Prediction Efficiency in Predictive *p*-CSMA/CD

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Abstract. Predictive *p*-persistent CSMA protocol is an important MAC solution developed for networked sensor/control applications and used in Local Operating Networks (LonWorks) technology. The protocol uses a built-in network load prediction to support collision avoidance. The paper presents an analytical study of prediction efficiency for a channel with collision detection. The approach based on Markov chains is applied. The procedure of performance analysis includes the definition of transition probabilities of Markov chain for a specified load scenario, calculation of stationary distribution of contention window, and the probabilities of successful/unsuccessful transmission. It is shown that the predictive *p*-CSMA protocol manages to control the size of a competition window in order to guarantee the sustained probability of a successful transmission. The simulative validation of analytical results is provided.

Keywords: MAC protocols, sensor networks, performance analysis, Markov chains.

1 Introduction

Predictive *p*-persistent CSMA protocol is the heart of LonTalk/EIA-709.1 protocol used for communication between smart devices in Local Operating Networks (LON, LonWorks). LON has become a classic solution in building automation, and home networking, but is also used in a wide range of applications including, among others, semiconductor manufacturing, petrochemical industry, and wastewater treatment.

In the predictive *p*-CSMA the *collision avoidance* is applied for resolving uncoordinated access to the network. In order to cope with overload situations, the predictive *p*-persistent CSMA has been designed as an adaptive version of pure *p*-CSMA. In *p*-persistent CSMA, a node transmits with a fixed probability *p* if the channel is idle, and defers the transmission with the probability (1-*p*), when the channel is busy [10]. In the predictive *p*-CSMA, the probability *p* is variable and dynamically adjusted to expected traffic load using backoff scheme. The advantage of the predictive *p*-CSMA performance is the *throughput optimization*, which consists in keeping a high throughput even if a network is overloaded. Consequently, although the predictive *p*-CSMA is a random access scheme, LonWorks networks offer „guaranteed bandwidth" regardless of the offered traffic rate [3].

Under light traffic load, the predictive CSMA is reduced to the pure 0.0625-persistent CSMA regardless of the structure of the traffic in a channel [3]. However, the destiny of protocol operation is to cope with high traffic corresponding to the maximum load of a network. This is when a user derives benefits from load prediction built in the protocol. Indeed, transient overload situations occur in LonWorks networked systems since the LON architecture is *event-triggered* and data are transmitted in response to external events [11,12]. The *send-on-delta* concept rather than the uniform sampling is a natural sensor reporting paradigm in event-triggered applications [5,11]. Thus, the traffic in the channel is non-uniform and might be bursty. Moreover, the event-triggered architecture is prone to *event showers*, i.e. burst of correlated events, often released by a single physical event that causes congestion of the system [9]. Such an effect occurs, e.g. when a fire is detected in a building by a number of redundant temperature and smoke sensors which begin to report the event.

The present study addresses the issue of the asymptotic characteristics of predictive CSMA and the efficiency of protocol predictability. Both problems have not been quantitatively displayed in the scientific literature. To recognize ability of the protocol to cope with congestion, the channel must be stimulated by heavy load. We choose the *saturation conditions* for the protocol analysis where each node has always a packet to send. The saturation condition represents the largest possible load offered to the network by a given number of nodes, and constitutes the worst-case channel load.

It is intuitively comprehensible that due to the negative feedback, the size of the contention window grows with the number of competing nodes. However, there is still no answer to the questions what is the relationship between the mean size of competition window and the number of nodes trying to access the channel. Several papers deal with the performance analysis of predictive *p*-persistent CSMA protocol [1-4, 6-8]. Main benefits of the predictive *p*-CSMA scheme have been displayed in [2]. Simulation analyses have been carried out in [3,7]. Analytical approaches are presented in [6,8]. The former is the first complex analysis of the predictive *p*-CSMA based on the queuing theory. The latter follows a classical approach developed for the *p*-CSMA in 70s [10]. The saturation throughput analysis for the predictive *p*-CSMA without collision detection is presented in [4]. The present study deals with the predictive *p*-CSMA with collision detection, i.e. the predictive *p*-CSMA/CD. With the collision detection the protocol behavior is quite different from the one when a detection is absent since the contention window increase due to collisions is activated. Load scenario, where the acknowledged service (ACK) is used and all the transactions are unicast, is assumed.

The paper is organized as follows. In Sect. 2, we present the protocol specification and the backlog counting principles. In Sect. 3, the framework of the analytical approach is described. Sect. 4 presents the analysis of results for the saturation performance. In Sect. 5, the simulative validation of the analytical results is given.

2 Protocol Specification

The LonTalk/EIA 709.1 packet cycle consists of two phases (Fig. 1). The first phase is optional and dedicated to priority messages. During the other phase nodes randomize their access to the medium. Since the goal of our analysis is the predictive *p*-CSMA, we assume that there are no priority slots in the packet cycle.

2.1 LonTalk/EIA 709.1 Packet Cycle

The predictive *p*-CSMA belongs to the slotted-CSMA algorithms where the time axis is split into segments called *slots* with the duration equal to β_2.

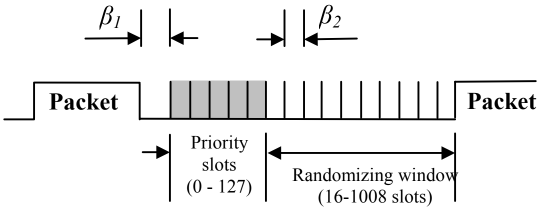

Fig. 1. LonTalk packet cycle

The algorithm operates in the following way. A node attempting to transmit monitors the state of the channel. If the channel is busy the node continues sensing. When the node detects no transmission during the β_1 period, it delays a random number of time slots of β_2 duration. If the channel is still idle when the random delay expires, the node transmits. Otherwise, the node receives an incoming packet and competes for the channel access again. If more than one node choose the same slot, and when that slot is the earliest one among the slots selected by all the contending nodes, then a *collision* happens. All the packets involved in a collision are corrupted. The time by which the competing node defers the transmission is expressed as a pseudorandom number of time slots β_2 drawn from the uniform distribution between 0 and W, where W is the *size of the randomizing* (*competition*) *window*.

The size of the randomizing window is dynamically adjusted to the current channel load. If the channel is idle, the randomizing window consists of 16 time slots. When the channel load increases, the number of slots grows by factor BL, called the *estimated channel backlog*. The backlog BL can range from 1 to 63 and the size of the window varies from 16 to 1008 time slots since the following relationship is met:

$$W = BL \cdot W_{base} \quad \textbf{(1)}$$

where W_{base} is the size of the *basic randomizing window* (16 slots). Thus, the level of the persistence of the predictive *p*-CSMA has either the lower (1/16=0.0625), or the upper bound (1/1008=0.0009).

2.2 Backlog Switching Rules

The backlog estimation is based on the calculation of the number of packets expected in the competition for the channel during the next packet cycle [1]. The backlog concept relies on monitoring the information included in the header of each packet transmitted in the channel. This information, encoded in 6-bit long field $Delta\_BL$, represents the number of acknowledgements that will be generated by receiver(s) as a result of packet reception. Thus, $Delta\_BL = 1$ for unicast and $1 < Delta\_BL \leq 63$ for multicast messages.

The channel backlog BL is increased by $Delta\_BL$ as a result of sending or successful receiving the message. Next, the backlog counter BL is decreased by *one*: (i) at the end of each successful packet cycle or (ii) if no node occupies the channel. If the collision detection is enabled, the backlog is increased by *one* in the case of collision. On a basis of the backlog counting algorithm we can conclude that after a successful transmission of the message, the backlog BL grows by $(Delta\_BL-1)$. Each node calculates the backlog autonomously basing on the backlog counter implemented in the LonWorks node firmware. To keep the *consistency* of backlog states, all nodes in the network should modify their backlog counters in the same way. We assume that both Physical Layer and Link Layer of protocol do not introduce the backlog inconsistency, i.e. the channel might be assumed to be noise-free and all transceivers are able to detect collisions even if they are not senders of colliding packets. Then, the backlog is a *global* channel parameter.

3 System Modeling

Following the definition, the saturated status of a network is reached if each node has a packet to send. We assume that the network consists of a fixed number of *n* nodes and the backlog consistency between the nodes is kept.

3.1 Analytical Model of Channel Backlog

Let $BL^{(n)}(l)$ be a stochastic process representing the *backlog stage* at the *l*th packet cycle in a network consisting of *n* nodes, where $BL^{(n)}(l)=1,\ldots,63$. As it was stated, we assume that the process $BL^{(n)}(l)$ is a global measure of the channel. $BL^{(n)}(l)$ is the Markov chain with transition probabilities $p_{i,j}^{(n)}, i, j=1,\ldots,63$. The first goal of our analysis is to find a stationary distribution of backlog $\boldsymbol{\pi}=[\pi_k]$, $k=1,\ldots,63$. Next, the *saturation backlog* $\overline{BL}^{(n)}$ is calculated as the expected backlog in the long term:

$$\overline{BL}^{(n)}=E[BL^{(n)}(l\to\infty)]=\sum_{k=1}^{BL_{\max}}k\pi_k \qquad (2)$$

where $E[\cdot]$ is the expectation operator. The *saturation window* is defined as the mean size of the randomizing window in the saturation conditions:

$$\overline{W}^{(n)}=16\overline{BL}^{(n)} \qquad (3)$$

We assume the load scenario called ACK/unicast in short, where all the packets sent through the network use the acknowledged service and unicast addressing. Thus, after each packet reception, a receiving node generates a single acknowledgement. In such a scenario we distinguish three types of packet cycles (see Sect. 2.2): (1) an unsuccessful transmission due to the collision, which causes the channel backlog BL to increase by one in the next packet cycle: $BL^{(n)}(l+1) = BL^{(n)}(l)+1$, (2) a successful transmission of the unicast message, when the channel backlog BL does not change: $BL^{(n)}(l+1) = BL^{(n)}(l)$, and (3) a successful transmission of the acknowledgement which decreases the backlog BL by one: $BL^{(n)}(l+1) = BL^{(n)}(l)-1$.

The key assumption in our model is that probabilities of the successful transmission of the acknowledgement and the message are the same. The validity of this assumption will be checked in Sect. 5. According to this assumption, if the probability of a collision at a certain backlog stage $BL^{(n)}(l) = k$ with n competing nodes amounts to $p_k^{(n)}$, then both the probabilities of a successful transmission of a message and an acknowledgement equal $(1-p_k^{(n)})/2$.

Suppose that the backlog enters the stage k at the lth packet cycle, i.e. $BL^{(n)}(l) = k$. Let $\Pr^{(n)}\{BL^{(n)}(l+1) = k+s \mid BL^{(n)}(l) = k\} = p_{k,k+s}^{(n)}$ be the *transition probability* that the backlog enters the stage $(k+s)$ in the (l+1)th packet cycle from the stage k in the lth cycle. Taking the specification of the packet cycle types (1)-(3) into account and backlog limits we calculate the probabilities of switching between backlog stages:

$$p_{k,k+1}^{(n)} = \Pr^{(n)}\{BL^{(n)}(l+1) = k+1 \mid BL^{(n)}(l) = k\} = p_k^{(n)}, \qquad k = 1,\ldots,62$$

$$p_{k,k}^{(n)} = \Pr^{(n)}\{BL^{(n)}(l+1) = k \mid BL^{(n)}(l) = k\} = \begin{cases} 1-p_k^{(n)} & k = BL_{\min} = 1 \\ (1-p_k^{(n)})/2, & k = 2,\ldots 62 \\ (1+p_k^{(n)})/2 & k = BL_{\max} = 63 \end{cases} \qquad \textbf{(4)}$$

$$p_{k,k-1}^{(n)} = \Pr^{(n)}\{BL^{(n)}(l+1) = k-1 \mid BL^{(n)}(l) = k\} = (1-p_k^{(n)})/2, \qquad k = 2,\ldots,63$$

$$p_{k,k+s}^{(n)} = \Pr^{(n)}\{BL^{(n)}(l+1) = k+s \mid BL^{(n)}(l) = k\} = 0, \qquad |s| > 1, k = 1,\ldots,63$$

The diagram of the Markov chain for a given scenario is shown in Fig. 2.

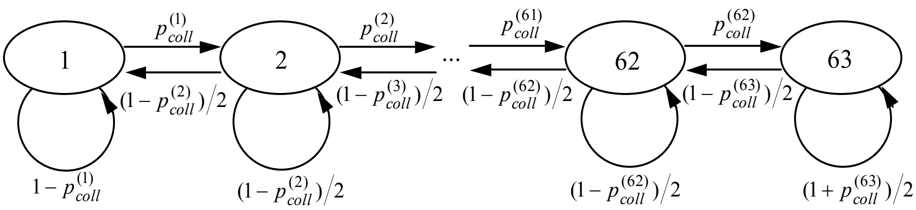

Fig.2. The state transition diagram of the Markov chain for ACK/unicast scenario

3.2 Backlog Stationary Distribution

In order to find the saturation backlog, the *steady-state vector*, or the *stationary distribution* $\boldsymbol{\pi} = [\pi_k]$, $k = 1,...,63$ of the Markov chain has to be calculated. The stationary distribution $\boldsymbol{\pi}$ is an eigenvector of the transition matrix $\mathbf{P}$, associated with the eigenvalue equal to one. The vector $\boldsymbol{\pi} = [\pi_k]$ includes the long-term probabilities π_k that the channel backlog will be at the stage k in the steady state, that is:

$$\pi_k = \lim_{l\to\infty} \Pr\{BL(l) = k\} \quad \textbf{(5)}$$

Using the direct method of the steady-state vector $\boldsymbol{\pi}$ computation, the following linear equation has to be solved:

$$[\mathbf{G} \mid \mathbf{e}]^T \boldsymbol{\pi} = \mathbf{b} \quad \textbf{(6)}$$

where $\mathbf{P}^{(n)} = [p_{i,j}^{(n)}]$ is a transition matrix 63 x 63; the elements $p_{i,j}^{(n)}$ are given by (4), $\mathbf{G} = \mathbf{P}^{(n)} - \mathbf{I}$, $\mathbf{I}$ is an identity matrix 63 x 63; $\mathbf{e} = [e_i]$ is a vector, where $e_i = 1; i = 1,...,63$; $[\mathbf{G} \mid \mathbf{e}]$ is 63 x 64 matrix, where the last column of this matrix is a vector $\mathbf{e}$; $\mathbf{b} = [b_i]$ is a vector, where $b_i = 0, b_{i+1} = 1; i = 1,...,63$.

3.3 Probabilities of Successful and Unsuccessful Transmission

In order to find $p_{i,j}^{(n)}$ we have to calculate $p_k^{(n)}$, i.e. the probability that the transmission is in a collision if n nodes compete for the channel, and the current window consists of $16k, k = 1,...,63$ time slots. To be precise, $p_k^{(n)}$ is the probability that more than one node selects the same time slot and all the other nodes choose later slots:

$$p_k^{(n)} = 1 - p_{ks}^{(n)}(k) \quad \textbf{(7)}$$

where $p_{ks}^{(n)}(k)$ is the probability of a successful transmission for the window containing $16k$ time slots, i.e. the opposite event to collision occurrence.

The probability $p_{ks}^{(n)}(k)$ describes the drawing when there is a single winner of a channel competition and is expressed as the sum (according to all the $1,...,16k$ slots and $1,...,n$ nodes) of the following: (i) the probability that a winner selects a certain slot $s = 1,...,16k$ which equals $1/16k$, (ii) the probability that all the other $(n-1)$ nodes draw one from $(16k - s)$ later slots, which equals $\left((16k - s)/16k\right)^{n-1}$. Finally:

$$p_{ks}^{(n)}(k) = n\sum_{s=1}^{16k} \frac{1}{16k}\left(\frac{16k - s}{16k}\right)^{n-1} \quad \textbf{(8)}$$

Basing on the ditribution of the contention window $\boldsymbol{\pi} = [\pi_k]$, we can estimate the *saturation probability of collision* $p_{coll}^{(n)}$ as the following expectation:

$$p_{coll}^{(n)} = 1 - n \sum_{k=1}^{BL_{\max}} \pi_k \left[\sum_{s=1}^{16k} \frac{1}{16k} \left(\frac{16k - s}{16k} \right)^{n-1} \right] \quad \textbf{(9)}$$

Hence, $p_{succ}^{(n)}$, the *saturation probability of the successful transmission* equals: $p_{succ}^{(n)} = 1 - p_{coll}^{(n)}$.

4 Saturation Channel Backlog and Probabilities

Using the analytical approach outlined in Sect. 3 we obtained the following results. The graphs presenting $\overline{BL}^{(n)}$ and $p_{coll}^{(n)}$ vs. the number of nodes *n* for a specified load scenario (ACK/unicast) are shown in Fig. 3. Each point on the saturation backlog graph is found as a solution of the linear system given by Eq. (6) for a particular number of nodes and the expectation (Eq. (2)). $p_{coll}^{(n)}$ is calculated according to (9).

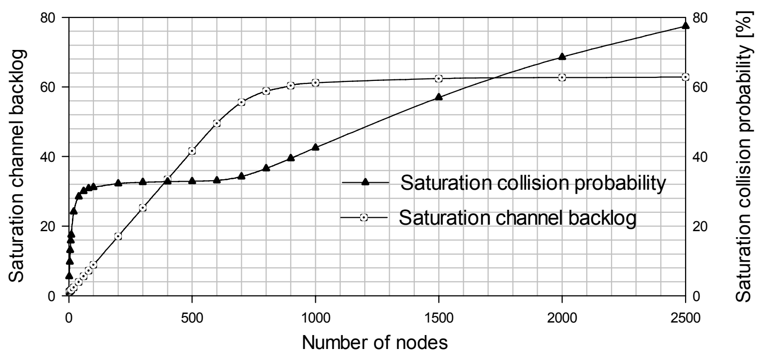

Fig.3. The saturation backlog and the saturation collision probability for ACK/unicast scenario

At the lower range the saturation backlog increases almost linearly as the number of nodes grows and the slope of the curve is about 0.06 per node. In particular, this means that adding a new node to the existing network causes the increase of the saturation window by about $0.06 * 16 \cong 1$ time slot of β_2 duration. For networks larger than about 700 nodes, the influence of the upper bound of the channel backlog prevents a further extension of the competition window. If a network contains more than 1000 nodes, then the saturation backlog is close to its maximum value 63, and the predictive protocol is reduced to the 0.0009-persistent CSMA. Summing up, the prediction is effective for the network sizes up to 700 nodes.

As regards the saturation collision probability $p_{coll}^{(n)}$, the probability $p_{coll}^{(n)}$ grows in proportion to the number of nodes for a network containing dozens of devices (Fig. 3). Next, $p_{coll}^{(n)}$ becomes steady at 33,3 % for the network sizes larger than 100 nodes. Thus, $p_{succ}^{(n)}$ is kept at 66,7 %. This is an important result for the predictive CSMA performance. It shows that the protocol manages to control the size of a competition window in order to guarantee the *sustained probability of successful transmission*, which in the analyzed scenario equals 66,7%.

The successful transmission sustained probability is the worst-case probability of successful transmission for the predictive CSMA if the prediction if *effective*, i.e. the current backlog is not limited by $BL_{\max} = 63$. Although, the effect of keeping the high throughput of the predictive CSMA has been known [2,3,7], there has been no explicit quantitative evaluation of sustained probability of successful/unsuccessful transmission. Note that sustained probabilities $p_{succ}^{(n)} = 66{,}7\%$ and $p_{coll}^{(n)} = 33{,}3\%$ are established at the equilibrium point, when the probabilities of the backlog increase ($p_{succ}^{(n)}/2$) and decrease ($p_{coll}^{(n)}$) are equal. Finally, for networks greater than 700 nodes, the influence of the maximum size of a competition window appears, and the shape of both measures is close to that of 0.0009-persistent CSMA.

5 Validation of Analytical Approach

In order to verify the analytical approach we have performed the simulations for a selected number of nodes in the network saturation status. The simulation starts when the channel is idle. Next, the transient zone appears, when the nodes permanently try to access the channel and the mean channel backlog grows, but does not reach the steady-state value. Since the simulation model belongs to non-terminating systems and the steady state theoretically is never reached, we detect it with a finite accuracy. The detection relies on the search of the constant value of the *mean* backlog rather than the constant value of the *current* backlog. Therefore, we used the *moving averages* defined on a window of observations (i.e. a certain number of packet cycles). Moving averages filter the higher frequency components in the mean backlog, arisen from the random behavior of the CSMA algorithm on the one hand, and remove also the influence of the transient zone on the estimation of the saturation backlog on the other. The saturation backlog is found under quasi steady-state conditions when the moving average of the channel backlog is kept inside of 5% wide confidence interval.

5.1 Validation of Transition Probabilities

The transition probabilities in the Markov model have been derived basing on the equality of the probabilities of the successful transmission of a message and an acknowledgement (see Sect. 3.1). This assumption is true if the mean number of nodes having a message waiting for the transmission (i.e. *message sources*) equals the mean number of nodes that possesses an acknowledgement ready for sending (i.e. *acknowledgement sources*). Fig. 4 presents simulation results showing the mean relative number of message and acknowledgement sources in the network steady state. It is clear that both numbers are equal to 50% with finite simulation accuracy.

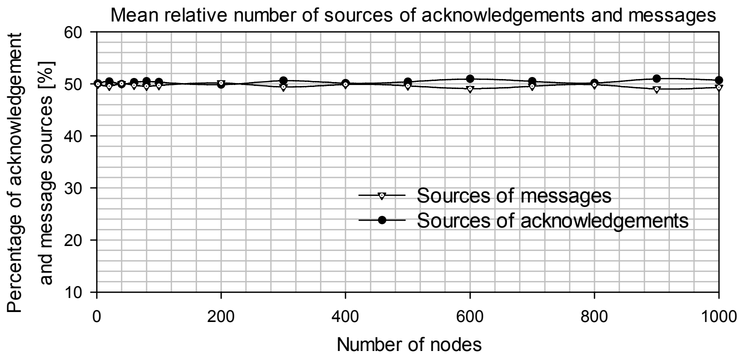

Fig. 4. Simulation results of the mean relative number of message and acknowledgement sources in the steady state

5.2 Simulation versus analytical results

The comparison of simulation and analytical results for the saturation backlog and the probability of collision $p_{coll}^{(n)}$ and its experimental equivalent (i.e. collision percentage $p'^{(n)}_{coll}$), is presented in Table 1. Since both results are very close to each other and the corresponding graphs overlap, they are not shown in figures together. The comparison shows a good conformity of simulation and the Markov-based analytical approach. The difference between both results stems from (i) the finite accuracy of the steady state detection in the simulation, (ii) the inaccuracy of the pseudorandom generators, (iii) the finite precision of analytical calculations.

Table 1. The comparison of analytical and simulation results for saturation backlog and saturation probability of collision for the ACK/unicast load scenario

n	$\overline{BL}^{(n)}$ (Markov model)	$\overline{BL}^{(n)}$ (simulation)	$p_{coll}^{(n)}$ [%] (Markov model)	$p'^{(n)}_{coll}$ [%] (simulation)	$p_{succ}^{(n)}$ [%] (Markov model)	$p'^{(n)}_{succ}$ [%] (simulation)
2	1,128	1,124	5,56	5,77	94,44	94,23
6	1,390	1,387	13,12	13,68	86,88	86,32
10	1,663	1,661	17,49	17,98	82,51	82,02
40	3,9476	4,028	28,48	28,96	71,52	71,04
100	8,8567	8,889	31,15	31,97	68,75	68,03
500	41,634	42,160	32,89	33,3	67,11	67,7
1000	61,194	61,428	42,53	42,72	57,47	57,28

6 Conclusions

The paper presents the analytical study of the efficiency of network load prediction built in the predictive *p*-CSMA/CD that is used as a MAC protocol in LonWorks/EIA-709 sensor/control networking technology. The approach based on the Markov chains is applied. The procedure of performance analysis includes the definition of transition probabilities of the Markov chain for a specified load scenario, the calculation of stationary distribution of contention window, and the probabilities of successful/unsuccessful transmission. The analysis is exemplified on the load scenario where the acknowledged message service and unicast transactions are used. The presented results allow to recognize the predictability of the protocol behavior in heavy load conditions. In particular, it is shown that the predictive *p*-CSMA protocol manages to control the size of a competition window in order to guarantee the sustained probability of successful transmission. The simulative validation of analytical results is provided. Further research should generalize the performance analysis for general case load scenario.

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