Performance Analysis of Wireless Control Area Networks

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Summary

It is widely known that Control Area Networks (CAN) are used in real-time, distributed and parallel processing which cover manufacture plants, humanoid robots, networking fields, etc. Where wireless conditions are encountered it is convenient, as we will demonstrate later, to continue the exchange of CAN frames within a baptized Wireless CAN (WCAN). While we define the WCAN, we adopted the RTS/CTS scheme to gain access to the medium in a first step and the exchange of ordinary CAN frames in a second step [1, 2, 3].

The latency time is the most important factor to consider when evaluating a control network. The latency incurred in message delivery has not been a metric to be optimized. So in the second part of this paper, we compute the throughput-latency time couple that would guarantee a maximum throughput and a minimum latency time in the case of wireless communications, precisely in WCAN. This work represents our real contribution by introducing the WCAN concept for the first time, by the correct definition of WCAN frames, by the evaluation of parameters boundaries of WCAN, and by the calculation of the latency time and its coupling to the throughput, according the medium access scheme.

Key words:

WCAN protocol, RTS/CTS Media Reservation Mechanism, Throughput - Latency time Analysis.

1. Introduction

CAN networks, called Controller Area Networks, can be used in the framework of real-time distributed industrial applications. Such applications cover manufactures, the distributed and parallel processing systems in industrial and networking fields, etc.

CAN networks guarantee sufficently short time latency and it has been shown that these systems exceed in performance token-based ones.

Access to the medium in wired CAN is shared based. It respects the CSMA/CA scheme which is “Arbitration on Message Priority” and “bit-wise Contention” technique. This technique, along with the mecahnism of detecting and correcting errors, gives high performance to the protocol CAN to be adopted for real-time applications where multiple access are applied. Unfortunately, the features of wired CAN cannot be adopted as they are without modification in the wireless case. Thus, we adopt the use of RTS/CTS (Request To Send/Clear To Send) mechanism along with the binary exponential backoff algorithm to gain access to the medium in first step and to exchange ordinary CAN frames in a second step.

Thus, in the second section, we describe the key WCAN concepts, essentially the RTS/CTS scheme used to reserve the medium. In the third section, we evaluate the WCAN throughput. The key parameter which affects directly the throughput is the payload [1]. It is sufficient to increase the WCAN payload to join the WLAN performances. The improvements, in modifying the other parameters in physical and MAC sublayers, are negligible. However, the most important factor to consider when evaluating a control network is the end-to-end time delay between sensors, controllers, and actuators.

The correct operation of a control system depends on the timeliness of the data coming over the network, and thus, a control network should be able to guarantee message delivery within a bounded transmission time. So, in the fourth section, we evaluate the latency time. After analysis, we deduce that when we increase the payload, the latency time along with the throughput increases respectively.

A second work, exposed in the fifth section, consists in computing the throughput-latency time couple that would guarantee a maximum throughput and a minimum latency time in the case of WCAN.

In the sixth section, we resume some important conclusions that can be taken as guidelines when designing a WCAN.

2. Overview of WCAN

This section presents briefly the WCAN as presented for the first time in the paper [1].

Both in WLAN and wired CAN, access to the medium is share-based and respects the CSMA/CA scheme which is a listen before talk access mechanism. So the medium access control used in CAN MAC sublayer can be used as MAC protocol for fix and mobile industrial Wireless based CAN protocol. However, depending on the CAN frame format, some modifications should be done in the wireless case. In fact, due to the absence of network terminator impedances, a station is unable to transmit and listen for collisions. The hidden problem, when every station may not necessarily hear all other stations is a second deep problem. The RTS/CTS mechanism is proposed to exactly resolve the problems cited above and it is considered as a “second carrier sensing” mechanism, often called a “virtual carrier sensing technique”[7]. In

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another hand, the maximum throughput achievable by the basic access mechanism is very close to that achievable by the RTS/CTS mechanism [4] and therefore the mean contention delay. *Those are the main reasons for choosing this mechanism for WCAN.*

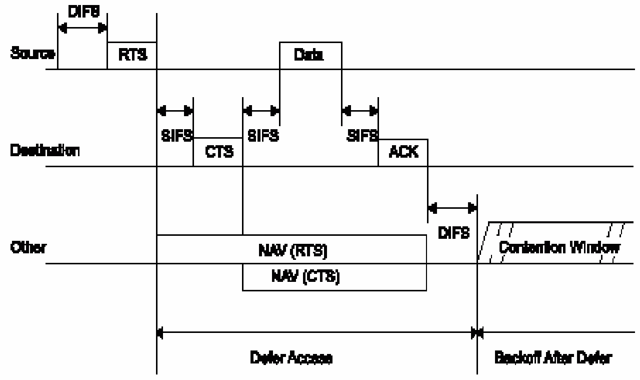

Fig. 1 RTS/CTS access mechanism [7]

The RTS/CTS mechanism enables a station to reserve the medium for a specified time through the use of RTS and CTS frames. So when a station wins the contest to access to the media, it doesn't send data packets right away but sends a RTS packet to the receiving station that responds with a CTS packet. RTS/CTS frames contain a duration field that specifies the period of time for which the medium is reserved for a subsequent transmission. If a station captures a RTS or CTS packet from another station and it is not the destination of this packet it reads the intended transmission duration from the RTS/CTS packet and stays silent for that time. The reservation information is stored in all stations in a variable called Network Allocation Vector (NAV) and represents the Virtual Carrier Sense. The priority access to the wireless medium is controlled through the use of timing intervals called "Inter-Frame Space (IFS)". These IFS represent the time interval between each transmission of frames. The 802.11 MAC recognizes three main timing intervals: "Short IFS (SIFS)", "Distributed IFS (DIFS)" and "Point coordination IFS (PIFS)". The SIFS interval is the smallest IFS followed by PIFS and DIFS. We assume that WCAN adopts a binary exponential backoff scheme as used in WLAN. A station generates a random backoff interval before transmitting (this is the Collision Avoidance feature of the MAC sublayer). The backoff time is uniformly chosen in the range (0, W-1). The value W is called Contention Window (CW), and depends on the number of transmission attempts. At the first attempt, W is set equal to a value CWmin. After each unsuccessful transmission, W is doubled, up to a maximum value $CWmax=2^{m}.CWmin$.

The backoff counter is decremented as long as the channel is sensed idle, “frozen” when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. The station transmits when the backoff time reaches zero [8, 9].

On what follow, we present the modifications on the CAN frame exchange protocol adopted for the wireless CAN. The new CAN frames are detailed in paper [1].

- Due to the broadcast nature of the CAN bus and the geometric limitation of Wireless CAN networks, the MAC-addresses are not used at all in the RTS, CTS and ACK frames. They will be simply replaced by the 29-bit CAN_ID, within the arbitration field. The CAN_ID has its signification only in “Data or Management” frames as target object IDs or Request IDs and no other meanings. No supplementary change will be inflicted to RTS and CTS frames in relation to those of WLAN.
- The 2-bits ACK field within the CAN frame is replaced by an ACK frame. In fact, even though mobile stations use multi-carrier OOK/OFDM modulation in the physical sublayer according to dominant and recessive bit principle, the conventional problems of this kind of transmission can take place and in particular delays due to the modulation, the emission, the demodulation, the synchronization and the automatic gain control, that is impossible in the presence of the multipath fading to use the bit-wise ACK slot to decide a positive or a negative acknowledgement [9]. Thus the ACK field is replaced by an ACK frame.
- The elimination of the EOF and Inter-mission within the CAN frame. They are replaced by WLAN DIFS, SIFS and PIFS timings. The adoption of CAN-CRC [7] as FCS generator polynom for the error control. FCS $\cong$ CAN-CRC $= x^{15} + x^{14} + x^{10} + x^{8} + x^{7} + x^{4} + x^{3} + 1$, for compatibility with current CAN controller VHDL implementations.

We still use the IFS (Inter-Frame Space) access priority and binary exponential back-off algorithm to gain access to the medium. However, due to the geometric limitation of Wireless CAN networks, "backoff timer” will be necessarily smaller than in WLAN, as well as the maximal number of retransmissions. The physical sublayer can be also adopted as in IEEE 802.11b or IEEE 802.11a. However the maximal bit rate in standardized CAN specification is 2 Mbps and it is much lower than the 11 Mbps or 54 Mbps in WLAN physical sublayer. WCAN physical sublayer synchronization function must be made in relation to these fields.

3. Throughput Analysis

In this section, the performance evaluation of the throughput on the Wireless CAN networks is briefly reviewed [2]. The throughput is a fundamental performance figure for the evaluation of networks protocol. We use an analytical model as in papers [4, 8] to compute the throughput of the RTS/CTS mechanism in wireless

CAN, in the assumption of ideal channel conditions and finite state number of stations n, each always having a packet available for transmission, i.e., the transmission queue of each station is assumed to be always nonempty.

We define the normalized throughput S as the fraction of the average time the channel is used to successfully transmit payload bits by the average length of a slot time [4, 8].

$$S = \frac{E\left[\text{Payload information in a slot time}\right]}{E\left[\text{Length of a slot time}\right]} \qquad (1)$$

Figure 2 shows the throughput versus the number of stations. We notice that the throughput in the WCAN is distinctly very lower than in the WLAN. This important remark pushed us to look for parameters that act directly on the throughput in the case of the WCAN. The analysis of the throughput according to the format of the MAC layer as well as the parameters of the physical layer showed that working on these parameters does not influence significantly the throughput. However, as shown in figure 3, it is clear that the greater the payload is, the greater the throughput both on WCAN and WLAN. We deduce that the key parameter which affect directly the throughput is the payload.

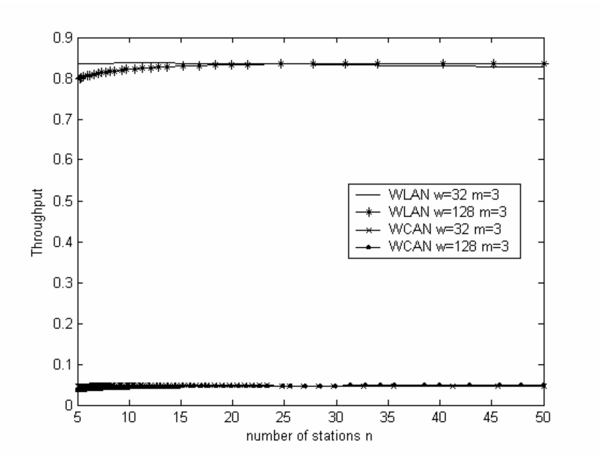

Fig. 2 Throughput versus the number of stations

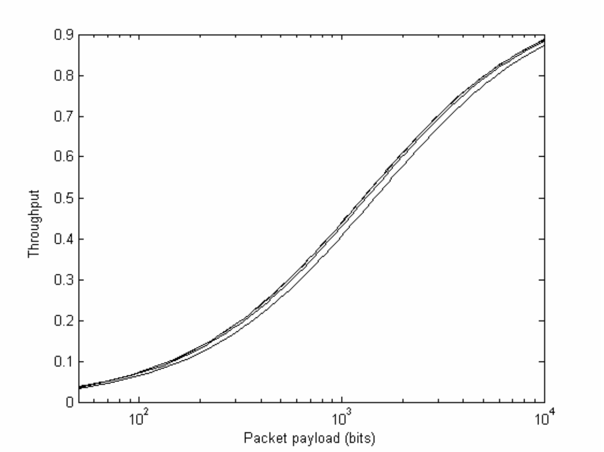

Fig. 3 Throughput versus packet payload

Can we change the maximum payload (fixed at 8 bytes) in CAN frames to improve the throughput in WCAN? Can this modification affects the performance of the WCAN protocol?

We mentioned in the introduction that the CAN protocol finds all his importance in systems with hard real-time constraints.

However, in these systems, the latency time is an important criteria to take in account in order to respect real-time constraints and it is the reason for which the payload, in the CAN frames, has been limited to 8 bytes in order to reduce to a maximum the latency time.

Therefore, we conclude that the throughput can not be the only one criterion to evaluate real-time networks as is the case when using the WCAN protocol because latency time must be taken in to consideration as well.

The core contribution of this paper is to compute the latency time expression and to determine the throughput-latency time couple that would guarantee a maximum throughput and minimum latency time in the case of WCAN networks.

4. The WCAN Latency-time analysis

The performance evaluation of the latency time is based on the evaluation of both the worst-case queuing delay in the MAC and physical sublayers and the longest time needed to transmit a message.

The analysis of the worst-case response time can be derived from tasks scheduling theory and real-time scheduling algorithms that can be applied by the transmitter and the receiver to guarantee a minimum latency time for the exchanged frames.

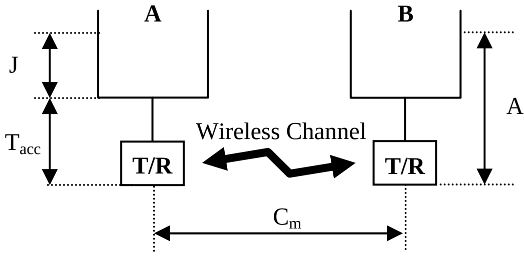

Fig. 4 Definition of Latency time

The latency time is defined as the difference of time between the instant indicating the beginning of the transmission request and the real beginning of the action generated by this one.

Let J be the queuing jitter of a message from the upper layer to medium access control layer, T_{acc} the time taken by a station to gain access to the medium, C_{mes} the longest time needed for transmitting successfully a WCAN frame and A_r the time taken by a receiver station to analyze the transmitted frame. We are now able to express the latency time T_{lat} as:

$$T_{lat} = J + T_{acc} + C_{mes} + Ar \quad (2)$$

In what follows, we assume that the jitter J and A_r have constant values. Knowing that C_m is the longest time taken to successfully transmit a WCAN frame, then we have:

$$C_{mes} = RTS + SIFS + \delta + CTS + SIFS + \delta + H + E[P] + SIFS + \delta + ACK + DIFS + \delta \quad (3)$$

To calculate the latency time in WCAN, we are going to imagine the worst scenario that would happen to a station in order to succeed the transmission of a frame. This permits us to calculate the worst-case response time of the system. For this, we assume that a station having a packet to transmit:

1. Does not succeed in transmitting at the first attempt.
2. At every backoff stage, the other stations win the access to the medium, once at most, and they transmit with success.
3. At every time the backoff counter reaches 0 and the station transmits a packet, a collision arrives. What leads the station to pass to the following backoff stage, i.e. to double the value of the contention window W.
4. Succeed the transmission at the last backoff stage m.

These assumptions implicate that a station must run through all backoff stages in order to succeed a transmission. At every stage i from 0 to m, the backoff counter is interrupted by the other stations transmission. Therefore the time elapsed Ti at every backoff stage i is equal to the backoff interval to which we add the time needed by N stations of the network to transmit with success. We assume

$$N = \begin{cases} n-1 & W_i > n \\ W_i - 1 & W_i < n \end{cases} \quad (4)$$

We obtain

$$T_i = N \cdot (C_{mes} + DIFS) + (W_i - 1) \cdot \sigma \quad (5)$$

At every stage i from 0 to m-1, when the backoff counter reaches 0, the station transmits a packet which collides. The time Tc needed to a station to detect a collision can be expressed as follows:

$$T_c = RTS + DIFS + \delta \quad (6)$$

At the backoff stage m, the station succeeds the transmission of a packet with success time

$$T_s = DIFS + C_{mes} \quad (7)$$

Thus, by relation (5), (6) and (7), the latency time is expressed as

$$T_{lat} = J + \sum_{i=0}^{m} T_i + \sum_{i=0}^{m-1} T_c + T_s + Ar \quad (8)$$

Finally, we obtain the latency time expression

$$T_{lat} = J + \left[\sum_{i=0}^{m} N \cdot (C_{mes} + DIFS) + (W_i - 1) \cdot \sigma \right] + \left[\sum_{i=0}^{m-1} (RTS + DIFS + \delta) \right] + DIFS + C_{mes} + Ar \quad (9)$$

5. Coupling the two criteria: Throughput and Latency Time

Through the results shown in figure 5 we deduce that when we increase the payload, the latency time along with the throughput increase respectively. We observe that the latency time remains constant while the payload is lower than 1000 bits which is greater than the 64 bits (8 bytes) that represents the maximum payload recommended in the wired CAN. We conclude that the value 1000 bits (128 bytes) as WCAN payload can improve considerably the throughput while the latency time remains at the same value. The latency time increases significantly when the payload is greater than the prescribed value. The WLAN and the WCAN throughputs versus the payload have practically the same curves which indicate that the payload in WLAN must be fixed approximately to 1000 bits when we want to have a minimum latency time, in voice and video transmission as real-time applications and that is not 8184 as recommended in the IEEE 802.11 standard.

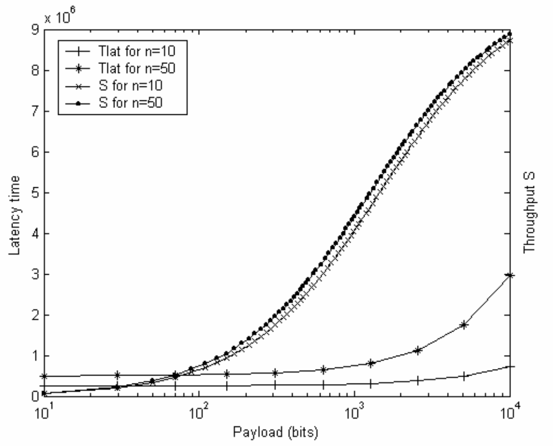

Fig. 5 Latency time and throughput versus the payload

It is clear through the figure 6 that when using important W and m values, the latency time increases significantly. *We conclude that we must minimize as possible these values around respectively to W=128 and m=4.*

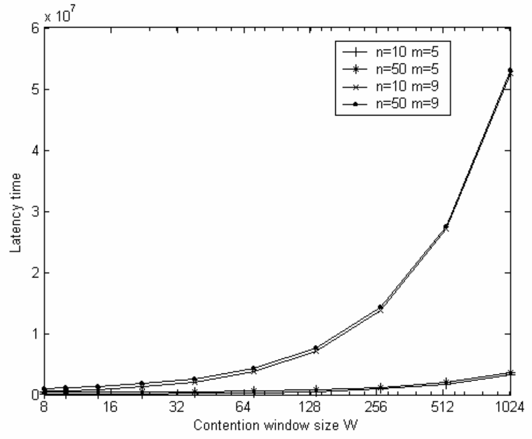

Fig. 6 Latency time versus the initial contention windows

6. Conclusion

We tried to use other values of IFS parameters than specified in the IEEE standard, in hope to increase the throughput in the WCAN case. We do the same for the physical header. The improvements are negligible. The MAC protocol format and the type of physical sublayer do not influence the throughput when their sizes are approximately the same. Through the analysis of results related to WCAN, we concluded that the RTS/CTS access scheme and physical layer can be kept unmodified for the WCAN case. The last result is very important when we think of the reuse of some hardware controllers and transceivers implementations. The payload is the real parameter that affects directly the throughput. Performance evaluations in WCAN case, do not limit, as we make often, to the only payload parameter. The throughput must be coupled to the latency time as a second criterion.

As parameters to retain for WCAN, we find that the value 128 bytes is the ideal payload for both WCAN and WLAN which improves considerably the throughput for the former while the latency time remains at the same value for the later.

When the initial contention window is less than 64 and the maximum number of retransmissions is greater than 5, the throughput is maximized and is independent from the number of mobile stations, leading to a consolidation of our RTS/CTS scheme choice for the WCAN. So the stages number m and the initial contention window W must be chosen carefully to guarantee a maximum throughput and minimum latency time in the case of WCAN. We also conclude that we must minimize as possible the contention window and the number of retransmission values around respectively W=128 and m=4 in WCAN case.

In the absence of real-time constraints and the need for an important payload that would give a more important throughput, WLAN is the best choice. On the other hand, in the presence of real-time constraints and the need to extend a wired CAN network, the WCAN is the best choice.

7. Actual and Future Works

We are evaluating an hybrid technique scheme using a prioritized backoff window, based on the CAN-ID itself and the Request-Power-To-Send/Acceptable-Power-To-Send (RPTS/APTS) mechanism. The key challenge remains to provide predictable delay and/or prioritization guarantees while minimizing overhead packets and energy consumption. Implementing such distributed prioritization among cooperative sources is another important challenge [10, 11].

CAN and therefore WCAN networks are basically distributed computing platforms and by consequence are adapted for very data-centric systems. Simulation tools are generally limited to request-response or interrupt-query paradigms. Simulations for these platforms must take into account the publish/subscribe paradigm naturally supported by these data-centric systems, above a well defined transport protocol.

References

[1] Salem Hasnaoui, "RTS/CTS Access scheme in Wireless CAN Networks", Proc. CCCT'05, Vol.2, pp 254-261, July 2005.

[2] Sofiene Dridi, Bechir Ben Gouissem, Salem Hasnaoui, Houria Rezig, "Performance Evaluation of RTS/CTS

Mechanism on Wireless LAN and Wireless CAN networks", Proc. CCCT'05, Vol.2, pp 247-253, July 2005.

[3] Oussema Kallel, Salem Hasnaoui, Rabeh Attia, "Implementation of a Controller for Wired and Wireless CAN networks", Proc. CCCT'05, Vol.2, pp 262-267, July 2005.

[4] G.Bianchi. Performance Analysis of the IEEE 802.11 Distributed Coordination Function. IEEE Journal on Selected Area in Comm. V18, N3, March 2000.

[5] H. Wu, Y. Peng, K. Long, S Cheng, J. Ma, Performance of Reliable Transport Protocol over IEEE 802.11 Wireless LAN: Analysis and Enhancement. IEEE Journal on Selected Area in Communications,VOL.18, NO.3, 2002.

[6] G.Bianchi. L.Fratta, M.Oliveri. Performance Evaluation and Enhancement of the CSMA/CA MAC Protocol for 802.11 Wireless LANs. Proc. PIMRC'1996. Taipei, Taiwan, pp.392-396, Oct.1996.

[7] IEEE standard for Wireless LAN Medium Access Control (MAC) and physical Layer (PHY) specifications, ISO/IEC 8802-11:1999(E), Aug. 1999.

[8] B.P. Crow, J.G. Kim, IEEE 802.11 Wireless Local Area Networks, IEEE Communications magazine, Sept. 1997.

[9] Salem Hasnaoui, "Wireless Industrial Networking Using CAN MAC-Sublayer", IEEE IAS proceedings, Vol.1, pp 475-480, 2001.

[10] Tarek Guesmi, Salem Hasnaoui, "Using RT-CORBA Scheduling Service And Prioritized Network Traffic to Achieve End-to-End Predictability", Accepted paper for the Parallel and Distributed Processing Techniques and Applications PDPTA'06, June 26-29, Las Vegas, USA.

[11] Tarek Guesmi, Salem Hasnaoui, "Building of a Fault-Tolerant CORBA Infrastructure within the Context of Embedded orb and the CAN Bus", Communication In Computing CIC'06, June 26-29, Las Vegas, USA.

Short Biography

Sofiene Dridi was born in 1977 in Mateur, Tunisia. He received the degree in electrical engineering from National School of Engineering of Tunis, Tunisia, in 2001, and the postgraduate research degree in communication networks, in 2002, from National School of Engineering of Tunis, since 2002 he is a PHD student in the Department of Computer and Communication Technologies of National School of Engineering of Tunis in Tunis El Manar University of TUNISIA. His research interests are wireless industrial networks, wireless MAC protocols for real-time and distributed applications.

Salem Hasnaoui is a professor in the Department of Computer and Communication Technologies at the National School of Engineering of Tunis. He received the Engineer diploma degree in electrical and computer engineering from National School of Engineering of Tunis. He obtained a M.Sc. and third cycle doctorate in electrical engineering, in 1988 and 1993 respectively. The later is extended to a PhD. degree in telecommunications with a specialization in networks and real-time systems, in 2000. Salem is author and co-author of more than 40 refereed publications, a patent and a book. His current research interests include real-time systems, sensor networks, QoS control & networking, adaptive distributed real-time middleware and protocols that provide performance-assured services in unpredictable environments.

Prof. Hasnaoui is the responsible of the research group "Networking and Distributed computing" within the Communications Systems Laboratory at the National School of Engineering of Tunis. He served on many conference committees and journals reviewing processes and he is the designated inventor of the Patent "CAN Inter-Orb protocol- CIOP and a Transport Protocol for Data Distribution Service to be used over CAN, TTP and FlexRay protocols".