Performance Analysis of Wireless Controller Area Networks with Priority Scheme

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Abstract

For large-scale distributed systems, Data centric communication based on the publish/subscribe paradigm plays a key role on traffic volume control. More data filtering efficient and adaptive to different traffic conditions bring some solutions at the high layers of the communication model. Data Distribution Service (DDS) and OLE for Process Control Data Exchange (OPC-DX) are the most adopted solutions, in real-time data centric sensor networks. Some Real-time transport and Medium access control (MAC) protocols are proposed in the literature to support these types of networks.

Existing MAC protocols, scheduling based, collision free, contention based or hybrid schemes focus more on optimizing system throughput and do not adequately consider the requirements of sensor networks. The key challenge remains to provide predictable delay and/or prioritization guarantees while minimizing overhead packets and energy consumption.

It is widely known that Control Area Networks (CAN) protocol is used in real-time, distributed and parallel processing. In this paper, we introduced a novel approach based on WCAN protocol in data centric communications model to manage concurrency and we use a Markov chain model for this protocol in order to evaluate his performances.

Keywords: Wireless CAN, RTS/CTS Media Reservation Mechanism, Industrial sensor networks, Markov Chains, analytical model, concurrency management, data centric.

Introduction

Wireless industrial networks are data-centric where the timeliness is perhaps the most difficult requirement to meet where these networks are deployed in critical applications, due to the tradeoffs between power consumption, interference mitigation, and scheduling and routing efficiency.

Several research challenges in the networking, operating systems and middleware layers must be coordinated to identify adequate solutions. Existing MAC protocols for multi-hop wireless networks can be classified into four categories: 1) scheduling based; 2) collision free; 3) contention based; and 4) hybrid schemes.

We choice in this work to apply the contention based using the Request To Send/Clear To send (RTS/CTS) mechanism with priority considerations to manage concurrency.

In this paper we propose an algorithm to manage access to the support that privileges the most data priority, to manage concurrency between sensor, and we propose a Markov chain model to evaluate his performances.

In the first section, we introduce our proposed communication layers architecture for industrial networks.

In the second section, we present the Wireless CAN (WCAN) protocol and algorithms to manage priority.

In the third one, we develop a Markov chain model for WCAN with priority.

In the forth section, we discuss results of the analytical model for WCAN with priority.

In the last section, our future works are presented.
1. Communication Architecture

Layers

Distributed computer control in complex embedded systems oversees diverse electronic control units connecting hundreds or thousands of analogue and digital sensors and actuators. These systems are also called today sensor networks. Nodes in sensor networks can sense, compute, build links and communicate (including relaying, setup and discovery) without a central control.

This communication model as depicted in Figure 1 represents our proposed architecture for industrial sensor networks. For homogenous networks, we use DDS applications over CAN or WCAN protocol. In the case of heterogeneous networks DDS or Data Acquisition from Industrial Systems (DAIS), applications are used with General Inter-ORB Protocol (GIOP) to permit interoperability. CAN Inter-ORB Protocol (CIOP) [1] protocol is used for the relaying between the GIOP layer and transport layer.

![Diagram](https://example.com/diagram.png)

Fig.1 General view of the architecture.

2. WCAN with priority:

WCAN[1] with priority is an extension of the WCAN protocol by the integration of algorithms to manage concurrency.

WCAN is an adaptation of the CAN protocol for use in Wireless industrial communications.

RTS/CTS mechanism can be adopted easily for the WCAN case [1]. However, depending on the CAN frame format, some modifications should be done. The new CAN frames are detailed in paper [2].

- In the RTS, CTS and ACK frames, the MAC-addresses are replaced by the 29-bit CAN_ID, within the arbitration field.
- The 2-bits ACK field within the CAN frame is replaced by a dedicated ACK frame.
- We still use the IFS (Inter-Frame Space) access priority and binary exponential back-off algorithm to gain access to the medium.

The main modification of the RTS/CTS scheme in the WCAN case is that the MAC address is substituted by the Arbitration field. This characteristic means that the WCAN protocol is Data-Centric so he is based on total diffusion or directed diffusion. However, the RTS/CTS mechanism can not be used for MPDUs with broadcast and multicast immediate address because there are multiple destinations for the RTS, and thus potentially multiple concurrent senders of the CTS in response. In another hand, the RTS/CTS mechanism need not be used for every data frame transmission, because the additional RTS and CTS frames add overhead inefficiency. The mechanism is not always justified, especially for short data frames.

In this work we propose an algorithm based on the RTS/CTS frames to:

- Manage priority between data frames.
- Minimise numbers of CTS in response of an RTS.
- Optimise Energy consumption.

2.1 RTS/CTS with priority for Producer/Consumer:

For this kind of applications, the producer of data diffuses it for all sensors. Sensors that need this data referenced by the Object-ID can consume it.

RTS/CTS mechanism is used in 802.11 standards to enable a station to reserve the medium for a specified time through the use of RTS and CTS frames.

In the case of our proposition this mechanism is used for medium reservation and essentially for priority arbitration by Object-ID.

2.1.1 Producer:

The producer in our architecture is a DAIS application that captures information and diffuses it for consumers.

The producer senses the medium when it is in the idle state he waits for a period of short...
Inter Frame Space (SIFS) and sends his RTS frame. After sending his RTS frame, the producer waits, for an extended SIFS (ESIFS), for eventual CTS frame that indicate that there is another producer having a more priority data level.

The priority arbitration in our scheme is calculated by the bit by bit comparison of the Object-ID. For priority arbitration we use the same mechanism used by the CAN protocol where “0” represent a dominant bit and “1” represent the recessive. The position of the first recessive bit indicate the range of Object-ID where the data to be transmitted have more priority. In order to economise time for high level priority data we calculate the PriorityPeriod as:

\[
\text{PriorityPeriod} = \sum_{i=0}^{n-1} 2b_i (n - i)(n - i + (n + i/n - i))/S \quad (1)
\]

\(n = \text{posfirst1}\)

\(b_i: \text{value of the bit in the position } i \text{ of the immediate more priority Object-ID.}\)

\(S = a\text{SlotTime}\)

In this step, the node must calculate the Object-ID of the immediate more priority data level. To deduct this value the producer makes a binary subtraction of his Object-ID by 1. The resulting Object-ID is used to determine the \(n\) parameter used in the above formula. In this formula \(n\) is the position of first bit that the value is equal to “1”.

If after ESIFS “Extended SIFS” no CTS frame was received the node concludes that his data have the most priority and send his data frame.

\[
\text{ESIFS} = \text{SIFS} + (\text{PriorityPeriod} \times a\text{SlotTime}) \quad (2)
\]

\(a\text{SlotTime}: \text{The value of the correspondingly named PHY characteristic.}\)

In the case of receiving a CTS frame that indicates the presence of a data to transmit with more priority level, the node updates his network allocation vector (NAV) with the value of Duration/ID field in the CTS frame.

To save energy, the node sleeps for the duration of NAV if he is not a consumer of the data designated by the Object-ID of the received CTS frame.

\[\text{Sense medium}\]
\[\text{If idle}\]
\[\text{Wait SIFS}\]
\[\text{Send RTS}\]
\[\text{Sense medium for ESIFS}\]
\[\text{If CTS Then}\]
\[\text{Update NAV}\]
\[\text{If \text{!consumer Then}}\]
\[\text{Sleep for NAV}\]
\[\text{EndIf}\]
\[\text{Else}\]
\[\text{Send data}\]
\[\text{EndIf}\]

### 2.1.2 Consumer:

Consumers in our architecture are nodes that need the data referenced by the Object-ID. Every node that receives an RTS frame must compare his Object-ID with that in the RTS frame if he has data to transmit. If he has not data to send, he updates his NAV with the duration mentioned in the Duration/ID field of the received RTS frame. If he is not a consumer, he sleeps for the period of the NAV.

In the case of having a more priority level the node senses a medium. If the medium is in the Idle state for Priority SIFS (PSIFS) he sends a CTS frame. The PSIFS duration permit as to encourage the send of the CTS frame of the data that have the most priority.

In the case of receiving a CTS frame during the PSIFS what indicate that there is a more data priority level, the node must update his NAV and if he is not a data consumer he must sleep during the NAV period.

If no CTS received during PSIFS the node conclude that he has the most priority to send and send his data after an SIFS.

\[
\text{PSIFS} = \text{SIFS} + \left( \sum_{i=0}^{n-1} 2a_i (n - i)(n - i + (n + i/n - i))/S \right) \times S
\]

\(n = \text{posfirst1}\)

\(S = a\text{SlotTime}\)

\(a_i: \text{value of the bit in the position } i.\)
2.2 Acknowledgement frame:

The WCAN protocol uses a dedicated frame for acknowledgement to indicate the state of received data frame.

In our scheme RTS/CTS to manage priority, low level priority data frame take too time to be transmitted where the network is not used. To optimise our network use we choose to send acknowledgment frames in this time using the standard CSMA/CA. If there are a RTS or CTS frame received that have an ESIFS greater than DIFS and the sender node not receives an ACK frame for DIFS+SIFS time he concludes that the data was not received and proceed for retransmission.

3. Throughput performance

Analysis:

In this section, we analyzed the performance of WCAN with priority protocol. In this paper, we focus on the saturation throughput, which is defined as the limit reached by the system throughput as the offered load increases, and represents the maximum load that the system can carry in stable conditions [3].

3.1. Markov chain model:

We use the same model, developed by Bianchi, in papers [4,5] with the same assumption for our analysis. The contending stations are supposed to be a fixed number, n. Let b(t) be the stochastic process representing the back-off time counter for a given station at slot time t. Note that the slot time is referred to as the constant value $\sigma$ and the variable time interval between two consecutive back-off time counter decrements.

Since the value of the back-off counter of each station depends also on its transmission history, the stochastic process b(t) is non-Markovian. However, define for convenience $W=\text{CWmin}$. Let m, “maximum back-off stage,” be the value such that $\text{CWmax}=2^mW$, and let us adopt the notation $W_i=2^iW$, where $i \in (0,m)$ is called “back-off stage”. Let s(t) be the stochastic process representing the back-off stage (0,…,m) of the station at time t.

As in paper [4], the key approximation in this model is that the probability $p$ that a transmitted packet collides is independent of the state $s(t)$ of the station. Thus, the bi-dimensional process $\{s(t), b(t)\}$ is a discrete-time Markov chain, which is shown in Figure 2.

In this Markov chain, the only non-null one-step transition probabilities are:

\[
\begin{align*}
P_1[i,k][i+1,k+1] = 1 & \quad k \in (0, W_i-2) \quad i \in (0,m) \\
P_1[0,k][i,0] = (1-p)/W_0 & \quad k \in (0, W_0-1) \quad i \in (0,m) \\
P[i,k][i-1,0] = p/W_i & \quad k \in (0, W_i-1) \quad i \in (1,m) \\
P[0,m,k][m,0] = p/W_m & \quad k \in (0, W_m-1)
\end{align*}
\]  

Fig.2 Markov chain Model for the back-off window size
Let $b_{i,k} = \lim_{t \to \infty} P\{s(t)=i, b(t)=k\} \forall i \in (0,m), k \in (0,W_i-1)$ be the stationary distribution of the chain. We note that

$$b_{i,0} \cdot p = b_{i,0} \quad \Rightarrow \quad b_{i,0} = \frac{p^i}{b_{i,0}} b_{0,0}$$

$$b_{m-1,0} \cdot p = (1-p) b_{m,0} \quad \Rightarrow \quad b_{m,0} = \frac{p}{1-p} b_{0,0}$$

(5)

Owing to the chain regularities, for each $(i,0) \in W_i$, it is

$$\begin{cases} (1-p) \sum_{j=0}^{m} b_{j,0} & i=0 \\ p \cdot b_{i,1-0} & 0<i<m \\ p \cdot (b_{m-1,0} + b_{m,0}) & i=m \end{cases}$$

(6)

With (5) and transitions in the chain, equation (6) can be simplified as

$$b_{i,k} = \frac{W_{i-k}}{W_i} b_{i,k} \quad 0 \leq i \leq m$$

(7)

Therefore, by using the normalization condition for stationary distribution, we have

$$1 = \sum_{i=0}^{m} W_{i-k} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \frac{W_{i-k}}{W_i} = \sum_{i=0}^{m} b_{i,0} \frac{W_{i-k}+1}{2}$$

(8)

from which,

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$$

(9)

We can now express the probability $\tau$ that a station transmits in a randomly chosen slot time. As any transmission occurs when the backoff time counter is equal to zero, regardless of the backoff stage, it is

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$$

(10)

In the stationary state, a station transmits a packet with probability $\tau$, so we have

$$p = 1 - (1-\tau)^{n-1}$$

(11)

Therefore, equations (10) and (11) represent a non-linear system in the two unknown’s $\tau$ and $p$, which can be solved by numerical results. Note that we must have $p \in (0,1)$ and $\tau \in (0,1)$.

3.2. Throughput analysis:

Let $S$ be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. To compute, let us analyse what can happen in a randomly chosen slot time. Let $P_a$ be the probability that there is at least one transmission in the considered slot time. And let $P_s$ be the probability that a transmission is successful, given the probability $P_a$. So we have

$$P_a = 1 - (1-\tau)^n$$

$$P_s = \frac{\tau}{1-\tau^n}$$

(12)

(13)

Now we are able to express the normalized system throughput $S$ as the ratio,

$$S = \frac{E[\text{Payload Information in a slot time}]}{E[\text{Length of a slot time}]}$$

(14)

$$= \frac{P_s \cdot P_a \cdot E[P]}{(1-P_{tr}) \sigma + P_s \cdot P_{tr} \cdot T_s + (1-P_s) \cdot P_{tr} \cdot T_c}$$

(15)

Where we use the symbols as those in papers [4,5]. Here, $T_s$ and $T_c$ are the average time the channel is sensed busy because of a successful transmission or collision respectively. The $E[P]$ is the average packet length and $\sigma$ is the duration of empty slot time.

Let packet header be $H = \text{PHYhdr + MAChdr}$ and let propagation be $\delta$. Then we must have the following expression, which is same as in paper [4], for the RTS/CTS access method.

In the case of our protocol “WCAN [1,2] with priority” only RTS/CTS access mechanism is used, so collision can be only between two RTS frames.

Every node that has data to send must wait for an ESIFS time to send his data if there are no node that has more priority data level. Based on these constraints we obtain:

$$T_{\text{success}} = \text{RTS} + \text{ESIFS} + \delta + H + E[P] + \delta$$

(16)

4. Results Analysis:

In this section, we present the results analysis of WCAN with priority protocol.

In the first time “Fig.3” we consider the ESIFS time versus level of priority of data to send. By this figure we concludes that for height
level priority Object-ID we have very low ESIFS time, but this time grow exponentially for low level priority Object-ID that’s guarantee that the most priority level data gain access to the support. In another hand based in this values of ESIFS the global performance of this protocol have to decrease if we have a lot of low level priority data.

5. Future work:

In this paper we proposed a mechanism to manage data priority for industrial sensor networks and a Markov chain model for this protocol in the goal of evaluate his performance.

In this model, the Throughput considered is the saturation Throughput and we consider also that all nodes have the same data level priority that is not the case in the real network case. The actual works are oriented to analyse the performance of the designed RTS/CTS access scheme by queuing systems process [7].

This mechanism must be implemented in the NS2[8] simulator to be simulated and emulated, for real life simulation, with real life DDS and DAIS applications.

REFERENCES