Analysis of Queue Load Effect on Channel Access Prioritization in Wireless Sensor Networks

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***Abstract*—Resource allocation in Wireless Sensor Networks (WSNs) is certainly a challenging issue. WSNs are characterized by special features, like energy constraints and limited computing resources. Latest trends define that sensors should be able to provide Quality of Service (QoS) demanding data transmission. A modern approach in bandwidth sharing considers both the packet queue load as well as the traffic priority. A new QoS aware channel sharing approach is introduced, analyzing the effect of queue load in WSN Medium Access Control (MAC). The analysis reveals that the queue load factor has a great impact on QoS provision in bandwidth sharing, while packet priorities are also considered.**

***Index Terms*— MAC, WSN, QoS, queue load analysis**

I. Introduction

WIRELESS Sensor Networks (WSNs) constitute a major trend in modern networking. Small devices capable of "sensing" the surrounding environment and transmitting the data collected for further processing are employed by WSNs. Sensors can be used in different applications to collect various types of data, such as measurements of temperature, humidity, wind speed, pollutants, pressure, radiation, and electromagnetic fields. Moreover, sensors are utilized as monitor devices, collecting digital multimedia data via microphone or camera. Regardless of the application employed, WSNs are characterized by limited battery lifetime, low processing power and scarce network resources, hence special treatment is required.

Modern WSN applications demand efficient traffic differentiation, so that the different types of communication are treated by the network according to their specific characteristics, i.e. real-time applications require low end-to-end delay and jitter. Furthermore, critical data have to be favored during resource allocation. Since energy autonomy of the mobile devices is limited, low power sensors may need to be served first. Overall, modern WSNs require efficient Quality of Service (QoS) support, an issue that has not been thoroughly examined according to authors knowledge.

Due to the unreliable nature of the wireless medium, QoS support constitutes a challenging requirement. A part of the wireless network that is critical for QoS provision is the first hop. Moreover, the common channel has to be efficiently shared, so that a satisfactory network performance is achieved. Thus, Medium Access Control (MAC) protocols are employed to allot the available bandwidth effectively and are extensively examined in literature for wireless local (WLAN) and personal area networks (WPAN). In fact, a typical approach for the WSN MAC is the adoption of WLAN protocols, namely the legacy DCF [1] and the QoS supportive Enhanced Distributed Channel Access (EDCA) [2], and WPAN protocols, such as the one defined in IEEE 802.15.4 [3]. Channel access control mechanisms designed specifically for WSNs are capable of QoS support (as a general concept) taking into account the following basic factors: distance from the receiver, power saving, packet priorities, path length and queue load.

In this paper a new method for bandwidth sharing within common channel segments of a WSN is introduced considering packet priorities and queue load. The proposed method can be adopted by any relevant complete mechanism aiming at differentiating traffic based on its criticality and dealing with the overloaded queue problem, which may lead to extended packet delays and losses. Additionally, an analytical approach is presented to study the impact of queue load factor on bandwidth sharing. It is demonstrated that queue loading rate significantly affects the prioritization of traffic flows regarding their probabilities of gaining channel access.

The rest of the paper is organized as follows. Section II presents the related work focusing on WSN MAC protocols and QoS aware techniques to allocate network resources. In Section III, the introduced traffic prioritization method is described and the queue load is analyzed. Model verification and the related results are presented in Section IV. The paper concludes in Section V while also providing future research directions.

II. Related Work

Some all-purpose MAC protocols and techniques used for

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wireless networks could be possibly also applied to WSNs. Recently, advanced MAC protocols meeting WSNs specifications are introduced, some of which are presented below. In what follows, solutions focused on handling real-time traffic generated in sensing devices are examined meeting the increased QoS requirements.

A real-time architecture protocol including a packet scheduling policy, called velocity monotonic scheduling, is proposed accounting both time and distance constraints [4]. In S-MAC, which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), network nodes form virtual clusters according to common sleep schedules toward efficient energy conservation [5]. Moreover, it applies message passing to reduce contention latency for demanding applications. Contrary to S-MAC, T-MAC employs an adaptive duty cycle and achieves further energy efficiency [6]. PMAC also adopts adaptive sleep-wakeups exhibiting higher throughput compared to S-MAC under high traffic load [7]. In [8] RL-MAC is proposed where nodes do not rely on their own traffic load information, but actively infer the state of other nodes. B-MAC studied in [9] employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening. Besides, X-MAC uses shorter preamble than B-MAC achieving reduced energy usage and lower latency [10]. DMAC tries to solve the forwarding interruption problem, caused by sleep delays, via sleep schedule adjustment [11]. Furthermore, it provides a data prediction mechanism and other techniques that can improve the channel contention conditions. In [12] a hybrid TDMA-CSMA/CA approach, called Z-MAC, is proposed exhibiting robustness regarding synchronization errors, slot assignment failures and time-varying channel conditions. Q-MAC employs different priority levels to differentiate services introducing two different mechanisms that govern intra-node (Power Conservation MACAW, PC-MACAW) and inter-node (Loosely Prioritized Random Access, LPRA) scheduling [13]. To increase data delivery probability the QoMOR protocol is proposed, allowing each source node to transmit each new packet an optimal number of times in every interval [14]. In [15] H-MAC is developed based on the IEEE 802.11 Power Saving Mechanism (PSM) providing low latency, high throughput and improved channel utilization It should be stressed out that number of these protocols consider queue load to schedule transmissions and control energy conservation.

A quite promising and widely accepted solution for medium access control in WSNs emanates from WPANs such as the one proposed by the IEEE 802.15.4 standard [3]. Although it is based on CSMA/CA, it provides critical traffic flows with the ability of reserving time slots toward guaranteed QoS provision supporting both peer-to-peer and star topologies. Extended QoS support is provided by Hybrid Control Function (HCF) which is the evolution of IEEE 802.11e MAC scheme [2]. HCF includes a contention based mechanism, called EDCA, and a contention free mechanism, called Hybrid Control Channel Access (HCCA). EDCA is based on CSMA/CA implementing multiple queues according to the traffic priorities. The HCCA process is determined by resource reservation and uses fixed time slots allocated via polling.

Another MAC protocol for wireless networks that provides extended QoS support is Adaptive Weighted and Prioritized Polling (AWPP) [16]. AWPP is capable of providing deterministic QoS according to the priority and the rate of each traffic flow. Moreover, it ensures fairness among different nodes by taking into account the time that has been elapsed since a node was last served. AWPP depends on polling and doesn't require resource reservation.

III. QUEUE LOAD AWARE BANDWIDTH ALLOCATION

A. *New Prioritization Method*

A simple bandwidth sharing technique is introduced which can be applied in the MAC protocol of sensors contending for medium access. This method can be employed to analyze the queue load impact on medium access prioritization.

According to the proposed method, it is assumed that in every node a different queue of packets is formed for each corresponding traffic priority. This assumption is typical in well known protocols relevant to the proposed one, as EDCA [2]. The amount of the available bandwidth in terms of time division that can be allocated to serve a queue, i.e. to transmit its packets, is proportional to the queue load and the respective traffic priority. This is a quite straightforward technique according to QoS provision principles which define that high priority traffic should be favored as well as overloaded node must have high channel access probability, so that extended packet delays and drops are averted. Accordingly, energy is also conserved, since retransmissions of the dropped packets, due to buffer overload or lifetime expiration, are avoided. Let N denote the total number of different queues. A packet queue i, $i=1,\ldots,N$, is characterized by a number $Q_i(t)$, which is indicative of its priority and load, defined at a given time t by

$$Q_i(t) = z^{p_i} L_i(t) \tag{1}$$

where z, $z \geq 0$, is a preset priority factor expressing the fraction of the channel access probabilities among two consecutive priority levels of traffic flows, p_i is the priority of ith queue and $L_i(t)$ denotes the actual load of ith queue at a given time t. Suppose there are two queues $i=\{A, B\}$ within a network segment and z equals 2. Moreover, let queue A has priority higher than B by 1 and both queues carry the same load, then A will be allowed to use twice the bandwidth of B. Let $normQ_i(t)$ denote the normalized portion of bandwidth allocated to ith queue by the proposed channel allocation technique, defined by

$$normQ_i(t) = \frac{Q_i(t)}{\sum_{k=1}^{N} Q_k(t)} . \tag{2}$$

In practice, each node could be characterized by a parameter determined by the $Q_i(t)$ values of the queues supported, i.e. the sum of $Q_i(t)$ values. Bandwidth sharing among different nodes is based on this parameter, while the access of each specific queue depends on the specific $Q_i(t)$

values. The proposed approach constitutes a general method applicable to both distributed and centralized MAC protocols. The detailed operation of the MAC mechanism is out of the scope of this paper.

B. Analysis of the Queue Load Factor

In what follows, the impact of queue load rate on bandwidth sharing is examined, taking into account the queue load and traffic priority levels. Queue load might affect channel allocation proportionally as derived by (1), but this is not the case for the load rate, since the latter cannot be predetermined directly. Thus, when a traffic flow is characterized by a certain priority and a known load rate, i.e. like most multimedia streams, the respective channel access probability cannot be estimated compared to other flows. Consequently, the satisfaction of traffic flow according to the service level offered by the network cannot be estimated, hence it is inevitable to decide whether appropriate changes to the priority levels or the bandwidth sharing are necessary.

Suppose there are two queues ($N=2$) corresponding to different traffic flows with discrete priority levels, respectively. The total number of bits of ith queue that have been transmitted till time t is given by $f_i(t)$ and the respective sending rate is given by its first derivative $f_i'(t)$. The analysis presented aims to determine the two queues sending rate ratio denoted by c, in which converges. The available bandwidth capacity b is measured in bps. Note that the analysis holds when the total load rate exceeds b, otherwise, the sending rate of each queue matches its load rate. Thus, it holds

$$\frac{f_1'(t)}{f_2'(t)} = c \xrightarrow{f_1'(t)+f_2'(t)=b} f_1'(t) = c(b - f_1'(t)) \longrightarrow$$
$$f_1'(t) = \frac{cb}{1+c} \xrightarrow{(1),(2)} \frac{z^{p_1}L_1(t)}{z^{p_1}L_1(t) + z^{p_2}L_2(t)} b = \frac{cb}{1+c} \longrightarrow$$
$$z^{p_1}L_1(t) = cz^{p_2}L_2(t)\,. \tag{3}$$

Without loss of generality, we assume that each queue load rate remains constant in time, otherwise its mean value a_i can be used. Let $G_i(t)$ denote the total load that has been arrived to the ith queue from the beginning ($t = 0$) until time t. Evidently, the first derivative of $G_i(t)$ is equal to a_i. Since a_i is constant, $G_i(t)$ is a linear function of t. Moreover, the first derivative of $f_i(t)$ is also constant in time, therefore $f(t)$ is a linear function of t, too. Thus,

$$(3) \xrightarrow{G_i(t)-f_i(t)=L_i(t)} z^{p_1-p_2}(G_1(t) - f_1(t)) = c(G_2(t) - f_2(t))$$
$$\xrightarrow{G_i'(t)=a_i} z^{p_1-p_2}(a_1 t - f_1'(t)t) = c(a_2 t - f_2'(t)t)$$
$$\xrightarrow{p_1-p_2=r} z^r\left(a_1 - \frac{cb}{1+c}\right) = c\left(a_2 - \left(b - \frac{cb}{1+c}\right)\right) \longrightarrow$$
$$a_2c^2 + (a_2 - b - a_1z^r + bz^r)c - a_1z^r = 0\,. \tag{4}$$

Solving the quadratic equation (4) c values can be calculated by the following quadratic formula

$$c = \frac{-(a_2 - b - a_1z^r + bz^r) \pm \sqrt{(a_2 - b - a_1z^r + bz^r)^2 + 4a_1a_2z^r}}{2a_2}\,. \tag{5}$$

where $c \geq 0$, since the ratio of the queues sending rates cannot be negative.

Scaling up this analysis to multiple queues is quite intuitive, when only two traffic flows with different priority levels are supported. According to (1) the portion of the available bandwidth which is allocated to a queue is straightly proportional to its load. Thus, in the proposed analysis multiple queues of the same priority are grouped into a single queue assigned with the same priority. The load rate of the unified queue is equal to the total load rates of the individual queues. Evidently, there would be two unified queues each one corresponding to a different priority level. Through equation (5) the sending rates of each unified queue are estimated. The sending rates of the individual queues are determined by dividing the sending rate of the corresponding unified queue proportionally to the load rates of its individual ones.

We consider the case that there are l and m queues of priority p_1 and p_2, respectively. Then, equation (1) can be rewritten as follows

$$Q_{ik}(t) = z^{p_i}L_{ik}(t) \tag{6}$$

where $k = \{l, m\}$, $Q_{ik}(t)$ is a parameter indicative of the priority and load regarding the kth queue for the traffic flow of ith priority level as well as $L_{ik}(t)$ denotes its respective actual load. Let $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$ represent the priority levels of the two unified queues supported. Since $\boldsymbol{P}_1 = p_1$ equation (1) can be rewritten regarding the first unified queue as follows

$$Q_1(t) = z^{P_1}L_1(t) \longrightarrow \sum_{k=1}^{l} Q_{1k}(t) = z^{P_1}L_1(t) \longrightarrow$$
$$\sum_{k=1}^{l} z^{p_1}L_{1l}(t) = z^{P_1}L_1(t) \xrightarrow{P_1=p_1} L_1(t) = \sum_{k=1}^{l} L_{1k}(t). \tag{7}$$

Similarly to (7) and given that $\boldsymbol{P}_2 = p_2$, for the second unified queue it holds

$$L_2(t) = \sum_{k=1}^{m} L_{2k}(t)\,. \tag{8}$$

From (7) and (8) it can be deduced that the load of each unified queue is equal to the aggregate traffic load of the corresponding individual queues assigned with the same priority level. To calculate the two queues sending rate ratio given by (5), the load rate a_i of the unified queues needs to be determined, that is

$$G_1(t) = \sum_{k=1}^{l} G_{1k}(t) \longrightarrow a_1 t = \sum_{k=1}^{l} a_{1k} t \longrightarrow a_1 = \sum_{k=1}^{l} a_{1k} \tag{9}$$

$$G_2(t) = \sum_{k=1}^{m} G_{2k}(t) \longrightarrow a_2 t = \sum_{k=1}^{m} a_{2k} t \longrightarrow a_2 = \sum_{k=1}^{m} a_{2k} \tag{10}$$

where $G_{ik}(t)$ is the kth queue load rate for traffic flow of ith priority level. Evidently, each unified queue exhibits load rate equal to the sum of the load rates of its individual queues. Given the two queues sending rate ratio both $f_1'(t)$ and $f_2'(t)$ can be calculated. Accordingly, the sending rate $f_{ik}'(t)$ of each individual queue can be determined by

$$f_{1k}'(t) = \frac{Q_{1k}(t)}{Q_1(t)} f_1'(t) = \frac{L_{1k}(t)}{L_1(t)} f_1'(t) =$$
$$\frac{G_{1k}(t) - f_{1k}(t)}{G_1(t) - f_1(t)} f_1'(t) = \frac{(a_{1k} - f_{1k}'(t))t}{(a_1 - f_1'(t))t} f_1'(t) \longrightarrow$$

$$f'_{1k}(t) = \frac{a_{1k}}{a_1} f'_1(t) \tag{11}$$

and

$$f'_{2k}(t) = \frac{a_{2k}}{a_2} f'_2(t) \tag{12}$$

for the first and second queue, respectively.

Considering the general case where multiple queues and several traffic flows corresponding to different priority levels are used, the analysis becomes more complex. The concept implies to treat two queues at a time individually, as it has already been presented, calculating the bandwidth assigned to each queue. Eventually, the sending rate of each individual queue can be computed via solving a set of equations. The notations for the general case are as follows

- $f'_t(t)$ is the sending rate of tth unified queue, $t = \{i, j\}$, $i, j \in S$, $S = \{1, ..., N\}$, which is equal to the bandwidth allocated to the queue,
- b_{ij} denotes the aggregate bandwidth allocated to i and j queues, $i \neq j$,
- $c[b_{ij}]$ the ratio $f_i'(t)/f_j'(t)$ that is computed by (5) as a function of b_{ij}.

For example, suppose that there are three unified queues $N = 3$ of different priorities and the value of b is given. The following set of equations is formed

$$f'_1(t) = \frac{c[b_{12}]b_{12}}{1 + c[b_{12}]} \tag{13}$$

$$f'_2(t) = \frac{c[b_{23}]b_{23}}{1 + c[b_{23}]} \tag{14}$$

$$b_{12} = f'_1(t) + f'_2(t) \tag{15}$$

$$b_{23} = f'_2(t) + f'_3(t) \tag{16}$$

$$f'_3(t) = b - f'_2(t) - f'_3(t) \tag{17}$$

Solving the above set of equations, we get the sending rates $f_1'(t)$, $f_2'(t)$, $f_3'(t)$, as well as the aggregate bandwidth parameters b_{12} and b_{23}.

Note that the presented theoretical approach assumes that the queues have infinite capacity. However, a more realistic approach where packet queues have limited capacity should be examined. In this case the system might reach an equilibrium point that is the sending rates ratio converges, under significantly high queue load. In fact, the constraint of limited queue capacity leads to two possible cases when adequate time has elapsed. In the first case, a queue is loaded to its maximum capacity, since it is assigned lower bandwidth that its load rate. According to the second case, a queue exhibits sending rate equal to its load rate, consequently the queue load remains constant. The steps of the algorithm employed to determine which of the two cases occurs and calculate the sending rates has as follows

- Step A: Suppose that all queues are full. The algorithm calculates the bandwidth portion of ith queue, which would be allowed to use, by

$$W_i = \frac{z^{p_i} C_i}{\sum_{k=1}^{N} C_k} b \tag{18}$$

where C_i is the maximum capacity of ith queue.

- Step B: In case that $W_i \geq a_i$, the sending rate of ith queue is set equal to a_i and the algorithm continues with the next step. Otherwise, the algorithm goes to the Step A with the next queue until all queues are assigned with a sending rate equal to a_i or none of the rest queues satisfies the inequality of Step B.
- Step C: The sending rate value of ith queue determined in the previous steps is subtracted from the available bandwidth. Next, the process is repeated for the rest queues starting from Step A considering as available bandwidth the remaining one.

Obviously, if we get to a point that no queue is entitled with a portion of bandwidth equal to its load rate, then all the queues will get full. In this case, the sending rates of each queue are determined based on the normalized Q_i values. Note that when the queues capacity is high or the sending rates converge fast to the equilibrium point, then the outcome of the algorithm regarding the case of limited queues is close to the one provided by the analysis considering infinite queues.

IV. Model Verification and Results

The presented analytical model has been verified via simulation results through an emulation software developed in C#. Bandwidth allocation cycles have been generated by the emulator according to the proposed method described in subsection IIIA. The loop implementing the bandwidth allocation cycle for the case of two queues is presented below

```
do
  {
   L1 += a1;
   L2 += a2;
   Q1 = Math.Pow( z, p1 ) * L1;
   Q2 = Math.Pow( z, p2 ) * L2;
   normQ1 = Q1 / ( Q1 + Q2 );
   normQ2 = Q2 / ( Q1 + Q2 );
   S1 = normQ1 * b;
   S2 = normQ2 * b;
   if ( S1 > L1 )
    {
     S1 = L1;
     S2 = b - S1;
     if ( S2 > L2 )
      S2 = L2;
    }
   else if ( S2 > L2 )
    {
     S2 = L2;
     S1 = b - S2;
     if ( S1 > L1 )
      S1 = L1;
    }
   L1 -= S1;
   L2 -= S2;
} while <TERMINATION CONDITION>
```

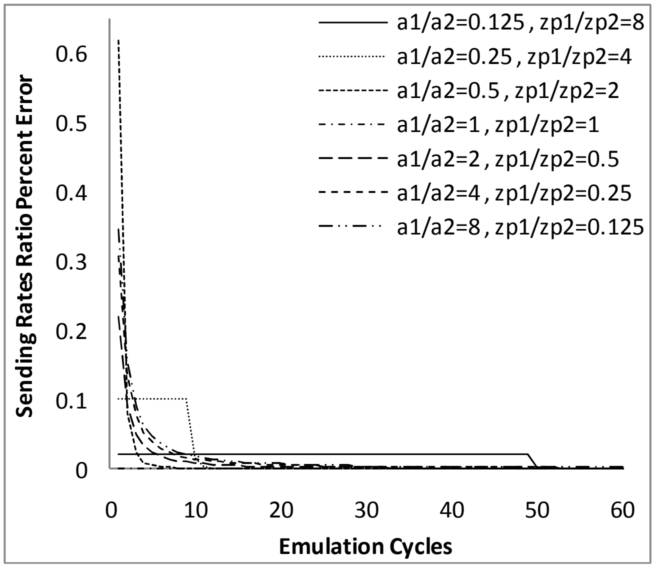

Fig. 1. Sending rates ratio percent error versus emulation cycles

where *S1* and *S2* are the actual sending rates of the first and the second queue, respectively. Actually, in this emulation software *b* represents the total number of bits that can be sent by all queues during an operation cycle, *a1* and *a2* represent the number of bits during an operation cycle that enter the first and the second queue, respectively, as well as *S1* and *S2* represent the number of bits during an operation cycle that are sent by the first and the second queue, respectively. The termination condition may vary and it can be a predefined number of cycles or a convergence condition, i.e. a maximum allowed divergence of the sending rates ratio $S1/S2$ between two consecutive cycles.

The convergence of $S1/S2$ to the value provided by *c* in (5) is depicted in Fig. 1 for different values of the loading rates ratio $a1/a2$ and the formed priorities ratio z^{p1}/z^{p2}. The values of the parameters involved in the examined scenarios are: b=1000, $a2$=1000, z=2 and $p2$=4. It is observed that the sending rates ratio percentage error given by $|c - S1/S2|/c$ converges to 0, as the number of the emulation cycles increases.

The log-log plot shown in Fig. 2 depicts the impact of the formed priorities ratio on the way that the sending rates ratio is affected by the loading rates. We observe that while the total bandwidth is distributed proportionally to the actual queue load, this is typically not the case for the load rate. Actually, it can be observed that the sending rates ratio is proportional to the load rates ratio only when both queues are assigned with the same priority (z^{p1}/z^{p2}=1). Generally, the sending rates ratio increases with the increase of ratio z^{p1}/z^{p2}. This increase can be categorized as ascending or descending when z^{p1}/z^{p2} is above or below unity, respectively.

In Fig. 3, the queues sending rates ratio versus the ratio of the queues priorities ratio (z^{p1}/z^{p2}) and the ratio of the queues loading rates ($a1/a2$) is plotted in log-log-log plot. Note that both variables, z^{p1}/z^{p2} and $a1/a2$, employed in the graph are independent each another. It is observed that the resulted surface, which depicts the performance of the proposed model,

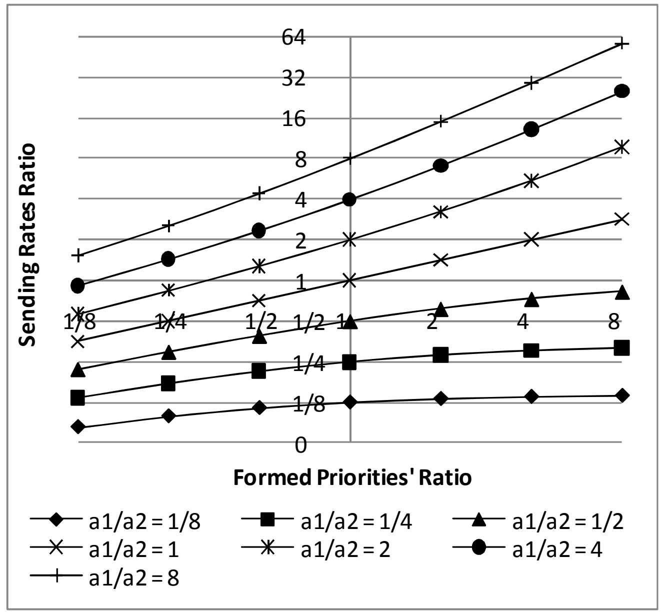

Fig. 2. Sending rates ratio versus formed priorities ratio

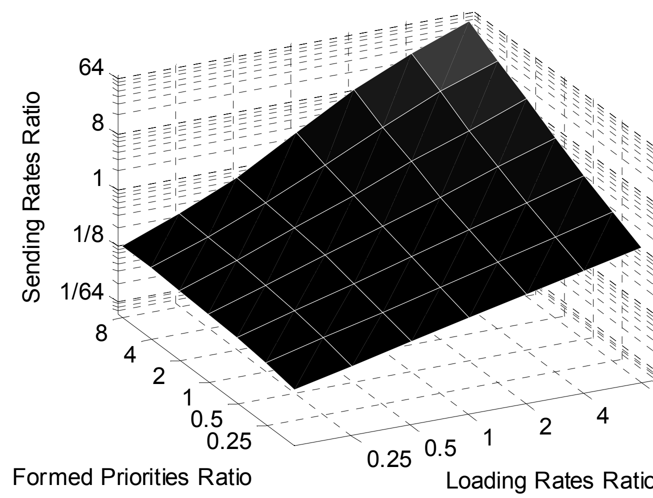

Fig. 3. Sending rates ratio as a function of the loading rates ratio and the formed priorities ratio

complies with the behavior described in the previous paragraph demonstrated in Fig. 2.

V. Conclusion

The impact of queue load on bandwidth sharing in MAC protocols for WSNs is thoroughly examined in this paper. In this work, a new resource allocation model that assigns bandwidth in proportion to different packet queues load is proposed. The results demonstrate a nonlinear relationship between the ratio of the bandwidth allocated to different queues and their loading rates ratio, unless the queues are characterized by the same traffic priority. The analysis presented and its outcome were validated through an emulator developed for this purpose. The results and the derived outline are very useful in the area of QoS provision in WSNs. To this end, this work could lead to the development of efficient MAC schemes that can deterministically provide superior QoS in WSN applications.

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