Analysis of Channel Access Delay of Slotted CSMA/CA in a WSN

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Abstract. Wireless sensor networks are often designed to operate on remote areas. Thus, sensor devices need to operate for years and have to save energy by switching their radio component off as often as possible. IEEE 802.15.4 is a standard that induces a low energy consumption. It divides time into an active period, where devices communicate, and an inactive period, where devices sleep. Many research has been done on how to optimize the medium access delay during the active period. Surprisingly, few studies take into account the inactive periods when analyzing the delay.

In this paper, we give a macroscopic analysis of the medium access delay of a low-power wireless sensor network that operates in the beacon-enabled mode of IEEE 802.15.4. We conduct multiple simulations in order to study the impact of the network parameters such as the number of devices in range and the traffic production. We also propose an estimation of the access delay in the case of a traffic uniformly distributed among devices, and in the case of a traffic non-uniformly distributed among devices.

Keywords: IEEE 802.15.4, slotted CSMA/CA, low-power WSN, medium access delay, estimation model.

1 Introduction

Recently, many industrial applications have been developed based on the technology of wireless sensor nodes. Sensor nodes are cheap energy-constrained devices that perform some monitoring tasks. They are often deployed in low populated or dangerous areas. The goal of such networks is to monitor the environment for several years without requiring to change the batteries of the devices. The IEEE 802.15.4 standard [IEE06] describes a medium access control (MAC) protocol that suits the requirements of such sensor nodes. The standard describes two modes of operation for the MAC sublayer, one of them being slotted CSMA/CA (which stands for Carrier Sense Multiple Access with Collision Avoidance), which is the focus of this paper.

Slotted CSMA/CA divides time into two periods: an active period and an inactive period. During the active period, all the devices can communicate together. They are often in competition for the medium access. During the inactive

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period, they save energy by turning their radio component off. Low-power wireless sensor networks tend to have devices inactive most of the time. This has a clear impact on delay, as communications are only possible during the short active periods.

In this paper, we give a macroscopic analysis of the medium access delay of a low-power wireless sensor network that operates with the slotted CSMA/CA algorithm of IEEE 802.15.4. We conduct multiple simulations in order to study the impact of the network parameters such as the number of devices in range and the traffic production. We also propose an estimation of the access delay in the case of traffic uniformly and non-uniformly distributed among devices.

Section 2 describes the IEEE 802.15.4 standard and slotted CSMA/CA. It describes related analytical and experimental analyzes and shows that previous research mainly focuses on active periods, while we concentrate on inactive periods. In Sect. 3, we study the medium access delay in scenarios where the traffic is uniformly distributed among the data sources. In Sect. 4, we extend this study to scenarios where the traffic is non-uniformly distributed among the data sources. Then, we propose a linear estimation model for the delay in Sect. 5 and we present a discussion in Sect. 6. Section 7 concludes our work.

2 State of the Art

In this section, we first describe the IEEE 802.15.4 standard and slotted CSMA/CA. Then, we present the related work on slotted CSMA/CA that is devoted to the delay analysis, with analytical or experimental approaches.

2.1 Overview of the IEEE 802.15.4 MAC Layer

The IEEE 802.15.4 standard [IEE06] supports two operational modes: (i) the beacon-enabled mode in which periodic beacon frames are transmitted to synchronize nodes according to a superframe structure depicted in Fig. 1, and (ii) the non-beacon-enabled mode in which unslotted CSMA/CA is used. In this paper, we focus on the beacon-enabled mode as it is more energy-efficient than the non-beacon-enabled mode.

In the beacon-enabled mode, the active period (also called the superframe) is divided into two periods: the contention access period (CAP) during which slotted CSMA/CA is used to avoid collisions, and the contention free period (CFP) where nodes have guaranteed time slots ensuring a collision free transmission. Note that slotted CSMA/CA is only used during the CAP. The interval that separates two consecutive beacons (BI) and the superframe duration (SD) are determined by two parameters: the superframe order (SO) and the beacon order (BO). BI and SD are defined as follows:

$$\begin{cases} \text{BI} = \text{aBaseSuperframeDuration}.2^{\text{BO}}, \\ \text{SD} = \text{aBaseSuperframeDuration}.2^{\text{SO}}, \end{cases}$$

where $0 \leq \text{SO} \leq \text{BO} \leq 14$ and aBaseSuperframeDuration = 15.36 ms.

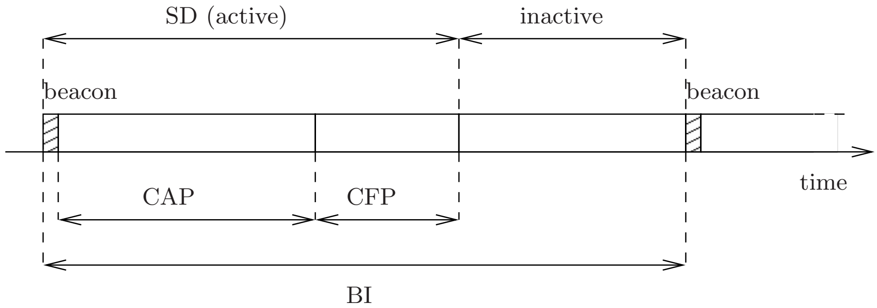

Fig. 1. Beacon interval in IEEE 802.15.4 beacon-enabled mode

Two topologies are proposed by the standard: star and peer-to-peer. The peer-to-peer topology suffers from beacon frame collisions when the beacon-enabled mode is used (see Task Group 4b [IEE] or [KCA07, CGM08]). Thus, in what follows we only consider the star topology.

2.2 Slotted CSMA/CA

In IEEE 802.15.4, the slotted CSMA/CA algorithm is applied before the transmission of any frame occurring during the CAP (except beacons and acknowledgements). This algorithm is based on a time unit called backoff period which lasts 320 μs. The boundaries of the backoff periods are aligned with the boundaries of the superframe slots, *i.e.*, the start of the first backoff period of all devices is aligned with the beacon transmission. Any activity of the MAC sublayer (such as the channel sensing and the transmissions) starts at the boundary of a backoff period.

The slotted CSMA/CA algorithm uses three variables: the first is NB (Number of Backoff periods), which is the number of times a backoff has been drawn for this transmission attempt. The second is CW (Contention Window length), which is the number of consecutive backoff periods during which a device senses the channel. The third is BE (Backoff Exponent), which defines the range of possible backoff periods a device waits for until it assesses the channel.

Figure 2 represents the stages of slotted CSMA/CA. In Step 1, the MAC sublayer initializes the three variables and locates the boundary of the next backoff period: NB is set to 0, CW is set to 2 and BE is set to 3. In Step 2, a random number of backoff periods is chosen from $[0; 2^{\mathrm{BE}} - 1]$. In Step 3, the MAC sublayer assesses the channel by performing a clear channel assessment (CCA). The MAC sublayer asks the physical layer to perform two CCAs (since CW = 2) at the next backoff boundary. The next step depends on the result of each CCA. If the channel is assessed to be busy, the MAC sublayer goes to Step 4. Otherwise, it goes to Step 5. In Step 4, NB and BE are incremented by one, provided that BE does not exceed aMaxBE, and CW is set to 2. If NB exceeds macMaxCSMABackoffs (denoted by macMaxCB. on the figure), the algorithm

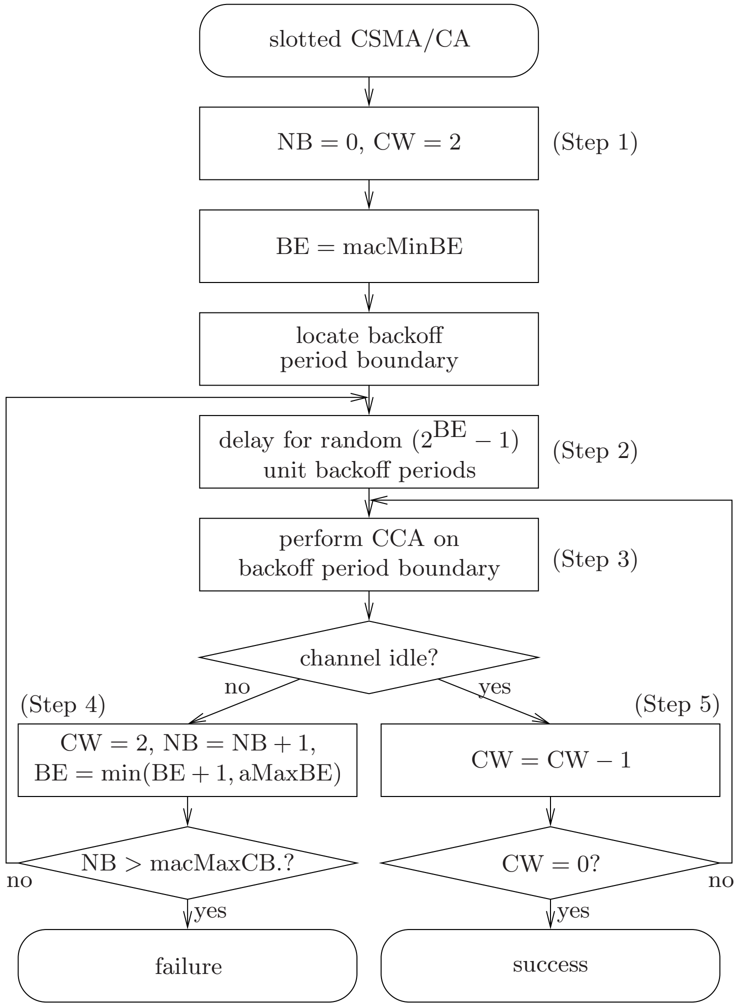

Fig. 2. IEEE 802.15.4 slotted CSMA/CA (without the battery life extension)

terminates with a channel access failure, otherwise it goes back to Step 2. In Step 5, CW is decremented. If CW becomes equal to zero, the transmission begins at the boundary of the next backoff period. Otherwise, the MAC sublayer returns to Step 3.

2.3 Analytical Analyzes of the Delay of Slotted CSMA/CA

Here, we focus on the papers that propose analytical models to evaluate the performance of slotted CSMA/CA. In all the following papers, authors focused on the evaluation of the delay during the active period. The key difference between their approach and ours is that we claim that the inactive period accounts for most of the delay.

In [PEE+06], the authors considered both saturated and periodic traffic scenarios in a star topology. They validated their analytical results on throughput and energy consumption by simulation. They simulated a long active period of 10^8 backoff periods, that is, of more than 8 hours.

In [PKC+05], the authors evaluated slotted CSMA/CA in terms of throughput and energy consumption, in saturation conditions in a star topology. They assumed that each time a frame is sent, a new frame arrives at the MAC sublayer. Their analysis is validated by simulations with the network simulator NS-2. Again, as the authors focused on the active period, they fixed a long beacon interval (BO = 10 which corresponds to 15.4 seconds).

In [TPGZ06], the authors proposed a Markov chain in order to analyze the throughput of slotted CSMA/CA. The authors developed a custom C simulator to validate their analysis. However, since no value for BO, SO, BI or SD is given, we assume that their simulation did not take into consideration the inactive period.

In [SS07], the authors studied the throughput and energy consumption of slotted CSMA/CA in both saturated and periodic traffic conditions. Their main contribution is the use of a single, simple, one-dimensional Markov chain while [PEE+06], [PKC+05] and [TPGZ06] use complex two-dimensional Markov chains. They validated their analysis through simulations. However, they simulated a single active period of 5.10^5 backoff periods, that is, of 160 seconds.

2.4 Experimental Analyzes of the Delay of Slotted CSMA/CA

Researchers have also performed simulation analyzes on slotted CSMA/CA. Among multiple parameters, they varied BO and SO and observed the impact on the performance of the protocol.

In [LKR04], the authors studied the delivery ratio, the throughput and the delay as a function of the duty cycle and the energy consumption of slotted CSMA/CA. Concerning the delay, they have shown that delay increases as the duty cycle decreases by plotting the average delay as a function of $2^{\mathrm{SO}}/2^{\mathrm{BO}}$, for a single source. In this paper, we propose a more detailed analysis of this phenomenon. Notably, we relate the medium access delay to the frame production time. We also study scenarios where multiple sources transmit data frames.

In [KAT06], the authors observed the effect of BO and SO on the behavior of slotted CSMA/CA and analyzed its impact on the average delay, the throughput and the number of collisions. However, in all their simulations, the values of BO and SO are the same. Thus, there is no inactive period.

In [CHGM09], the authors have shown that the deference mechanisms used towards the end of the CAP have a major impact on the delay of slotted CSMA/CA. Although deference mechanisms occur rarely, their penalty on delay is so large that deference becomes significant for short global cycles. In this paper, we encounter the same situation: the inactive period has a large impact on delay. We give here a macroscopic analysis of the medium access delay, as opposed to [CHGM09].

3 Analysis of Uniform Traffic

We start our analysis by a scenario where the traffic is uniformly distributed among the sources. After describing the simulation setup, we give results for a single source. Then, we extend the results to a scenario with multiple sources.

3.1 Simulation Setup

Our simulations are done with NS-2, version 2.31. We used a simple star topology with one coordinator and ten end-devices. We deployed the nodes so that they are in range of each other. We used the two-ray ground shadowing model with default parameters, and we used 1.33×10^{-6} W for the reception and carrier sense threshold. However, we deployed the nodes close enough to ensure that the propagation model has no impact on the reception of frames.

The PHY and MAC layers used in our simulation are those of the `wpan` module of NS-2, and correspond to IEEE 802.15.4 specifications. The coordinator generates periodic beacons, according to the value of BO. After all the end-devices are associated to the coordinator, some of them are chosen as traffic sources. Each traffic source periodically sends data frames to the coordinator. Data frames have a MAC payload of 30 bytes, plus 7 bytes added by the PHY layer. Each data frame is acknowledged. We set the size of the frame queues to 100 frames to reduce the effect of queue overflows (this is discussed in the following). Lastly, simulations are run 100 times and last for 100 seconds; frames in the queues when the simulation stops are discarded.

In the following, we consider two scenarios: one with a single traffic source, the other with multiple traffic sources. The varying parameters are described at the beginning of the corresponding subsection.

3.2 Single Source Scenario

In the single source scenario, only one end-device is configured as a traffic source. We set BO to 7, which results into a global cycle of $2^7 \times 15.36 = 1966.08$ ms (*i.e.*, about two seconds). In most simulations, we vary SO from 4 to 6, which results into activity durations from 245.76 ms to 983.04 ms (from 12.5% to 50% of the global cycle). This is a typical case for LP-WPANs. We also vary the traffic generation frequency from five frames per second to twenty frames per second.

Figure 3 shows a graphical representation of the medium usage on two sample simulations: one with a traffic frequency of five frames per second (referred to as low traffic), the other with a traffic frequency of twenty frames per second (referred to as high traffic), both with SO = 6. The medium usage is shown on a time axis for about 3 seconds, which is larger than one global cycle. Beacons,

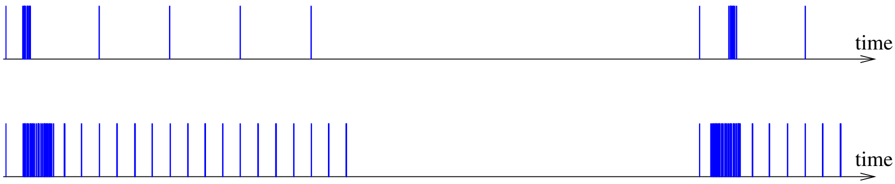

Fig. 3. Medium occupation in the single source scenario, for low traffic (upper part) and high traffic (lower part). Medium occupation is high at the very beginning of the active period.

data frames and acknowledgments are represented by a vertical line at the time when they are transmitted. Active and inactive periods can be clearly seen on the figure. It can also be seen that the beginning of the active period is the period when the channel is the most busy. This is more obvious when the traffic frequency is high. The modeling of this phenomenon is the basis of this paper.

As we have seen, the medium is highly occupied at the beginning of the active period (which follows the beacon transmission), and is mostly idle the remaining of the time. This means that frames produced in the middle of the active period can be transmitted quickly, while frames produced at the beginning of the active period might experience larger delays. Our goal now is to quantify the delay of frames with respect to their production time.

Figure 4 shows the average medium access delay as a function of the traffic frequency. The delay is computed as the time that separates the frame production (at the application layer) to the frame transmission (at the physical layer). Note that in our simulation, the frame is only delayed at the MAC layer. The traffic frequency varies from five frames per seconds to twenty frames per second. Note that all times are normalized according to the beginning of the active period and are averaged over 100 simulations. Thus, each point of the figure represents the average of 5,000 global cycles (100 simulations for 100 seconds, with a global cycle of 2 seconds). Finally, times are rounded to 0.1 seconds.

Figure 5 displays the frame loss as a function of the traffic frequency. As the average medium access delay only takes into account the received frames, delay and frame loss have to be considered at the same time. As expected on this figure, frames are lost when the queues are full, that is towards the end of the inactive period, and at the beginning of the active period.

The active and inactive periods are shown very clearly on Fig. 4. As the active period directly follows the beacon frame transmission, it is normal that frames experience small delay on the left part of the graph. All the frames produced during the inactive periods experience large delays (reaching a peak at 1 second, which is the length of the inactive period).

There are two main results that can be extracted from Fig. 4 and from Fig. 5. First, it can be seen that the average delay decreases linearly during the inactive period, with a speed that depends on the traffic. When the number of frames accumulated during the inactive period is small, these frames are sent quickly by

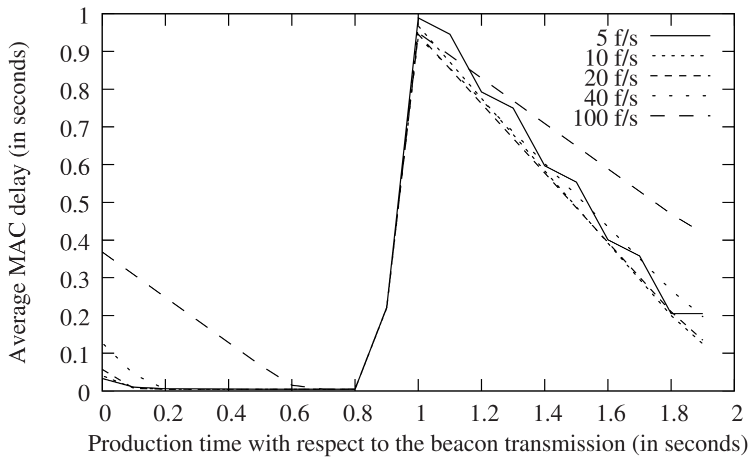

Fig. 4. The average medium access delay is very large for frames produced during the inactive period, but it can be large for frames produced at the beginning of the active period too

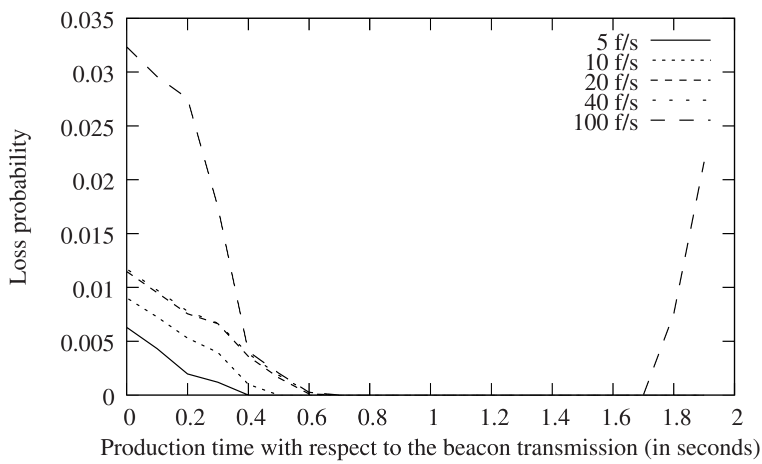

Fig. 5. Frames are dropped when queues are full, *i.e.*, at the end of the inactive period and at the beginning of the active period

slotted CSMA/CA. Thus, the average delay decreases from 1 s to nearly 0 s at the end of the inactive period. However, as more frames are accumulated, more time is required to send them, which delays all the remaining frames. Slotted CSMA/CA is not able to cope efficiently with more than 40 frames per second in our scenario.

Second, under high traffic conditions, frames produced at the beginning of the active period experience a large delay (and have a high probability of being lost). This is due to the fact that frames produced during the inactive period are already queued, and are trying to access the medium. When 100 frames are produced per second, more than 60% of the active period is devoted to transmitting the frames produced in the previous inactive period.

3.3 Multiple Sources Scenario

In the multiple source scenario, we varied the number of sources and kept the traffic constant. We used the following settings: 100 frames per second for one source, 20 frames per second for five sources, and 10 frames per second for ten sources. The overall traffic generated is 100 frames per second. Traffic production starts randomly within the first second for each source.

Results on delay are shown on Fig. 6. It can be seen that delay is reduced when the number of sources is increased. This general behavior is known for CSMA/CA algorithms. When a single node transmits data, it cannot use the medium very often. Indeed, it has to wait for the mandatory backoff (between 0 and 7 backoff slots) before transmitting any frame. Thus, it cannot use the medium to its full extent. When there are more sources in the network, the probability that one source transmits while the other performs the backoff is larger. This increases the medium usage, and reduces the average delay.

Results on frame loss are shown on Fig. 7. When there was only one source, queue overflow was the only cause of frame loss. As soon as multiple sources are competing for the channel, frame collisions appear. Many frames queued during the inactive period are dropped due to collisions. This number increases with the number of sources. The number of frames dropped due to queue overflows is negligible.

Slotted CSMA/CA is not very efficient in avoiding collisions. Let us consider a simple example when a collision occurs. Let us assume that the channel is idle, and two sources decide at the same time to perform the first CCA (this situation can happen even if the two sources have drawn different backoffs, provided that the difference of backoff cancels the difference of time when the decisions were taken). Both CCAs return idle, and both sources perform the second CCA. Again, both CCAs return idle. Then, the two sources start the transmission, and a collision occurs. Slotted CSMA/CA performs a few retries (four by default) before discarding the frame. Notice that in a real scenario, the capture effect might lessen this problem.

4 Analysis of Non-uniform Traffic

In this section, we used a non-uniform traffic in order to determine if the traffic distribution among sources had an impact on the average medium access delay. We used the same simulation setup as before, except for the traffic production. We decided to have five sources producing a total of 100 frames per second, that is an average of 20 frames per second and per source, but distributed among the sources in a non-uniform manner. Sources 1 and 2 produce 25 frames per second,

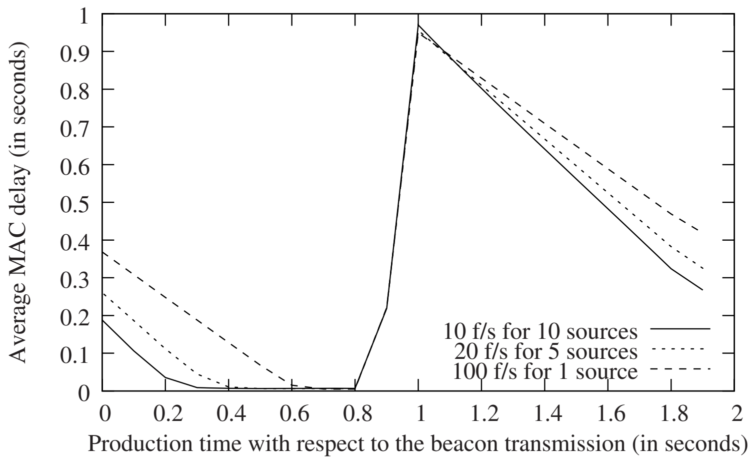

Fig. 6. The average medium access delay is reduced when several sources send traffic

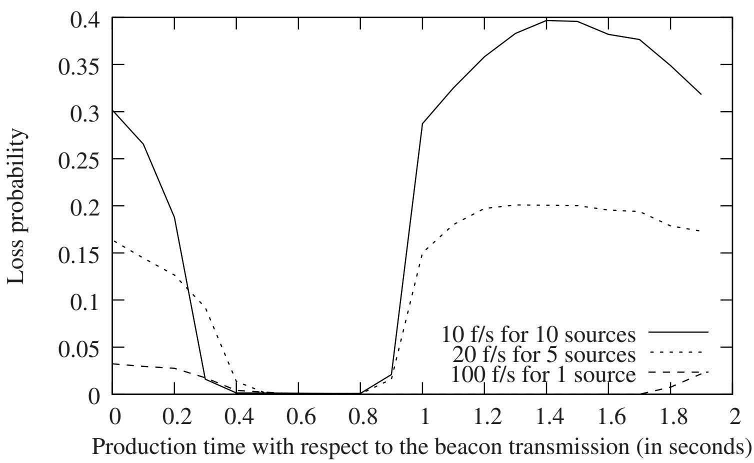

Fig. 7. The more sources, the more collisions

sources 3 produce 20 frames per second, and sources 4 and 5 produce 15 frames per second.

Fig. 8 present the medium usage for five sources on a sample simulation. It can be seen that sources 4 and 5, which produce less traffic than the other nodes, only suffer from the contention of the medium at the beginning of the CAP. The medium usage is high for sources 1 and 2 for more than a third of the active period. However, this medium usage snapshot is obtained only from one simulation.

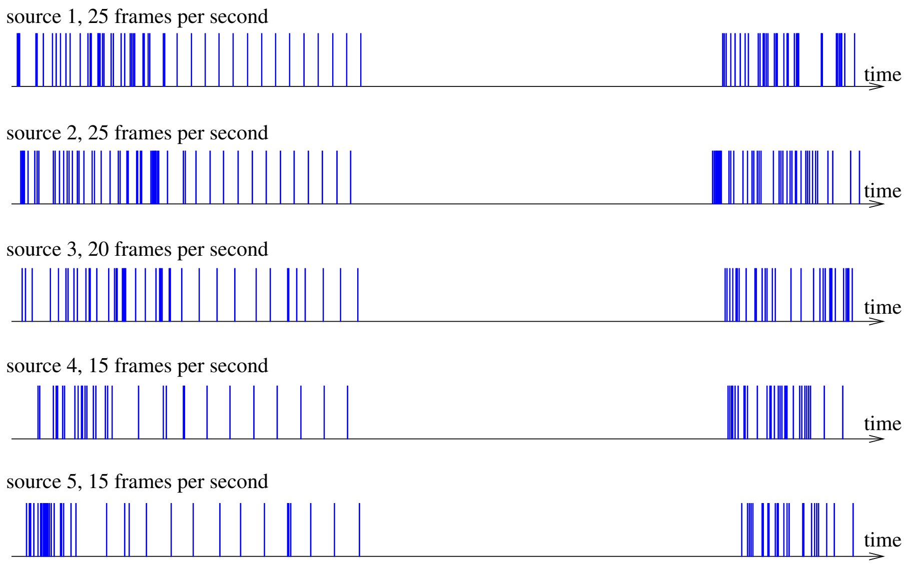

Fig. 8. Medium usage for five sources with non-uniform traffic load

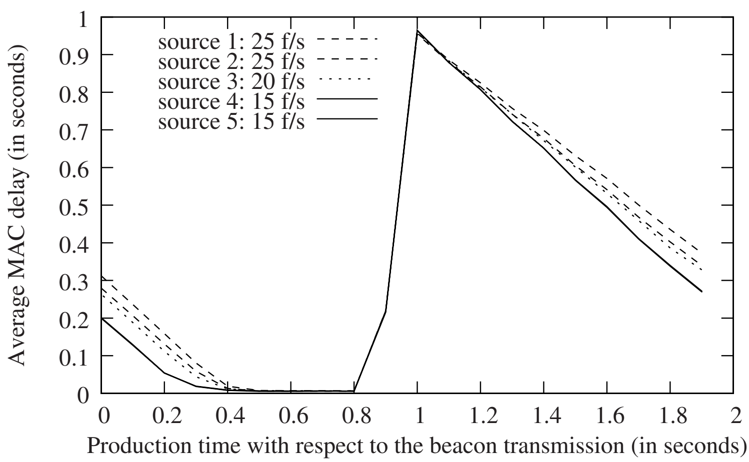

Fig. 9. The average medium access delay depends in a limited manner on the production of each source

Fig. 9 show the average medium access delay per source. Note that as the production of a source increases, its MAC delay also increases. As the traffic increases, the variation of delay also increases: sources 4 and 5 (having a small traffic production of 15 frames per second) experience a similar delay, whereas sources 1 and 2 (having a high production of 25 frames per second) experience a delay that slightly varies.

5 Linear Model of the Delay

As can be seen on Fig. 4, 6 and 9, the average MAC delay can be approximated as a linear function of the time. In this section, we propose such a model.

Figure 10 shows the important points of our model. Notice that O denotes the origin, that is, the beacon transmission time. b represents the beacon interval, and s represents the superframe duration (that is, the duration of the active period). Frames produced shortly before point A can be sent without a large delay. However, once the inactivity period starts, frames experience large delays. This is represented by point B. Frames accumulated during the inactivity period cannot be sent instantaneously at the beginning of the next active period. It takes up to a certain time, represented by point C, to have all the accumulated frames sent. We assume that the traffic load does not change a lot from one active period to the next active period. That is why our model uses in fact a point C', which corresponds to point C but in the current active period.

Our goal now is to determine the coordinates of each point. Trivially, $x_O = y_O = y_A = y_C = y_{C'} = 0$. We also have $x_B = x_A = b$ and $x_C = x_{C'} + b$. From the IEEE 802.15.4 standard, we know that $b = 15.36 \times 2^{BO} \times 10^{-3}$ seconds and $s = 15.36 \times 2^{SO} \times 10^{-3}$ seconds. As the nodes queues are traditionally of a first in first out (FIFO) type, the first frame that is queued at the beginning of the inactivity period is the first that is transmitted. This transmission occurs at the beginning of the active period (after waiting for a backoff and winning the competition for the medium). As the channel access time during the active period is negligible compared to the inactive period duration, the delay for the first frame (which is the highest delay) is equal to the inactive period duration. Thus, $y_B = b - s$.

The remaining value, $x_{C'}$, is computed using our experimental values, which are summarized in Table 1. Let n denote the number of sources and l the total

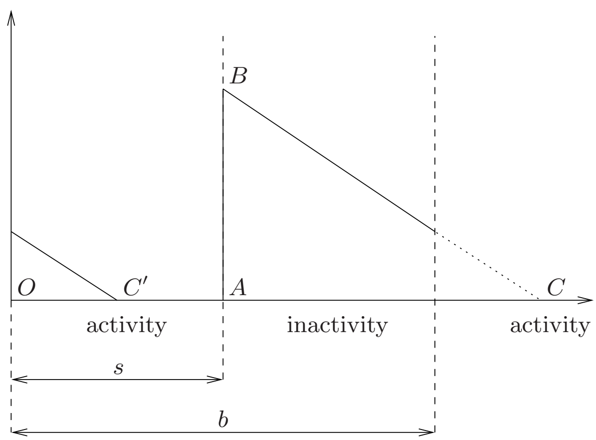

Fig. 10. A simple linear model of the average MAC delay

Table 1. Value of x_C as a function of the number of sources n and the traffic load l

Sources	Load	x_C	Sources	Load	x_C
1	5	0.1	5	100	0.35
1	10	0.1	10	100	0.25
1	20	0.1	5	40	0.15
1	40	0.15	10	40	0.15
1	100	0.6			

traffic load produced. From the values corresponding to $n = 1$, we have $x_{C'} \approx 6.5 \times 10^{-5} l^2 - 1.5 \times 10^{-3} l + 0.1$ (by using a polynomial regression of order 2). The number of sources only has a significant impact on the delay when l is high. That is why we started by expressing $x_{C'}$ as a function of l. From the previous expression of $x_{C'}$ as a function of l, we injected n in the following way. We noticed that:

- $x_{C'}$ for $n = 5$ and a given l is close to $x_{C'}$ for $n = 1$ and $6 \times l/8$,
- $x_{C'}$ for $n = 10$ and a given l is close to $x_{C'}$ for $n = 1$ and $5 \times l/8$.

Then, we found out a logarithmic fit for those values. We obtained the following formula for $x_{C'}$:

$$x_{C'} = 6.5 \times 10^{-5} (8.18 \times 0.94^n \times l/8)^2 - 1.5 \times 10^{-3} (8.18 \times 0.94^n \times l/8) + 0.1.$$

This model uses the total traffic load in the vicinity of the sensor, which can be obtained by overhearing, by computing the average number of clear channel assessments that failed, by computing the average number of frame failures or by other mechanisms.

Our model could be improved by determining the final equation as a function of n and l at the same time, rather than estimating it from l first, and adjusting it with n. Also, our model could be improved by taking into consideration the traffic load of each source independently, in addition to the total traffic load. However, from the results of Sect. 4, we expect only a small improvement in the approximation accuracy. A better improvement is certainly to model what happens at point C'. Indeed, the delay is not linear at this point, especially when the traffic load is high.

6 Discussion on Aperiodic Traffic

In this section, we discuss about non-periodic traffic. While all the simulations done for this paper concerned periodic traffic, we believe that the traffic distribution is not a parameter that has a significant impact on the results presented in this paper.

During the inactive period, the traffic is accumulated in the source queues. They serve as buffers, in the way of a leaky bucket: although they might be filled with aperiodic traffic, they are still emptied with linear speed (see the left part of Fig. 4 and 6).

During the active period, the traffic arrival distribution has an impact on delay. It is easier to deal with periodic frames in a fast manner than with burst of frames. However, this impact is limited. During the part of the active period when all the accumulated frames have been sent (or dropped), frames can be dealt with very efficiently. For example, we can see on Fig. 4 that it takes approximately 0.2 seconds for one node to transmit 40 frames (on the line with 40 frames per second, approximately 40 frames have been accumulated during the inactive period). Thus, even large bursts of 40 frames could be dealt with quickly. During the part of the active period when there are still some accumulated frames that have neither been sent nor dropped, the bursty frames accumulate with the previous frames, in the same manner as during the inactive period.

7 Conclusion

Low-power wireless sensor networks are designed to operate for years. The price to pay for the long energy autonomy of the devices is a larger medium access delay due to the long inactive periods. While many researchers have focused on optimizing the delay in the active period, we studied in this paper the impact of the inactive period on the delay.

We have shown that inactive periods cause a bottleneck at the beginning of the activity period. This bottleneck takes a significant amount of time to be dealt with, which increases the delay of all the waiting packets, and increases the frame loss probability. We have also shown that having more sources can reduce the delay, but at the cost of greatly increasing the frame loss probability. We have concluded our analysies by providing an estimation model of the average delay as a function of the number of sources and the traffic load.

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