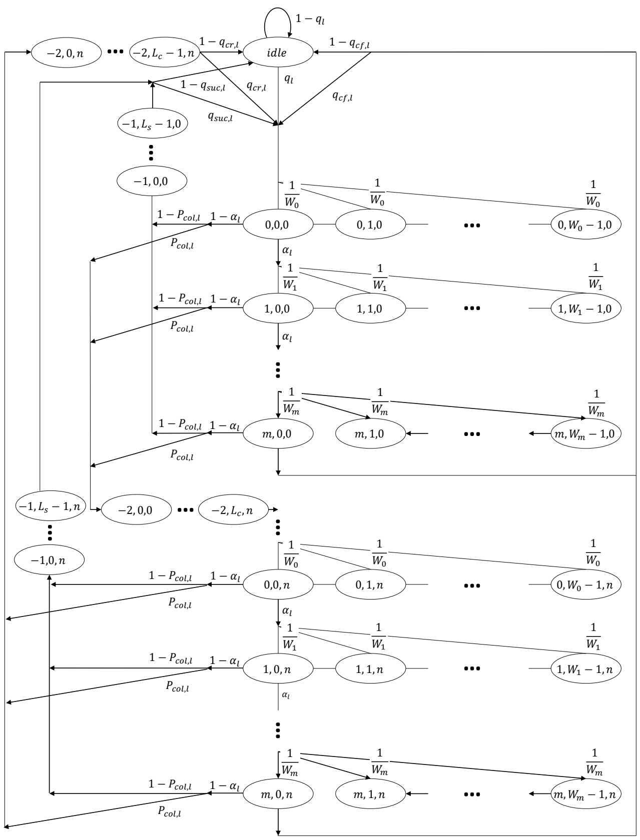


Fig. 1: Markov chain model of the CSMA/CA algorithm of a transmitting node of class l for unslotted IEEE 802.15.4 MAC.

the node performs CCA. We call α_l the probability that a node of class l finds the channel busy upon CCA, and $P_{c,l}$ the collision probability for nodes of class l.

The states $(-1, j, r)$ represent the transmission of a frame, with $0 \leq j < L_s$, and L_s the duration in slots of a successful transmission[1]. Similarly, the states $(-2, j, r)$ represent the collision of a frame, with $0 \leq j < L_c$, and L_c the duration in slots of a collided transmission[2].

The traffic generation for a node of class l is modeled with a packet generation probability in idle state q_l. We also include in the model the probabilities of having a packet ready to be transmitted after a successful transmission $q_{suc,l}$, after a channel access failure $q_{cf,l}$ and after a collision failure $q_{cr,l}$. The expressions of these probabilities are derived afterward.

From this model, we can compute the probability τ_l that a node belonging to class l performs CCA in a randomly chosen time slot. Following [5], this probability is

$$\tau_l = \left(\frac{1-\alpha_l^{m+1}}{1-\alpha}\right)\left(\frac{1-y_l^{n+1}}{1-y_l}\right) p_l(0,0,0), \tag{1}$$

where $p_l(0,0,0)$ is the steady state probability of state $(0,0,0)$ for nodes of class l and $y_l = P_{c,l}\left(1-\alpha^{m-1}\right)$. The expression for $p_l(0,0,0)$ is given in Eq. (2) at the top of the next page.

The collision probability for nodes of class l is

$$P_{c,l} = 1 - \left(1-(1+\gamma)\,\tau_l'\right)^{N_l-1} \prod_{\substack{i\in M\\ i\neq l}} \left(1-(1+\gamma)\,\tau_i'\right)^{N_i}, \tag{3}$$

where γ is a corrective factor that introduces into the model the fact that the contention period $(2t_{ta})$ is longer than a backoff slot. Assuming that $p(0,j,r) \approx p(1,j,r)$, then

$$\gamma = \frac{2t_{ta}-t_s}{t_s}, \tag{4}$$

catches correctly this effect. Additionally, the term τ_l' represents the probability that a node of class l performs a CCA, conditioned by the fact that the channel is not busy (if it were busy, the CCA would have failed and there could not be a collision). From the Markov chain of Fig. 1, this probability is

$$\tau_l' = \frac{\tau_l}{1-\tau_l\,(1-\alpha_l)\,L_s}, \tag{5}$$

where we have assumed that $L_c \approx L_s$. In order to compute the probability of finding the channel busy when performing CCA, α_l, previous works have assumed that this probability does not depend on the specific backoff stage of the node. Nevertheless, this is not accurate when the traffic load is low. In that case, the probability of finding the channel busy in the first CCA is low, but if the channel is found busy in the first attempt, it is likely that the packet that caused the first CCA failure is still occupying the channel on the second attempt, thus increasing the probability of finding the channel busy in that attempt.

The introduction of this effect into the model would imply the use of a different $\alpha_l^{(j)}$ for each backoff stage j of the Markov chain in Fig. 1, which is too complex. In order to reduce the complexity of the model, we propose to use a unique term α_l in the Markov chain and compute it with the expression

$$\alpha_l = \frac{\sum_{j=0}^{m}\prod_{k=0}^{j}\alpha_l^{(k)}}{1+\sum_{j=0}^{m-1}\prod_{k=0}^{j}\alpha_l^{(k)}} \approx \alpha_l^{(1)}\frac{1+\alpha_l^{(2)}}{1+\alpha_l^{(1)}} \tag{6}$$

The probability $\alpha_l^{(1)}$ is given by

$$\alpha_l^{(1)} = \alpha_{l,\text{pkt}} + \alpha_{l,\text{ack}}, \tag{7}$$

where $\alpha_{l,\text{pkt}}$ and $\alpha_{l,\text{ack}}$ are the probabilities of finding the channel busy during the first CCA because of the transmission of a data packet and an ACK respectively.

To compute $\alpha_{l,\text{pkt}}$, let $\mathcal{T}_i$ be the event that at least one node of class i is transmitting when a node of class l performs CCA. Then

$$\alpha_{l,\text{pkt}} = P\left(\bigcup_{i=1}^{M}\mathcal{T}_i\right) = \sum_{i=1}^{M} P\left(\mathcal{T}_i \bigcap_{j=1}^{i-1}\mathcal{T}_j^C\right), \tag{8}$$

with

$$P\left(\mathcal{T}_i \bigcap_{j=1}^{i-1}\mathcal{T}_j^C\right) = L\left(1-(1-\tau_i)^{N_j'}\right)(1-\alpha_i)\prod_{j=1}^{i-1}(1-\tau_i)^{N_i'}, \tag{9}$$

[1]This value is $L_s = L + t_{ack} + L_{ack} + IFS$, with L the total transmission time of a frame, t_{ack} is the ACK waiting time, L_{ack} is the transmission time of the ACK frame and IFS is the Inter-Frame Spacing.

[2]This value is $L_c = L + t_{m,ack}$, with $t_{m,ack}$ the timeout of the ACK.

$$p_l(0,0,0) = \begin{cases} \Big[\frac{1}{2}\left(\frac{1-(2\alpha_l)^{m+1}}{1-2\alpha_l}W_0 + \frac{1-\alpha_l^{m+1}}{1-\alpha_l}\right)\frac{1-y_l^{n+1}}{1-y_l} + (L_s(1-P_{c,l}) + L_c P_{c,l})\left(1-\alpha_l^{m+1}\right)\frac{1-y_l^{n+1}}{1-y_l} \\ + \frac{1-q_{cf,l}}{q_l}\frac{\alpha_l^{m+1}(1-y_l^{n+1})}{1-y_l} + \frac{1-q_{cr,l}}{q_l}y_l^{n+1} + \frac{1-q_{suc,l}}{q_l}(1-P_{c,l})\frac{\left(1-\alpha_l^{m+1}\right)\left(1-y_l^{n+1}\right)}{1-y_l}\Big]^{-1}, \text{ if } m < \hat{m} = m_{max} - m_{min} \\ \Big[\frac{1}{2}\left(\frac{1-(2\alpha_l)^{\hat{m}+1}}{1-2\alpha_l}W_0 + \frac{1-\alpha_l^{\hat{m}+1}}{1-\alpha_l} + \left(2^{m_b+1}+1\right)\alpha_l^{\hat{m}+1}\frac{1-\alpha_l^{m-\hat{m}}}{1-\alpha_l}\right)\frac{1-y_l^{n+1}}{1-y_l} + (L_s(1-P_{c,l}) + L_c P_{c,l})\left(1-\alpha_l^{m+1}\right) \\ \times\frac{1-y_l^{n+1}}{1-y_l} + \frac{1-q_{cf,l}}{q_l}\frac{\alpha_l^{m+1}(1-y_l^{n+1})}{1-y_l} + \frac{1-q_{cr,l}}{q_l}y_l^{n+1} + \frac{1-q_{suc,l}}{q_l}(1-P_{c,l})\frac{\left(1-\alpha_l^{m+1}\right)\left(1-y_l^{n+1}\right)}{1-y_l}\Big]^{-1}, \text{ otherwise} \end{cases} \quad (2)$$

where $N_i' = N_i$ if $i \neq l$ and $N_i' = N_i - 1$ if $i = l$. On the other hand, $\alpha_{l,\text{ack}}$ is the probability of finding the channel busy because of the successful transmission of a frame, which happens when only one frame is being transmitted

$$\alpha_{l,\text{ack}} = L_{ack}\sum_{i\in M} N_i'\tau_i(1-\tau_i)^{N_i'-1}\prod_{\substack{j\in M\\ j\neq i}}(1-\tau_j)^{N_j'}. \quad (10)$$

The term $\alpha_l^{(2)}$ can be computed as

$$\alpha_l^{(2)} \approx 1\cdot P(\mathcal{E}_0) + \alpha_l^{(1)}(1-P(\mathcal{E}_0)), \quad (11)$$

where $\mathcal{E}_0$ is the event that the packet that has caused the CCA failure in the first attempt is still being transmitted when the second CCA is performed. From the Markov chain of Fig. 1, the probabilities of the states $(-1,j,r)$, with $0 \le j < L_s$ and a fixed r, are all equal. Therefore, if a device performs CCA and the channel is busy with a successful transmission, we can be at any of the states of the form $(-1,j,r)$ with equal probability (i.e., they follow a discrete uniform distribution in $[0, L_s-1]$). Likewise, if the channel is busy with a collided transmission, we can be at any of the states of the form $(-2,j,r)$ with equal probability (i.e., they follow a discrete uniform distribution in $[0, L-1]$). On the other hand, the first stage of the backoff also follows a discrete uniform distribution in $[0, W_0-1]$. Therefore, if $S=\mathcal{U}(0,L_s-1), C=\mathcal{U}(0,L-1), B_0=\mathcal{U}(0,W_0-1)$ are discrete uniform random variables, then

$$P(\mathcal{E}_0) = P_{c,l}P(C>B_0) + (1-P_{c,l})P(S>B_0), \quad (12)$$

with

$$P(C>B_0) = \begin{cases} \frac{(W_0-1)/2+L-W_0}{L}, \text{if } L > W_0 \\ \frac{L-1}{2W_0}, \text{ otherwise,} \end{cases} \quad (13)$$

and

$$P(S>B_0) = \begin{cases} \frac{(W_0-1)/2+L_s-W_0}{L_s}, \text{if } L_s > W_0 \\ \frac{L_s-1}{2W_0}, \text{ otherwise.} \end{cases} \quad (14)$$

Eqs. (1), (3) and (6) form a system of coupled nonlinear equations with variables τ_l, α_l and $P_{c,l}$ that can be solved numerically to obtain the point of operation of the network. From them, different performance metrics can be obtained.

From the Markov chain of Fig. 1, the probabilities of a discarded frame due to a collision failure, $P_{cr,l}$ and due to a channel access failure, $P_{cf,l}$ are

$$P_{cf,l} = \frac{\alpha_l^{m+1}\left(1-\left(P_{c,l}\left(1-\alpha_l^{m+1}\right)\right)^{n+1}\right)}{1-P_{c,l}\left(1-\alpha_l^{m+1}\right)} \quad (15)$$

and

$$P_{cr,l} = \left(P_{c,l}\left(1-\alpha_l^{m+1}\right)\right)^{n+1}. \quad (16)$$

Therefore, the probability of a successful transmission is $P_{suc,l} = 1 - P_{cf,l} - P_{cr,l}$.

We show now the expressions for the average delay experienced by a packet in a successful transmission and when it is discarded due to a channel access failure or a retry limit[3].

Let $T_{suc,l}$ be the delay of a packet transmitted successfully, $\mathcal{C}_j$ the event of having a successful transmission after j previous collisions, and $T_{suc,l}^{(j)}$ the delay experienced by a packet when the event $\mathcal{C}_j$ occurs. Following [5],

$$\mathrm{E}\left[T_{suc,l}\right] = \sum_{j=0}^{n} P(\mathcal{C}_j)\mathrm{E}\left[T_{suc,l}^{(j)}\right], \quad (17)$$

with

$$P(\mathcal{C}_j) = \frac{\left(1-P_{c,l}\left(1-\alpha_l^{m+1}\right)\right)P_{c,l}^j\left(1-\alpha_l^{m+1}\right)^j}{1-\left(P_{c,l}\left(1-\alpha_l^{m+1}\right)\right)^{n+1}} \quad (18)$$

and

$$\mathrm{E}\left[T_{suc,l}^{(j)}\right] = L_s + t_{TA} + jL_c + \sum_{h=0}^{j}\mathrm{E}\left[T_b\right], \quad (19)$$

being t_{TA} the turnaround time to the transmitting mode and T_b the random time that a node spends in backoff or sensing states during the CSMA/CA mechanism. The expected value of T_b is

$$\mathrm{E}\left[T_b\right] = \sum_{i=0}^{m} P(\mathcal{D}_i)\mathrm{E}\left[T_{b,i}\right], \quad (20)$$

where $P(\mathcal{D}_i)$ is the probability of finding the channel idle at the $i+1$th attempt, given that the channel has been found busy in the preceding i attempts and the frame has not been discarded due to a channel access failure; and $\mathrm{E}\left[T_{b,i}\right]$ is the expected time a node spends in backoff or sensing states given the event $\mathcal{D}_i$. $P(\mathcal{D}_i)$ can be calculated as

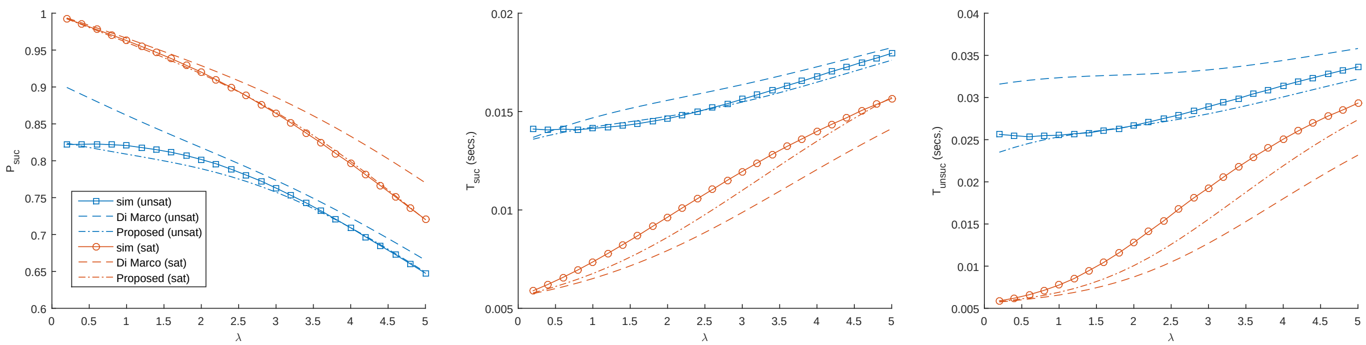
$$P(\mathcal{D}_i) = \frac{\alpha_l^i}{\sum_{k=0}^{m}\alpha_l^k}\alpha_l^i = \frac{1-\alpha_l}{1-\alpha_l^{m+1}}, \quad (21)$$

while

$$\mathrm{E}\left[T_{b,i}\right] = (i+1)t_{CCA} + \sum_{k=0}^{i} t_b\frac{W_k-1}{2}, \quad (22)$$

with t_b and t_{CCA} the durations of a backoff slot and CCA.

[3]We consider only the time from the instant the packet is ready to be transmitted until an ACK is received or until it is discarded because of the aforementioned failures (i.e., we do not include queuing time in this analysis).



(a) P_{suc} (b) T_{suc} (c) T_{unsuc}

Fig. 2: Performance metrics for a network with 1 saturated stations and 50 unsaturated stations as a function of the un traffic rate of unsaturated stations.

Regarding the delay suffered by a packet when it is discarded due to a channel access failure, $T_{cf,l}$, it can be derived following the same approach used to compute $T_{suc,l}$

$$\mathrm{E}\left[T_{cf,l}\right] = \sum_{j=0}^{n} P(\mathcal{F}_j)\mathrm{E}\left[T_{cf,l}^{(j)}\right], \tag{23}$$

where $\mathcal{F}_j$ is the event of having a channel access failure after j previous collisions and $T_{cf,l}^{(j)}$ is the delay suffered by a packet on the occurrence of event $\mathcal{F}_j$. It can be easily derived that $P(\mathcal{F}_j) = P(\mathcal{C}_j)$ and

$$\mathrm{E}\left[T_{cf,l}^{(j)}\right] = \sum_{h=0}^{j-1}\mathrm{E}\left[T_b\right]+jT_c+(m+1)\,t_{CCA}+\sum_{k=0}^{m} t_b\frac{W_k-1}{2}. \tag{24}$$

For $j=0$, the term $\sum_{h=0}^{j-1}\mathrm{E}\left[T_b\right]$ is 0.

The delay suffered by a packet when it is discarded due to a retry failure $T_{cr,l}$ is

$$\mathrm{E}\left[T_{cr,l}\right] = (n+1)\,L_c + \mathrm{E}\left[T_b\right]. \tag{25}$$

Finally, the probabilities of having a packet ready to be transmitted in idle state, after a successful transmission, after a channel access failure and after a retry limit failure are $q_l = 1-e^{-\lambda_l t_b}$, $q_{suc,l} = \lambda\mathrm{E}\left[T_{suc,l}\right]$, $q_{cf,l} = \lambda\mathrm{E}\left[T_{cf,l}\right]$ and $q_{cr,l} = \lambda\mathrm{E}\left[T_{cr,l}\right]$. A detailed explanation of their derivation can be found in [5]. Note that in case a station is saturated, $q_{suc,l} = q_{cr,l} = q_{cf,l} = 1$ and the idle state in the Markov chain of Fig. 1 is removed.

III. Results and Model Validation

To stress-test the proposed model, we have considered a network scenario with 50 sensor nodes generating messages at a low message rate, and one station with a backlog of saturated traffic. The results obtained through the model are validated against a system-level, discrete-event simulator of IEEE 802.15.4 PHY/MAC layers. All the simulated results represent the average of 10^8 frame transmissions. The MAC parameters used in the simulations are $m_{min} = 4, m_{max} = 7, m = 4, n = 0, L = 7, L_{ack} = t_{m,ack} = 2, IFS = t_{ack} = 0$, $t_b = 20 \cdot 16$ μs, $t_{CCA} = 8 \cdot 16$ μs, and $t_{ta} = 12 \cdot 16$ μs.

Fig. 2 shows the performance of the different classes of nodes as the traffic generation rate of the unsaturated nodes vary, comparing the results of our model with those of the one proposed in [5]. Fig. 2a depicts the probability of a successful transmission for the saturated and unsaturated nodes. As expected, this probability is close to 1 for the saturated node when the traffic of the unsaturated nodes is very low as it finds the channel idle most of the time. On the contrary, this probability starts approximately at 0.82 for the unsaturated ones as they have to contend with the saturated one. As λ increases, both probabilities converge since the unsaturated nodes tend to behave like the saturated one.

Fig. 2b shows the average delay incurred by a frame in a successful transmission, whereas Fig. 2c shows the average delay suffered by a frame when it is discarded due to a channel access failure or a retry limit. This delay corresponds to

$$T_{unsuc,l} = \frac{p_{cf,l}}{p_{cf,l}+p_{cr,l}}T_{cf,l} + T_{cr,l}\frac{p_{cr,l}}{p_{cf,l}+p_{cr,l}}. \tag{26}$$

In both cases, the delay is higher for unsaturated nodes as they will find the channel busy more frequently and will have to perform more backoffs.

IV. Conclusion

We have studied the performance of unslotted 802.15.4 with heterogeneous classes of nodes and class-specific frame generation rate. We have validated our model in a scenario with a saturated node and a fixed number of unsaturated nodes with varying traffic rate. The results show that the proposed model reflects the simulated performance of the reference network scenario better than previous state-of-art approaches.

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