Modelling of S-MAC for Heterogeneous WSN

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***Abstract*—Wireless Sensor Networks (WSN) have experienced an important resurgence, especially through applications designed for the Internet of Things. In that sense, a WSN can be constituted of different classes of nodes, having different characteristics. On the other hand, S-MAC was the first Medium Access Control (MAC) protocol for WSN to implement the Duty Cycling (DC). DC is a popular technique for energy conservation in WSN, that allows nodes to wake up and sleep periodically. In this work, a performance evaluation study of S-MAC is performed considering heterogeneous scenarios and diverse medium access priorities. To accomplish that, an analytical model with a pair of two-dimensional Discrete-Time Markov Chains (DTMC) is developed. Scenarios with two classes of nodes forming the network were studied. Performance parameters such as packet average delay, throughput and consumed energy, are obtained and validated by simulation, showing accurate results.**

***Index Terms*—Discrete-time Markov chain (DTMC) model, Duty-cycled MAC Protocols, heterogeneous wireless sensor networks, performance evaluation, S-MAC.**

I. Introduction

A WSN can be defined as a collection of nodes that perform sensing, processing and communication activities in a cooperative fashion with limited energy resources. Some examples of WSN applications are medical, industrial, agriculture and environmental monitoring. Furthermore, the technological evolution of sensors promises to facilitate the integration of WSN with Internet of Things (IoT), enhancing applications for WSN, such as smart grid, smart water, smart transport systems and smart homes [1]. Sensors nodes are considered energy-constrained devices as they are battery-supplied. The Medium Access Control (MAC) protocol is one of the major contributors of energy consumption [2]. Recent WSN MAC protocol developments employ Duty-Cycling (DC) to save energy and maximize the lifetime of battery-powered sensor nodes. In WSN MAC with DC, sensors are put to sleep periodically to save energy, waking up during the packet exchange periods. The S-MAC was the first MAC protocol for WSN to implement the DC technique, and is also one of the most popular [3]. On the other hand, a WSN may be constituted of different classes of nodes with different traffic patterns and even different priority requirements (heterogeneous scenario). For instance, heterogeneous WSN deployments, where emergency situations may arise, such as fires, earthquakes or some medical applications, need to send data to the destination node as soon as the event occurs. Thus, they need to have priority in the transmission of the information, in relation to other nodes constituting the WSN. Moreover, the modelling and performance study of WSN are of capital importance for their design and successful deployment.

Examples of modelling and performance analysis with applications to the S-MAC can be found in [4]–[7]. In those papers the authors have modelled the protocols using Discrete-Time Markov Chains (DTMC), considering homogeneous scenarios, where all nodes behave in the same way in terms of loads, communication and energy capabilities, and without the possibility of different access priorities to the channel. Markov-based models for heterogeneous WSN are presented in [8], [9]. In [8], different classes of nodes are considered, including the assignment of different arrival rates for each one, but without priority schemes. In [9], priority schemes including different classes of nodes are contemplated, but with equal arrival rates and number of devices for each class. Although these markovian models evaluate heterogeneous scenarios for WSN, they are not directly applicable for S-MAC. The main contribution of this work is the analytical modelling and performance evaluation of the S-MAC WSN, where nodes have different loads and access priorities. The model is based on two two-dimensional Discrete-Time Markov Chains (2D-DTMC). This model extends the capabilities of the models of [6] to enable different classes of nodes with different priority assignments in heterogeneous network scenarios.

The remainder of the article is organized as follows. In section II the transmission model and the general scenario are described. The mathematical modelling of the system is presented in section III. The analysis to obtain the performance parameters is developed in section IV. The results and their discussion are set out in section V. Finally the conclusions are presented in section VI.

II. Transmission model

A. S-MAC protocol

In S-MAC the time is divided into cycles of equal duration T, and each cycle consists of an *active* and a *sleep* periods. The *active* period is subdivided into two parts: the *sync* period of fixed-duration T_{sync}, where $SYNC$ packets are exchanged, and the *data* period, where the $DATA$ packets are exchanged. During a *sync* period, nodes choose a *sleep-awake* schedule and exchange it with its neighbours through $SYNC$ packets. These packets include the address of the node that sends the packet and the start time of its next *active* period. With this information, the nodes coordinate to wake up together at the beginning of each *sync* period. $SYNC$ packets are transmitted using a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism for contention-based access to the channel. CSMA/CA is based on the generation of a random backoff time and a carrier sensing procedure. If the channel is unoccupied when the backoff timer expires, then the node transmits the $SYNC$ packet. Nodes also use CSMA/CA to transmit $DATA$ packets during the *data* period. They generate new backoff times at each *data* period initiation and perform carrier sense. If the channel is idle when the backoff timer expires, then nodes can transmit $DATA$ packets using the RTS/CTS/$DATA$/ACK handshake. When a winning node receives a CTS in response to its previous RTS, it transmits one $DATA$ packet, and waits for the ACK. In S-MAC, a node goes to *sleep* until the beginning of the next *sync* period when: i) it loses the contention (hears a busy medium before its backoff expires); ii) it encounters an RTS collision; iii) after a successful transmission (only one packet per cycle is sent) [3].

B. Scenario and assumptions

We consider a heterogeneous WSN network with N nodes of different classes, where all nodes are reached in one hop and send the packets to a *sink* node. The scenario consists of a single cell cluster, but multiple clusters together can form a larger network. Two classes of nodes are considered, and it is assumed that class 1 nodes have priority in medium access over class 2 nodes. For convenience, one node of each class are selected as reference nodes, RN_1 and RN_2. It is assumed that the *sink* node behaves like a packet absorption node, it only receives packets (never transmits $DATA$ packets).

We also assume that: i) nodes are configured with infinite retransmissions, ii) all nodes contain the same initial energy; iii) the channel is error-free; iv) packets arrive to the buffer of a node following a renewal process, and the number of packets that arrive per cycle is characterized by independent and identically distributed random variables. A node has a buffer that can store at most Q packets, and it serves them according a FIFO discipline. We assume that the number of packets that arrive to a buffer follow a discrete Poisson distribution of mean λT, where λ is the packet arrival rate and T is the cycle duration. However, other distributions can be deployed.

We use a generic notation to identify the model parameters associated to any of both node classes, unless otherwise specified. In that sense, the expressions that are developed in sections III and IV, are equally applicable to both classes of nodes.

C. Assignment of medium access priorities

Figure 1 shows a diagram of the transmission process corresponding to the *data* period. In the figure, the synchronization period for both classes of nodes has been omitted. In this model, the media access priority is granted to class 1 nodes considering the following process. At the beginning of a cycle, the class 1 nodes activate the media access mechanism, contending only between the same class 1 nodes for accessing to the channel. The class 2 nodes wake up just after the class 1 contention window (W_1) has ended, and if they detect the medium unoccupied, they will try to transmit, activating their own contention procedure. If the class 2 nodes detect the medium occupied at that instant, they return to the *sleep* mode and they will wake up again in the next cycle. It is assumed that the duration of a packet transmitted by a class 1 node is longer than W_1 .

III. MODELLING OF THE SYSTEM

A. Access to the medium

The RN is an arbitrarily chosen node. A node is considered active when it has at least one packet in the queue. Active nodes generate a random back-off time selected from $[0, W-1]$. When the RN is active, it transmits a packet successfully if the other contending nodes select back-off times larger than the one chosen by the RN. The packet transmitted by the RN will fail (collide) when the RN and one or more of the other contending nodes choose the same backoff time, and this backoff time is the smallest among all contending nodes. If the backoff time generated by the RN is not the smallest among those generated by the other contending nodes, two outcomes are possible: either another node is able to transmit successfully, or other nodes collide when transmitting. Nodes that loose the contention (because they hear a busy medium before their backoff time expires) or encounter an RTS collision, go to *sleep* until the *sync* period of the next cycle.

N is the number of nodes of a given class. Consider a cycle where the RN is active and denote by $k, 0 \leq k \leq N-1$, the number of nodes that are also active in the same cycle in addition to the RN. Let $P_{s,k} = \sum_{i=0}^{W-1} \frac{1}{W} \left(\frac{W-1-i}{W}\right)^k$, $P_{sf,k} = \sum_{i=0}^{W-1} \frac{1}{W} \left(\frac{W-i}{W}\right)^k$, and $P_{f,k} = P_{sf,k} - P_{s,k} = \frac{1}{W}$, be the probabilities that the RN transmits a packet successfully, transmits a packet (successfully or with collision), and it transmits with failure (collision), respectively, when it contends with other k nodes. $P_{s,k}$ is the probability that the RN chooses a backoff value from $[0, W-1]$ and the other k nodes choose a larger value. $P_{sf,k}$ and $P_{f,k}$ can be described in similar terms. Conditioned on a successful or unsuccessful packet transmission by the RN when contending with other k nodes, the average backoff times are $BT_{s,k} = \frac{1}{P_{s,k}} \sum_{i=0}^{W-1} i \cdot \frac{1}{W} \left(\frac{W-1-i}{W}\right)^k$, or $BT_{f,k} = \sum_{i=0}^{W-1} i \cdot \left[\left(\frac{W-i}{W}\right)^k - \left(\frac{W-1-i}{W}\right)^k\right]$.

B. System with two classes and priorities

Here we model the evolution of the number of packets in the queue of RN_1 and RN_2, and the number of active nodes in

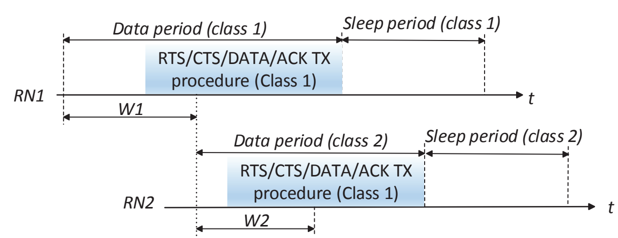

Fig. 1. Operation of MAC protocol during *data* period, for both classes of nodes.

the cluster over the time, by a pair of 2D-DTMC, one chain for each class of nodes. The system state is represented by (i, m), where $i \leq Q$ is the number of packets in queue of RN, and m, is the number of active nodes other than the RN, in the network of the corresponding class, $m < N$. Then, $P_{(i,m),(j,n)}$ is the transition probability from state (i, m) to state (j, n).

The first 2D-DTMC is taken from [6] and describes the evolution with time of the state of class 1 nodes. A second 2D-DTMC is proposed to define the state evolution of class 2 nodes. Some useful expressions and the state transition probabilities of the 2D-DTMC, are given in detail in [10, Table 1 for class 1 nodes and in Table 2 for class 2 nodes].

C. Solution of the 2D-DTMC

The solution of each of these 2D-DTMC can be obtained by solving the set of linear equations,

$$\boldsymbol{\pi} \boldsymbol{P} = \boldsymbol{\pi}, \quad \boldsymbol{\pi} \boldsymbol{e} = 1 \,, \tag{1}$$

where $\boldsymbol{\pi} = [\pi(i, n)]$ is the stationary distribution, $\boldsymbol{P}$ is the transition probability matrix, whose elements are defined in [10], and $\boldsymbol{e}$ is a column vector of ones.

The average probability, P_s, that the corresponding RN transmits a packet successfully, conditioned on the RN being active, is given by,

$$P_s = \frac{1}{G} \sum_{i=1}^{Q} \sum_{k=0}^{K} \pi(i, k) \cdot P_{s,k} \,, \tag{2}$$

and $G = \sum_{i=1}^{Q} \sum_{k=0}^{K} \pi(i, k)$. By solving the set of equations (1), $\boldsymbol{\pi}(P_s)$ can be determined for a given P_s. Then, a new P_s can be obtained from (2) for a given $\boldsymbol{\pi}$. Denote by $\boldsymbol{\pi}$ the solution of this fixed-point equation, i.e., the stationary distribution at the fixed-point.

IV. Performance Parameters

The procedure to obtain the performance parameters is applied equally to both classes of nodes.

A. Throughput

The node throughput η is defined as the average number of packets successfully delivered by a node in a cycle. The aggregate throughput, *Th*, expressed in packets per cycle, is the sum of the throughput of all N nodes of the corresponding class. Those parameters are obtained as,

$$\eta = \sum_{i=1}^{Q} \sum_{k=0}^{K} \pi(i, k) \cdot P_{s,k}, \; Th = N \cdot \eta \,. \tag{3}$$

B. Average packet delay

Let D be the average delay (in cycles) that a packet experiences from its arrival until it is successfully transmitted. Then, D can be determined by applying Little's law,

$$D = \frac{N_{av}}{\gamma_a}, \quad N_{av} = \sum_{i=0}^{Q} i \pi_i, \quad \gamma_a = \eta, \; \pi_i = \sum_{k=0}^{K} \pi(i, k) \,. \tag{4}$$

Note that: i) π_i is the stationary probability of finding i packets in the queue of the correspondent RN, and is determined by the expression (2); ii) N_{av} is the average number of packets in RN queue; iii) γ_a is the average number of packets that entered the RN queue (*accepted*) per cycle, that it is equal to η.

C. Average energy consumption

As described in Section II, the *active* period of a cycle is subdivided into the *sync* and *data* periods. The energy consumed during the *active* period represents the most significant contribution to the total energy consumption. In this section we calculate the energy consumed by the reference node RN in the *data* period. It should be noted that only the energy consumed by the radio frequency transceiver is studied. The energy consumed by the sensor nodes due to events related to specific sensing or monitoring tasks depends on the application and is not included here.

Let $E_{d,k+1}$ be the average energy consumed by the corresponding RN when it contends with other $k \geq 1$ nodes during the *data* period of a cycle. It is given by,

$$\begin{aligned}
E_{d,k+1} &= q_k [P_{s,k} E_{s,k}^{tx} + P_{f,k} E_{f,k}^{tx} + E_{oh,k}], \\
E_{s,k}^{tx} &= (t_{RTS} + t_{DATA}) P_{tx} \\
&\quad + (BT_{s,k} + t_{CTS} + t_{ACK} + 4D_p) P_{rx}, \\
E_{f,k}^{tx} &= t_{RTS} P_{tx} + (BT_{f,k} + 2D_p) P_{rx}, \\
E_{oh,k} &= (k P_{s,k} BT_{s,k} + (1 - k P_{s,k} - P_{sf,k}) BT_{f,k} + D_p) P_{rx} \,.
\end{aligned} \tag{5}$$

where $E_{s,k}^{tx}, E_{f,k}^{tx}, E_{oh,k}$ are energy consumption terms, when the RN contends with other k nodes and it transmits successfully, it transmits with failure (collision), and it overhears other transmissions, respectively.

Let $q_k = (k+1)/N$ be the probability that the corresponding RN is active, conditioned on finding $k+1$ nodes active. When the RN is active, $1 - P_{sf,k}$ defines the probability that it does not transmit, but the other k do. In that case: i) one of them transmits successfully (with probability $kP_{s,k}$); or ii) two or more collide (with probability $1 - kP_{s,k}$). It should be noted that if the RN is not active, then it will not listen to the channel, since we assume that nodes transmit to the *sink*, and the *sink* only receives, never transmits. In addition, $t_{RTS}, t_{DATA}, t_{CTS}$ and t_{ACK}, are the corresponding packet transmission times, P_{tx} and P_{rx} are the transmission and reception power levels, and D_p is the one-way propagation delay. It should be noted that $P_{s,0} = 1$, $P_{f,0} = 0$, $BT_{s,0} = (W-1)/2$, $E_{d,1} = q_0 E_{s,0}^{tx}$, and $E_{d,0} = 0$. The average energy consumed by the RN during the *data* period in a cycle is given by,

$$E_d = \sum_{k=0}^{N} E_{d,k} \cdot R_k \,. \tag{6}$$

where R_k is the stationary probability of finding *k* active nodes in a cycle, and is determined as: $R_k = \sum_{i=1}^{Q} \pi(i, k-1) + \pi(0, k),\; 1 \leq k \leq N-1,\; R_N = \sum_{i=1}^{Q} \pi(i, N-1),\; R_0 = \pi(0, 0)$. The *sleep* part of a cycle is not included, as we consider that the energy consumed is negligible, compared to the energy consumed in the data period.

For class 2 nodes, the same expressions are applied to obtain the consumed energy in the *data* period E_{d_2}, to which must be added $E_o = time\ slot \cdot P_{rx}$, that is the energy consumed to sense the channel in the wake up instant after W_1. The final equations for determining the consumed energy for both classes of nodes, are given by: $E_1 = E_{d_1}, E_2 = (1-R_{1,0})E_o + R_{1,0} \cdot E_{d_2}$. Where $R_{1,0}$ is the stationary probability of finding no active nodes of class 1, in a cycle. Due to $E_o \cong 0$, its value is set to 0. E_1 and E_2 are the consumed energy for nodes of class 1 and class 2, respectively.

V. Numerical results

A. Scenarios and parameter configuration

The analytical results are obtained from the developed 2D-DTMC models. The simulation results are obtained by means of a custom-based discrete event simulator developed in C language, where the transmission scheme is implemented. The developed simulator mimics the physical behavior of the system. That is, at each cycle a node receives packets according to a given discrete distribution, it contends for access to the channel with other nodes if it has packets in the buffer, and if it wins, it then transmits a packet according to the transmission scheme. The simulation results are completely independent of those obtained by the analytical model. That is, the calculation of the performance metrics in the simulations does not depend on the developed mathematical expressions.

The WSN is configured considering two classes of nodes and two scenarios, with the following parameters: DATA packet size $S = 50$ bytes, transmission power level $P_{tx} = 52$ mW, reception power level $P_{rx} = 59$ mW, queue capacity of a node $Q = 5$ packets, packet arrival rate for class 1 nodes, $\lambda_1 = \{0.5\}$ packets/s, packet arrival rate for class 2, $\lambda_2 = [0.5, 4.5]$ packets/s. In scenario 1 (SC1), the number of sensor nodes of class 1 and 2 are $N_1 = 3$ and $N_2 = 6$. In scenario 2 (SC2), the number of sensor nodes of class 1 and class 2 are $N_1 = 3$ and $N_2 = 9$. The time parameters are summarized in Table 1. The contention window (W) is set to 128, and equal for both classes, $W_1 = W_2 = W$.

In the following subsections the results of the performance parameters obtained from the analytical model and by simulation are shown.

B. Average packet delay

Figure 2 shows the average packet delay expressed in cycles, for both classes of nodes in SC1 and SC2, and a packet arrival rate $\lambda_1 = 0.5$. We denote by D_1 and D_2 the average delay of packets successfully transmitted by class 1 and class 2, respectively. Observe in Fig. 2 that D_1 takes a constant value. This is because λ_1 and the number of nodes N_1 are also constant values, and class 1 nodes have priority over class 2 nodes. However, for class 2 nodes the arrival rate of packets $\lambda_2 \in [0.5, 4.5]$. Note that D_2 increases with λ_2, as the fraction of packet that collide increases with λ_2, and more retransmissions are required. Therefore, for the class 2 nodes, it takes longer to transmit their packets. Note that class 1 nodes operate at low load, and have their queues empty most of the time. Then, when a packet arrives it is transmitted immediately and without collision. Note also that for SC1, $N_2 = 2N_1$, and for SC2 $N_2 = 3N_1$. For SC2, where the number of nodes is incremented, D_2 reaches higher values than in SC1. When the number of nodes increases, it takes longer to get channel access due to the increased contention. Then, packets have to wait longer time in the queue before being transmitted. In addition, more collisions occur which leads to more retransmissions.

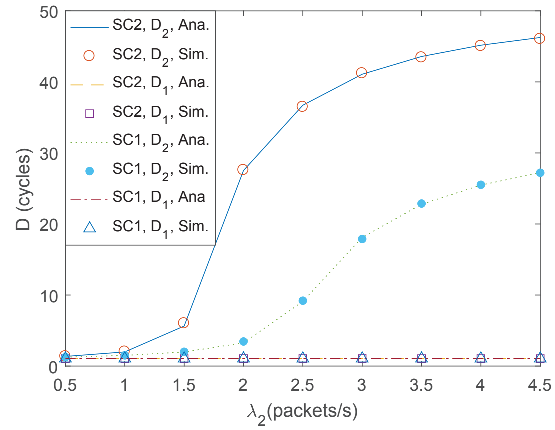

Fig. 2. Average packet delay in cycles. SC1, SC2, both classes.

TABLE I
Temporary parameters (milliseconds)

Duration of cycle (T)	60	Propagation delay (D_p)	0.0001
t_{RTS}, t_{CTS} and t_{ACK}	0.18	t_{SYNC}	0.18
t_{DATA}	1.716	Time slot (backoff)	0.1

C. Throughput

Figure 3 shows the throughput for class 2 nodes, considering both scenarios. A maximum throughput value is reached, from which a constant behaviour with λ_2 is observed. A saturation level is reached. In general, the throughput is higher for SC1 than for SC2. This is because in SC1, the number of nodes is smaller and therefore there is less contention. Nodes have more opportunities to access the channel and succeed in the transmission of packets, reaching higher throughput values. On the other hand, since there are fewer nodes, it is possible to operate at higher arrival rates without saturation.

D. Average energy consumption

Figure 4 shows the average energy consumption of both classes of nodes per cycle, in millijoules (mJ), considering both scenarios. From the figure, for the class 2 nodes, there is a higher energy consumption per node for the SC1 than for SC2. Recall that SC1 is composed with less number of nodes.

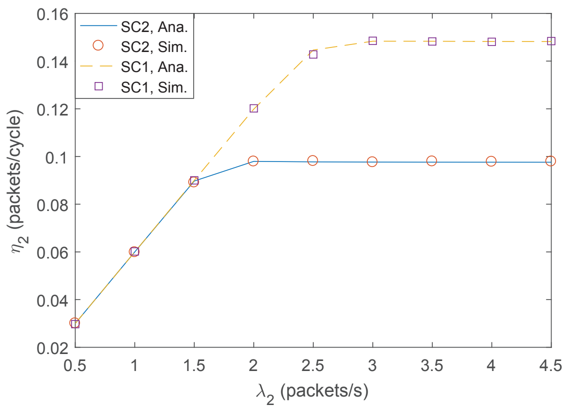

Fig. 3. Throughput per node. Both scenarios, class 2.

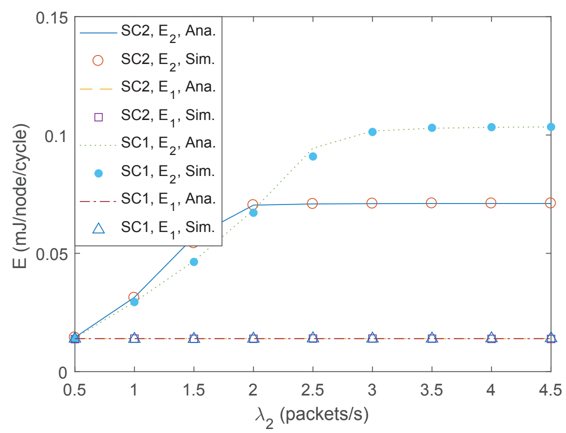

Fig. 4. Average energy consumption per node per cycle. Both scenarios, both classes.

This scenario of higher energy consumption corresponds to the scenario where a higher throughput is achieved (Fig. 3). Greater values of throughput implies to carry out more transmissions and packet deliveries, leading to a higher activity of the nodes, and therefore a greater energy consumption. Figure 4, also shows that for nodes of class 1, the energy consumed is constant with λ_2. This is because both, the packet arrival rate λ_1 and the number of nodes N_1 are constant. For class 2 nodes, the packet arrival rate is varied ($\lambda_2 \in [0, 4.5]$ packets/s), and the number of nodes that constitute the network is different for each scenario. The nodes eventually reach a limit of activity, that has associated a limit of energy consumption. Fig. 4 also shows, that for class 2 nodes, for SC1, the limit of energy consumption is higher and is reached at a higher traffic load, than that of SC2. As there are less nodes in SC1, the nodes can operate at higher packet arrival rates before reaching a saturation level of activity.

VI. Conclusion

A performance study of a heterogeneous WSN network has been accomplished, considering different classes of nodes and the assignment of medium access priorities. A analytical model was developed for a WSN MAC protocol that considers heterogeneity an priorities. It operates in WSNs with a synchronous duty-cycled MAC protocol like S-MAC. The model is based in two 2D-DTMC. Unlike existing analytical models for duty-cycled MAC protocols applied to S-MAC, our model takes into account the different classes of nodes, and the assignment of medium access priorities. The analytical model is solved for specific scenarios, obtaining values of performance parameters like average packet delay, throughput and average energy consumption. The analytical model is validated through discrete-event based simulations, showing accurate results. The study shows the impact on the performance parameters of class 2 nodes, due to the prioritization of the access to the medium for nodes of class 1. This occurs when the traffic and the number of nodes increase. An acceptable traffic coexistence between both classes is achieved, when the priority class contributes with a low load.

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