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Specification of Collision-Free CSMA MAC Protocols for Wireless LANs

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Abstract

Collision-free CSMA MAC protocols are interesting solutions for considering real-time traffic in a wireless context. The goal of this paper is precisely to make an exhaustive presentation (which, we think to be understandable and pedagogical) of the main collision-free CSMA MAC protocols for one-hop wireless LANs, considering priorities (static, hybrid [4]) associated to the frames. The priorities are represented by either the BlackBurst technique [10], [7] or an adaptation of the CAN bus protocol [1] to the wireless context we call CANlike protocol [11], [9], [5]. The cornerstone of this work is the concept of Ambiguity Time Window that we have defined for characterizing the Physical layer, and which allows to specify the parameters of the considered protocols. In our knowledge, such kind of study has never been done.

1. Introduction

Wireless networks and, more particularly, Wireless Local Area Networks (WLANs) are more and more used today in the industrial area where we have real time applications which require Quality of Service (QoS) guarantees. In this context, the MAC protocols which implement the scheduling of the frames (in which the application messages are encapsulated) on a shared radio channel have an essential role.

Two main types of MAC protocols are the TDMA (Time Division Multiple Access) type and the CSMA (Carrier Sense Multiple Access) type. The CSMA type is a totally distributed procedure whereas the TDMA type requires some centralized schemes. Then, in the CSMA type with respect to the TDMA type, the changes in a network (adding or withdrawing stations and/or applications) are easier to do. Furthermore, the CSMA type is more suitable for sporadic traffic. We consider here the CSMA type.

However, the big drawback of a strict CSMA type *i.e.* only based on the great fundamental principle “Listen before Send” is that collisions can occur. Protocols CSMA/CA have been defined in order to decrease the occurrence of the collisions (they use the concepts of con-

tentions window, Backoff technique and Interframe space; examples are IEEE802.11 DCF [2] and IEEE802.15.4 with the unslotted CSMA/CA mechanism [3]). However, these protocols cannot fully avoid collisions. Then all these protocols cannot provide QoS guarantees (for example, delay upper bound). If we want to get QoS guarantees and then to be able to consider real time traffic, we need a property of collision-free which can be obtained (by incorporating priorities to the CSMA type protocols).

The improvement of the protocols of the CSMA type, by using priorities associated to the frames (*i.e.* what would be a collision situation in the CSMA type is changed in a winner-looser(s) situation) is an important challenge.

Works have already been done on the association of priorities to the frames: some works [10], [7] have defined the priorities as BlackBurst messages which precede the frame sendings (a BlackBurst message is a sequence of energy pulses which is all the more long because the priority is high). The drawback of the BlackBurst message technique is that, if we have a great number of priorities, the length of the BlackBurst messages, which represents the high priorities, can be very high which gives important delays. Other works [11], [9], [5] avoid this drawback by considering an adaptation to the wireless context of the technique of the Dominance protocol used in the CAN bus [1] *i.e.* the priorities are in the ID (IDentifier) field which is at the beginning of a frame. (We call CANlike protocol such an adaptation).

After a careful reading of the quoted references and still many other papers, we think that these works do not clearly and rigorously state, at first, the specific problematic of the CSMA type (collision potentiality: why, when and how *i.e.* by considering and explaining the role of the physical parameters of the transceivers and the channel) and, then, the different mechanisms in order to define collision-free protocols. So these works do not, in our opinion, help to have a clear understanding. That is the reason of this paper where we want (hope) to give a pedagogical presentation on the collision-free CSMA MAC protocols in a wireless context.

The protocols, which are proposed, concern mono-channel WLANs where each station is in the transmission range of the others and any station can send a frame to

another station in a single hop (so no hidden and exposed terminal problems).

This paper includes three parts: the first part concerns preliminaries which are necessary to well understand and specify the complete problematic; the second part concerns the specification of protocols where the priorities are implemented by means of BlackBurst (BB) messages; the third part concerns the specification of the CANlike protocol (priorities in the ID field of the frames).

2 Preliminaries

We present knowledges which are absolutely essential for the specification of collision-free CSMA MAC protocols. They concern the physical layer and the MAC layer.

2.1 Physical layer

The basic component is the transceiver which allows both the transmission of the frames on the channel and the reception of the frames from the channel.

In a wireless context (contrarily to the wired context), a transceiver cannot simultaneously send and receive on a channel and has three states: Transmitter, Receiver, Sleeper. Here we do not consider the state “sleeper” which is used for considerations of energy economy.

Two time attributes characterize the transceiver behavior: The channel Sensing Time τ_{ST} and the Turnaround Time τ_{TT} . The time τ_{ST} allows the transceiver to test the channel state (busy or idle): it is busy or idle according to the detected energy on the time τ_{ST} is higher or lower than a prefixed threshold (this represents the “Clear Channel Assessment” (CCA)). The time τ_{TT} is the time to go from the receiver (transmitter) state to the transmitter (receiver) state. During a CCA, if the channel is detected busy, the transceiver stays in the receiver state; on the other hand, if the channel is detected idle, the transceiver (after a time τ_{TT}) goes in the transmitter state which allows the MAC entity to send a frame. After the frame transmission, the transceiver goes in the receiver state.

2.2 MAC layer

Concept of “Ambiguity Time Window”

We introduced this concept [7], [5] in order to quantitatively characterize the ambiguity in the context CSMA of the expression “Channel detected idle at an instant t in a MAC entity”, expression which is the condition to send a frame. This expression is ambiguous because it only expresses a local view whereas the channel is geographically distributed. So a local view can be different of a global view which can create collision situations. The concept of “Ambiguity Time Window” represents the maximal duration which is possible between the decision to send a frame by a MAC entity of a node and the inevitability of the occurrence of a collision on this frame. The quantitative characterization depends on the transceiver parameters (τ_{ST} , τ_{TT}) and the maximum propagation time between two nodes that is between the two most remote

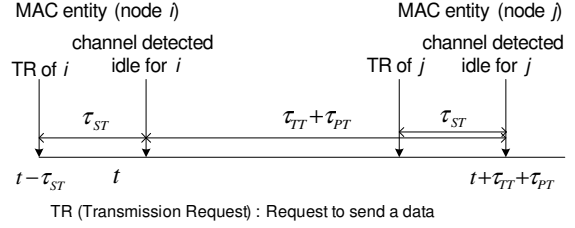


Figure 1. Ambiguity Time Window.

nodes (call τ_{PT} this Propagation Time).

The “Ambiguity Time Window” is represented on Fig. 1.

The MAC i entity receives a Transmission Request (TR) from the upper layer at the instant $(t - \tau_{ST})$ to send a data and then makes the CCA during τ_{ST} . We suppose that the channel is detected idle at the instant $(t - \tau_{ST} + \tau_{ST} = t)$ and then the MAC i entity decides to send a frame containing the data. After the time τ_{TT} , the frame is transmitted and arrives at the level of the most remote MAC j entity at the instant $(t + \tau_{TT} + \tau_{PT})$.

Suppose that the MAC j entity is just, at this instant, finishing to make a CCA (started by a TR at the instant $(t + \tau_{TT} + \tau_{PT} - \tau_{ST})$) and as the channel has been detected idle during τ_{ST} , it decides to send a frame at the instant $(t + \tau_{TT} + \tau_{PT})$. So we have, at this instant, a situation of an inevitable future physical collision. Actually the beginning of the arrival of the frame coming from the MAC i entity coincides with the instant where the transceiver of the MAC j entity turns around to go in the transmitter state (duration τ_{TT}). During this time τ_{TT} , the MAC j entity is blind. Then at the end of τ_{TT} , the MAC j entity will start to send its frame and we will then have the physical collision.

The duration $(\tau_{TT} + \tau_{PT})$ is the duration of the “Ambiguity Time Window”.

On the priorities associated to the frames

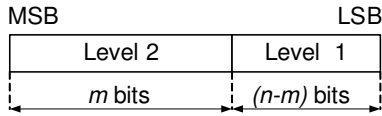
Generally, the priorities are static priorities *i.e.* each flow has a unique priority (specified *a priori* out of line) and all the frames of this flow have the same priority.

However, we can have also hybrid priorities *i.e.* priorities with two priority levels [4]. One level represents the flow priority which is a static priority (unique priority). The other level represents the frame transmission urgency. The urgency can be the same for all the frames of a flow and, in this case, the transmission urgency is also a static priority. The urgency can vary (for example, if the conditions of the applications, which uses the flow, change) and, in this case, the transmission urgency is a dynamic priority. This case is the more general and is implicitly considered here. Note still about flows with variable urgency that we can have different flows where the frames can have, in some situation, identical urgencies.

The priorities can be specified by means of a data structure which consists of a bit field (n bits).

With static priorities, we can specify 2^n flow priorities.

The consideration of hybrid priorities requires to structure the bit field in two levels (Fig. 2) where the level 1 repre-



MSB: Most Significant Bit LSB: Least Significant Bit

Figure 2. Bit field structure (hybrid priority).

sents the flow priority *i.e.* static priority (then $2^{(n-m)}$ flow priorities) and the level 2 represents the frame urgency priority *i.e.* dynamic priority (2^m urgency priorities).

The priorities allow to define a channel access tournament between the frames.

Concept of tournament

The tournament consists in the comparison of the priorities of the frames (which want to access to the channel), which transforms a situation, which would have been a “collision situation” (if we have the strict CSMA protocol *i.e.* only based on the scheme “Listen before Send”), into a “winner-looser(s)” situation.

Now we present the general framework of a tournament according to BB messages-based protocols or CANlike protocols.

Considering BB messages

With static priorities, we have one BB message per priority and its length is proportional to the priority. All the nodes which have a frame, candidate to the channel access, send the BB message concerning this frame and then we have a tournament between these BB messages. The longest BB message is the winner (we have only one winner). When the winner has detected its winner situation, it sends the frame.

With hybrid priorities, we have two BB messages per frame: a BB_s message which represents the static priority and a BB_d message which represents the dynamic priority. The BB_d messages, relative to the frames candidate to the channel access, are sent first (that represents the predominance of the urgency) and we can have either one winner or several winners (case where several frames have the same highest urgency); the winner(s) must detect its (their) winner situation and, after that, one (several) BB_s message(s) is (are) sent.

The tournament between the BB_s message(s) provides the global winner (if there was only one winner in the BB_d message tournament, it is obviously this one; if there were several winners in the BB_d message tournament, the one which has the highest static priority is the global winner).

When the global winner has detected its winner situation, it sends its frame.

Considering the CANlike protocol

The bit field (n bits), which represents the priority, is put at the beginning of a frame (we call it the ID (identifier) like in the MAC protocol of the CAN bus [1]).

It is the ID field which allows to do the tournament (by

making of comparison bit by bit between the IDs of the frames trying to access the channel) but, as in a wireless context, the transceivers cannot transmit and receive at the same time, we consider the proposal which has been done in [11], [9] for the bits of the ID field: a dominant bit consists, during its duration, in the sending of a carrier wave; a recessive bit consists, during its duration, in the sensing of the channel.

So, in each MAC entity, the tournament on each bit has the following characteristics:

- The MAC entity has a dominant bit: this MAC entity wins by definition the tournament related to this bit and then continues the tournament on the next bit.
- The MAC entity has a recessive bit: either it senses a carrier wave, then it loses the tournament related to this bit and stops the tournament phase, or it senses nothing (that means that there is no dominant bit sent by another MAC entity) and then it can continue the tournament on the next bit.

We can now precise the global tournament. All the nodes which have a frame, candidate to access to the channel, send this frame and the tournament is done, on all the nodes, through the comparison bit by bit of the IDs of the frames (the comparison starts on the MSB bit and ends on the LSB bit).

It is important to note that the tournament progress is identical whatever the priority type may be (static or hybrid). The winner is the frame which, during the tournament, did not lose on any bit.

Then we have not to consider like with the BB messages, two types of tournament (the one for static priorities and the one for the hybrid priorities).

Necessary channel observation times

The functioning of a tournament requires such observation times of the channel state.

First, whatever the technique may be (BB messages, CANlike), the start of a tournament must be preceded by an idle channel observation time noted TOBS1. The role of this time is to avoid intrusions in a tournament in progress (TOBS1 must be longer than the maximum time where, during the tournament till the instant where the winner sends the frame, the channel can be idle).

Second, for the technique of the BB messages, we need others idle channel observation times which allow to implement the detection of a winner situation:

- With static priorities: we need an observation time noted still TOBS2 which allows a MAC entity to declare itself winner and then to start the frame transmission.
- With hybrid priorities: we need an observation time noted TOBS2 which allows a MAC entity (several MAC entities) to declare itself (themselves) winner(s) of the first phase and then to start the second phase; we need also an observation time noted

TOBS3 (after the second phase) which allows a MAC entity to declare itself winner and then to start the frame transmission.

Implementation aspect

The good functioning of a tournament is dependent, in the case of the BB messages technique, of the BB message durations and, in the case of the CANlike protocol, of the duration of the ID field. *It is the consideration of the constraint done by the Ambiguity Time Window which allows to specify correctly these durations.*

3 Specification of the protocols based on BB messages

We consider successively the case of the static priorities (protocol noted BB-sta protocol) and hybrid priorities (protocol noted BB-hyb protocol).

With BB-sta, one BB message is associated to each frame. If we call k the priority of a frame, the associated BB message has a duration $kTBB$ where TBB is the duration of a BlackBurst (energy pulse).

With BB-hyb, two BB messages are associated to each frame. Call k_s and k_d respectively the static priority and the dynamic priority associated to a frame and call TBB_s and TBB_d the duration of a BlackBurst (energy pulse) concerning respectively the static priority and the dynamic priority. The BB messages associated to this frame have respectively the duration $k_s TBB_s$ and the duration $k_d TBB_d$.

3.1 Considering the BB-sta protocol

We present now the stages of this protocol and the basic parameters concerning the tournament.

The stages of the BB-sta protocol

The stages represented on Fig. 3 are self-explanatory.

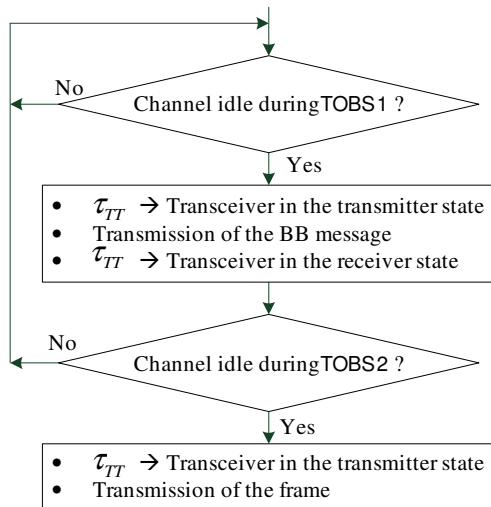


Figure 3. Principle of the BB-sta protocol.

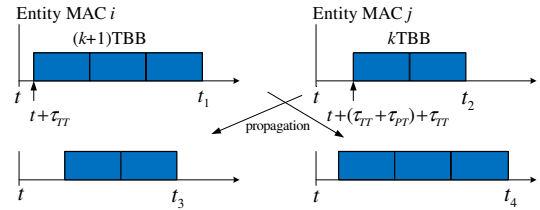
Basic parameters of the tournament

The first parameter to specify is the duration of TBB . From this value, we can then specify firstly the duration of $TOBS2$ and secondly the duration of $TOBS1$.

TBB duration

Consider the two most remote MAC entities i and j which must send respectively a frame with a priority $(k+1)$ and a frame with a priority k . We have to analyze the scenario which expresses the hardest constraint in order to guarantee that, in the hypothesis of a collision situation if we had used the strict CSMA protocol, this situation gives now the situation “MAC entity i is the winner; MAC entity j is the loser”.

This scenario is the scenario where, by considering the concept of “Ambiguity Time Window”, the MAC entity i decides to send the message $(k+1)TBB$ at the time t and the MAC entity j decides to send the message $kTBB$ at the time $(t + (\tau_{TT} + \tau_{PT}))$ *i.e.* at the latest time. This expresses the hardest constraint as the arrival of the BB message of the MAC entity j in the MAC entity i has more chances to go beyond the BB message sent by this MAC entity. This scenario is represented on Fig. 4.



$$t_1 = t + \tau_{TT} + (k+1)TBB$$

$$t_2 = t + (\tau_{TT} + \tau_{PT}) + \tau_{TT} + kTBB$$

$$t_3 = t + (\tau_{TT} + \tau_{PT}) + \tau_{TT} + kTBB + \tau_{PT}$$

$$t_4 = t + \tau_{TT} + (k+1)TBB + \tau_{PT}$$

Figure 4. BBsta : Evaluation of TBB.

Then the result (i : winner, j : loser) in this scenario requires that the two following conditions be satisfied:

- At the MAC entity i : the end of the sending of the BB message generated by the MAC entity i must be later than the end of the propagation of the BB message coming from the MAC entity j :

$$\begin{aligned} t_1 &\geq t_3 \\ \Rightarrow TBB &\geq 2\tau_{PT} + \tau_{TT} \end{aligned} \quad (1)$$

Then after the tournament, the MAC entity i will observe the idle channel.

- At the MAC entity j : the end of the propagation of the BB message coming from the MAC entity i must be later than the end of the sending of the BB message generated by the MAC entity j and the MAC entity j must detect such situation (*i.e.* we need a turnaround (τ_{TT}) after the sending, and the sensing of a busy channel (at least one τ_{ST}):

$$\begin{aligned} t_4 &\geq t_2 + (\tau_{TT} + \tau_{ST}) \\ \Rightarrow TBB &\geq 2\tau_{TT} + \tau_{ST} \end{aligned} \quad (2)$$

Then taking into account for the two constraints (1) and (2), we have: $TBB \geq 2\tau_{PT} + 2\tau_{TT} + \tau_{ST}$. We take:

$$TBB = 2\tau_{PT} + 2\tau_{TT} + \tau_{ST} \quad (3)$$

TOBS2 duration

The value of TOBS2 requires, at first, by considering the value of TBB, to evaluate in the loser MAC entity j the duration of the overtaking of the BB message of length $kTBB$ sent by the MAC entity j by the BB message of length $(k+1)TBB$ coming from the MAC entity i *i.e.* the difference between the time of the end of the arrival of $(k+1)TBB$ and the time of the end of the sending of $kTBB$: $t_4 - t_2 = 2\tau_{PT} + \tau_{TT} + \tau_{ST}$. As the turnaround time (τ_{TT}) is included in the overtaking, we then get:

$$TOBS2 = 2\tau_{PT} + \tau_{ST} \quad (4)$$

This time TOBS2 is also used by the winner (after the turnaround). In this way, when the winner starts to send the frame, the channel is globally idle (there is no residue of the tournament at the level of the MAC entities).

TOBS1 duration

Note (Fig. 3) that, TOBS2 is surrounded by two turnarounds (before TOBS2 and before the transmission of the frame by the winner). We then need:

$$TOBS1 > TOBS2 + 2\tau_{TT}.$$

It is enough that TOBS1 be higher than $(TOBS2 + 2\tau_{TT})$ at least one τ_{ST} (to see correctly the state of the channel). Then we take: $TOBS1 = TOBS2 + \tau_{TT} + \tau_{ST}$. We have:

$$TOBS1 = 2(\tau_{TT} + \tau_{PT} + \tau_{ST}) \quad (5)$$

Summary

We present on Tab. 1 the values of the parameters of the BB-sta protocol.

TBB	TOBS1	TOBS2
$2\tau_{PT} + 2\tau_{TT} + \tau_{ST}$	$2\tau_{PT} + 2\tau_{TT} + 2\tau_{ST}$	$2\tau_{PT} + \tau_{ST}$

Table 1. Parameters of the BB-sta protocol.

From these parameters, we can deduce the time for accessing the channel by the winner (suppose that the winner has a priority x). Call τ_a this time. We have:

$$\begin{aligned} \tau_a &= TOBS1 + \tau_{TT} + xTBB + \tau_{TT} + TOBS2 + \tau_{TT} \\ \tau_a &= 4\tau_{PT} + 5\tau_{TT} + 3\tau_{ST} + xTBB \end{aligned} \quad (6)$$

3.2 Considering the BB-hyb protocol

We first present the stages of this protocol. Then, as the tournament relative to the BB_d messages can give several winners, we need to introduce the concept of ‘‘guard time’’ for the BB_d messages. Finally, we present the basic parameters of this protocol.

The stages of the BB-hyb protocol

The stages presented on Fig. 5 are self explanatory.

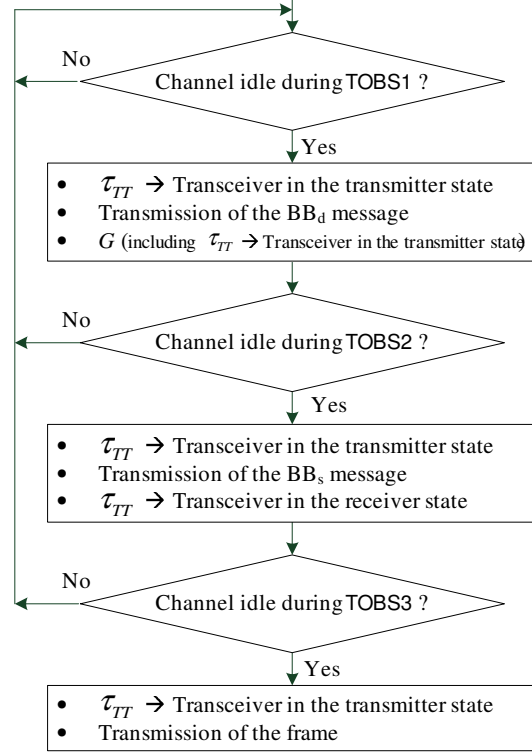


Figure 5. Principle of the BB-hyb protocol.

Necessity of a guard time G associated to the BB_d messages

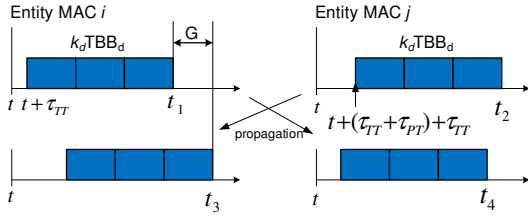
Consider a particular tournament in which we have several MAC entities which have a frame to send. Suppose that the frames of these MAC entities have the same dynamic priority k_d which is furthermore the highest in this tournament. All the BB_d messages relative to these frames must win *i.e.* after their sending, the concerned MAC entities must find the idle channel state.

However, having in mind the distance and the asynchronous behavior of the MAC entities, the busy state of the channel at the level of a MAC entity which must be a winner, can be longer than the duration of the BB_d messages sent by this MAC entity. This results from an overlap between the BB_d message which is sent and the arrival of a BB_d message from another MAC entity (which also must be a winner).

Then it is necessary, for a MAC entity, to add, after the sending of a BB_d message, a guard time G (time during which the MAC entity is blind) in order to, after this guard time, any winner will see the channel in the idle state.

In order to evaluate the guard time, we have in mind the concept of the Ambiguity Time Window and we consider the following scenario (Fig. 6): consider two MAC entities (i and j) and suppose that the MAC entity i decides to send the message $k_d TBB_d$ at the time t whereas the MAC entity j decides to send the message $k_d TBB_d$ at the latest *i.e.* at the time $t + (\tau_{TT} + \tau_{PT})$.

We see that, at the MAC entity i , the end of the propagation of the message $k_d TBB_d$ coming from the MAC entity j (time t_3) is higher than the end of the send-



$$t_1 = t + \tau_{TT} + k_d TBB_d$$

$$t_3 = t + (\tau_{TT} + \tau_{PT}) + \tau_{TT} + k_d TBB_d + \tau_{PT}$$

Figure 6. BB-hyb : Evaluation of G .

ing of its message $k_d TBB_d$ (time t_1). The difference is ($t_3 - t_1 = 2\tau_{PT} + \tau_{TT}$) which defines the guard time:

$$G = 2\tau_{PT} + \tau_{TT} \quad (7)$$

Note that, as the duration τ_{TT} is included in G , we can consider that the turnaround is done during the guard time and then, after the guard time, the MAC entity can observe the channel. We consider this aspect here.

Basic parameters of the tournament

TBB_d duration

We analyze the same scenario, which has been done for the evaluation of the TBB duration in the BB-sta protocol (Sect. 3.1), by considering now, in more, the guard time. So the scenario (Fig. 7) is: MAC entity i decides to send the BB_d message of length $(k_d + 1)TBB_d$ at the time t and the MAC entity j decides to send the BB_d message of length $k_d TBB_d$ at the time $t + (\tau_{TT} + \tau_{PT})$ i.e. at the latest time.

The result “MAC entity i : winner and MAC entity j : loser” requires the two following conditions:

- At the MAC entity i : the end of the sending of the BB_d message (time t_1) increased by the guard time (G) must not be overtaken by the end of the propagation of the BB_d message coming from the MAC entity j (time t_3):

$$t_1 + G \geq t_3$$

$$\Rightarrow TBB_d \geq 0 \quad (8)$$

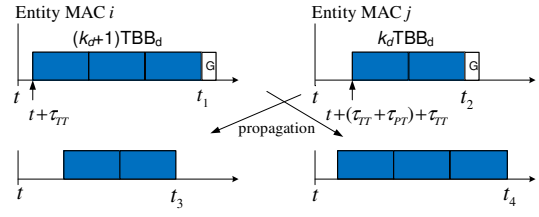
- At the MAC entity j : the end of the propagation of the BB_d message coming from the MAC entity i (time t_4) must overtake the end of the sending, by the MAC entity j , of its BB_d message (time t_2) increased by the guard time (G) and the MAC entity j must observe this overtaking:

$$t_4 \geq t_2 + G + \tau_{ST}$$

$$\Rightarrow TBB_d \geq 2\tau_{PT} + 2\tau_{TT} + \tau_{ST} \quad (9)$$

It is the constraint (9) which dictates the value of TBB_d . We consider the minimum value:

$$TBB_d = 2\tau_{PT} + 2\tau_{TT} + \tau_{ST} \quad (10)$$



$$t_1 = t + \tau_{TT} + (k_d + 1)TBB_d$$

$$t_2 = t + (\tau_{TT} + \tau_{PT}) + \tau_{TT} + k_d TBB_d$$

$$t_3 = t + (\tau_{TT} + \tau_{PT}) + \tau_{TT} + k_d TBB_d + \tau_{PT}$$

$$t_4 = t + \tau_{TT} + (k_d + 1)TBB_d + \tau_{PT}$$

Figure 7. BBhyb : Evaluation of TBB_d .

$TOBS2$ duration

Again we consider the type of analysis for $TOBS2$ in the BB-sta protocol (Sect. 3.1).

We compute, using the value of TBB_d (Equa.10), the value of the overtaking, in the loser MAC entity j (Fig. 7), of the message $k_d TBB_d$ (sent by this MAC entity j) increased by the guard time, by the message $(k_d + 1)TBB_d$ sent by the winner MAC entity i : $t_4 - (t_2 + G) = \tau_{ST}$.

Then we have:

$$TOBS2 = \tau_{ST} \quad (11)$$

TBB_s and $TOBS3$ durations

As these values concern the static part of the hybrid priorities, we can take the values obtained for TBB and $TOBS2$ in the BB-sta protocol.

$$TBB_s = 2\tau_{PT} + 2\tau_{TT} + \tau_{ST} \quad (12)$$

$$TOBS3 = 2\tau_{PT} + \tau_{ST} \quad (13)$$

Note that, $TBB_s = TBB_d$. Call TBB these durations.

$TOBS1$ duration

Note that (Fig. 5) $TOBS2$ is surrounded by G and τ_{TT} , and $TOBS3$ is surrounded by τ_{TT} and τ_{TT} . Then $TOBS1 > \max\{G + TOBS2 + \tau_{TT}; \tau_{TT} + TOBS3 + \tau_{TT}\} \Rightarrow TOBS1 > 2\tau_{PT} + 2\tau_{TT} + \tau_{ST}$.

$TOBS1$ must be higher than $(2\tau_{PT} + 2\tau_{TT} + \tau_{ST})$ at least one τ_{ST} in order to detect correctly the channel state. We then consider here:

$$TOBS1 = 2\tau_{PT} + 2\tau_{TT} + 2\tau_{ST} \quad (14)$$

Summary

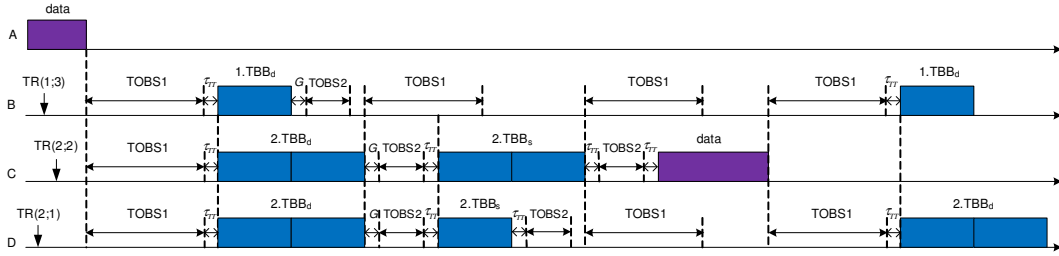
We present on Tab. 2 the values of the parameters which characterize the BB-hyb protocol.

From these parameters, we can deduce the time for accessing the channel (called τ_a) by the winner (suppose that the winner has a dynamic priority x_d and a static priority x_s): $\tau_a = TOBS1 + \tau_{TT} + x_d TBB + G + TOBS2 + \tau_{TT} + x_s TBB + \tau_{TT} + TOBS3 + \tau_{TT}$. We then have:

$$\tau_a = 6\tau_{PT} + 7\tau_{TT} + 4\tau_{ST} + (x_s + x_d)TBB \quad (15)$$

An example of a time diagram of the BB-sta protocol

We present on Fig. 8 a time diagram of the BB-hyb protocol (visualization of the tournament part relative to the



TR($k;h$): Transmission Request to send a frame which has a dynamic priority k and a static priority h .

Figure 8. Example of a time diagram of the BB-hyb protocol.

TBB	$2\tau_{PT} + 2\tau_{TT} + \tau_{ST}$	TOBS1	$2\tau_{PT} + 2\tau_{TT} + 2\tau_{ST}$
G	$2\tau_{PT} + \tau_{TT}$	TOBS2	τ_{ST}
		TOBS3	$2\tau_{PT} + \tau_{ST}$

Table 2. Parameters of the BB-hyb protocol.

BB_d messages and the BB_s messages; this last part is like in the BB-sta protocol). We consider three MAC entities B, C, D which, after the end of the sending of a frame by the MAC entity A, are in competition for sending a frame. For clarity reasons of the time diagram, but without removing the main aspects of the protocol, we consider neither the propagation time nor the Ambiguity Time Window (their values are zero).

In the first phase (BB_d messages), C and D are winner and B is a loser. In the second phase (BB_s messages), C is winner and then sends a frame. At the end of the sending of this frame, B and D start (after TOBS1) a new tournament (we show only the first phase where D will be the winner).

4 Specification of the CANlike protocol

4.1 Main points to consider

The start of the tournament by a MAC entity (*i.e.* the sending of the first ID bit) must be preceded by the sending of a synchronization (noted SYN) signal which is an energy pulse (carrier pulse like a dominant bit). The role of the SYN signal is to announce to the other entities the arrival of the ID of this MAC entity and then to provide for them a time reference for the analysis of this ID.

However, having in mind the time interval defined by the Ambiguity Time Window, several MAC entities can send the SYN signals which will be overlapping. Consequently, in each MAC entity among these MAC entities, the end of the SYN signal sending can be overtaken by the end of the SYN signal arrivals. Considering such situation, a MAC entity cannot send the first ID bit immediately after the sending of its SYN signal. We need to have a guard time following the sending of the SYN signal before to send the first ID bits (the guard time guarantees that after this time, we have a clean (idle) channel *i.e.* there is no more residue of the SYN activity).

Note that a MAC entity which has detected a SYN signal without itself having sent before a SYN signal, do not participate to the tournament.

Then, about this SYN phase before the tournament, we have to specify the length of the synchronization signal (noted l_s), and the guard time value (noted t_g).

Another very important point concerns the specification of the time length of a bit of the ID field (noted l_b). This specification must be based on the consideration that a MAC entity, when it has a recessive bit (listening state), must detect a dominant bit coming from another (others) MAC entity (entities) knowing that we can have shifts between the ID bits of the same rank of different MAC entities. These shifts will also impose the necessity of a guard time (t_g) associated to the ID bits as we explain in the next subsection.

Finally, as indicated in Sect. 2.2, we only need to specify the observation time TOBS1.

4.2 Basic parameters

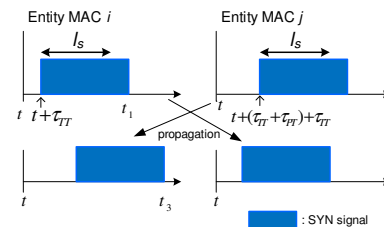
Initial synchronization

l_s duration: As it is enough that the synchronization signal be detected by a receiver MAC entity, we must have:

$$l_s \geq \tau_{ST}$$

t_g value: Suppose that a MAC entity i sends the SYN signal. The duration t_g is the biggest difference between the end of the SYN signal sending and the end of the propagation of a SYN signal of another MAC entity j .

In order to specify the t_g value, consider the Ambiguity Time Window concept with the most constrained scenario *i.e.* the MAC entity i decides to send its SYN signal l_s at the instant t and the MAC entity j decides to send its SYN signal at the latest with respect to the one sent by the MAC entity i (*i.e.* at $t + (\tau_{TT} + \tau_{PT})$). This scenario is represented on Fig. 9.



$$t_1 = t + \tau_{TT} + l_s; \quad t_3 = t + (\tau_{TT} + \tau_{PT}) + l_s + \tau_{PT}$$

Figure 9. SYN signals.

We can see (Fig. 9) that we have not an overtaking in the MAC entity j because it sends later) and that we have an

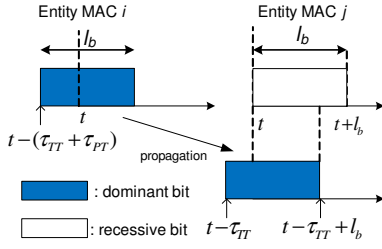


Figure 10. Evaluation of l_b : case 1.

overtaking in the MAC entity i (because it sent earlier). This overtaking ($= t_3 - t_1$) defines the value of t_g . Then we have:

$$t_g = 2\tau_{PT} + \tau_{TT} \quad (16)$$

In consequence, in each MAC entity which wants to undertake a tournament, this can be done only after the sending of the SYN signal followed by the guard time.

Remark: As the value τ_{TT} is included in the guard time, we consider that, during the guard time, a MAC entity makes the turnaround if necessary. That depends on the first ID bit: if it is a dominant bit, it is not necessary; if it is a recessive bit, we do the turnaround.

Bit of the ID field

In order to specify the length of an ID bit, we analyze the tournament (after the SYN phase) between the first ID bit of the MAC entity i (this bit is a dominant bit) and the first ID bit of the MAC entity j (this bit is a recessive bit) by considering, always in the context of the Ambiguity Time Window, the following scenarios:

- The MAC entity j starts to listen to the channel at the time t and end the listening state at the time $t + l_s$.
- The MAC entity i starts the sending of the carrier pulse either (case 1) at the time $t - (\tau_{TT} + \tau_{PT})$ *i.e.* at the earliest (Fig. 10), or (case 2) at the time $t + (\tau_{TT} + \tau_{PT})$ *i.e.* at the latest (Fig. 11).

Now, we analyze the consequences, in the MAC entity j , of these two cases:

- Case 1 (Fig. 10): The carrier pulse (sent by the MAC entity i) arrives at the MAC entity j at the time $t - (\tau_{TT} + \tau_{PT}) + \tau_{PT} = t - \tau_{TT}$ and lasts till the time $t - \tau_{TT} + l_b$. We then have an arrival of the carrier pulse just at the start of the turnaround (that is a consequence of the definition of the Ambiguity Time Window; see Sect. 2.2) which can be detected if $t - \tau_{TT} + l_b \geq t + \tau_{ST}$ *i.e.* if we have an overlap at the beginning of the listening state. Thus we have:

$$l_b \geq \tau_{TT} + \tau_{ST} \quad (17)$$

- Case 2 (Fig. 11): The carrier pulse arrives at the MAC entity j at the time $t + (\tau_{TT} + \tau_{PT}) + \tau_{PT} = t + \tau_{TT} + 2\tau_{PT}$ and lasts till the time $t + \tau_{TT} + 2\tau_{PT} + l_b$. We have an arrival of the carrier pulse after the listening state start and then the necessity of a detected

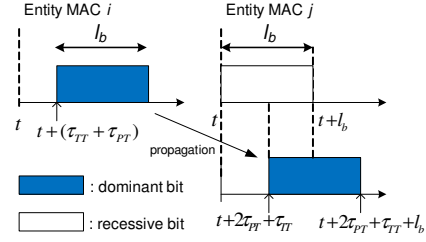


Figure 11. Evaluation of l_b : case 2.

overlap, before the end of the listening state, involves the constraint $t + \tau_{TT} + 2\tau_{PT} + \tau_{ST} \leq t + l_b$ which gives:

$$l_b \geq 2\tau_{PT} + \tau_{TT} + \tau_{ST} \quad (18)$$

Furthermore, this case 2 shows that, the end of the arrival of the carrier pulse being higher than $t + l_b$ (difference $2\tau_{PT} + \tau_{TT}$), we need a guard time t_g which allows to have a clean system (when the tournament between the bits of a given rank starts there is nothing (on the channel), from the tournament between the bits of the previous rank).

Then, from this case 2, we now specify the values of l_b and t_g which are associated to each ID bit.

l_b duration: Considering the constraints (17) and (18), we have $l_b \geq 2\tau_{PT} + \tau_{TT} + \tau_{ST}$. We take here:

$$l_b = 2\tau_{PT} + \tau_{TT} + \tau_{ST} \quad (19)$$

t_g value: This value is fixed by the difference between the end of the arrival of the carrier pulse and the end of the listening state. Then:

$$t_g = 2\tau_{PT} + \tau_{TT} \quad (20)$$

TOBS1 duration

This duration must be higher than the duration of the worst case, during the tournament, where the channel is idle *i.e.* the case where the ID bits are all recessive bits. That is an extreme case. So, as the ID field has n bits, we get: $\text{TOBS1} > n(l_b + t_g)$. We take:

$$\begin{aligned} \text{TOBS1} &= (n+1)(l_b + t_g) \\ \text{TOBS1} &= (n+1)(4\tau_{PT} + 2\tau_{TT} + \tau_{ST}) \end{aligned} \quad (21)$$

4.3 Summary

We present on Tab. 3 the values of the parameters which characterize the CANlike protocol. Concerning the duration of the SYN signal l_s , we only indicated its constraint in Sect. 4.2 ($l_s > \tau_{ST}$). We consider that it is not necessary to distinguish its duration from the ID bit duration and then we take the same value.

From these parameters, we can deduce the time for accessing the channel (called τ_a) by the winner. τ_a is composed of the observation phase, the SYN phase and the tournament phase.

$$\begin{aligned} \tau_a &= \text{TOBS1} + (l_s + t_g) + (n+1)(l_b + t_g) \\ \tau_a &= 2(n+1)(4\tau_{PT} + 2\tau_{TT} + \tau_{ST}) \end{aligned} \quad (22)$$

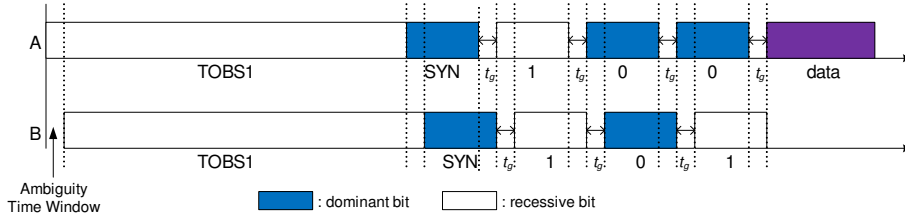


Figure 12. Example of a time diagram of the CANlike protocol.

$l_b = l_s$	$2\tau_{PT} + \tau_{TT} + \tau_{ST}$
t_g (for l_b and l_s)	$2\tau_{PT} + \tau_{TT}$
TOBS1	$(n+1)(4\tau_{PT} + 2\tau_{TT} + \tau_{ST})$

Table 3. Parameters of the CANlike protocol.

4.4 Example of a time diagram of the CANlike protocol

We present an example of the tournament of this protocol on Fig. 12 with taking into account to the parameter on Tab. 3. We consider an ID field of 3 bits and the tournament of 2 nodes A and B which have the priorities respectively (1; 0; 0) and (1; 0; 1), *i.e.* A has a higher priority than B. The node B starts the tournament later (of one Ambiguity Time Window) than the node A. At the 1st ID bit, the two nodes, which have recessive bits, find the channel idle; at the 2nd ID bit, the two nodes have dominant bits so they continue the next bit; at the last ID bit, A has a dominant bit so it is the winner by definition while B, which has a recessive bit, finds the channel busy and then B stops the tournament. A then sends its frame.

5 Conclusion

In this paper, we have tried to do an exhaustive presentation of the specification process of the collision-free CSMA MAC protocols which are based on the use of priorities which transform collision situations (with a pure CSMA protocol) into winner-loser(s) situations. We have, in particular, defined the concept of Ambiguity Time Window which formalizes quantitatively (in function of the parameters of the physical layer) the worst case of a collision situation and which then allows to specify the constraint for having winner-loser(s) situations. Thanks to this concept, we have been able to make an understandable and pedagogical (we hope!) presentation of the parameters of the BB messages-based protocols and CANlike protocol.

These protocols, which are very interesting, with respect to the protocols used very often in the wireless context (for example IEEE 802.11, IEEE 802.15.4), for considering real time traffics, have been implemented in the tool TrueTime [8]. Their interest for implementing process control applications has been shown in our works [7], [6], [5].

The future work might consider collision-free CSMA MAC protocols for multi-hop WLANs.

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