LIMITS OF PERFORMANCE OF ADAPTIVE VARIABLE-WINDOW CSMA

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Abstract: The paper addresses the limits of performance of adaptive variable-window CSMA random access protocol with collision avoidance. A unified method of traffic description based on scaling coefficients, integrating various addressing and message service types, is proposed. Furthermore, the fundamental tradeoff of the adaptive variable-window CSMA protocol operation is highlighted. In particular, it is shown that the maximization of the channel bandwidth utilization is obtained at the cost of minimization of the fraction of bandwidth devoted to a transmission of messages carrying application data. Copyright © 2007 IFAC

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1. INTRODUCTION

One of generic algorithms for random access control in networked systems is the $p$-persistent CSMA protocol. A node, contending for the shared channel according to the $p$-CSMA, transmits with probability $p$ if the channel is idle, and defers transmission with the probability $(1-p)$ (Kleinrock and Tobagi, 1975). The channel utilization in the $p$-persistent CSMA is strongly affected by the $p$ value which represents the persistence level of the protocol. In particular, large $p$ values cause excessive collisions, while small $p$ values degrade the bandwidth utilization forcing the channel to be idle. A tradeoff between large and small values is thus necessary to provide the bandwidth utilization on the satisfactory level. However, a given persistence level, $p$, maximizes the channel utilization only for a preselected number of contending nodes. If a number of contenders is unknown a priori or varies in time, the $p$ value cannot be set optimally, and consequently the performance of $p$-persistent CSMA may be considerably degraded. Therefore, the CSMA-based protocols with collision avoidance try to adapt to the number of contending nodes. In the class of variable-window CSMA protocols, the persistence level, maintained by each node, is modified basing on the feedback information from the network. The modification of $p$ value is usually accomplished by decreasing $p$ in case of collisions, and by increase of $p$ after each successful transmission.

The predictive $p$-persistent CSMA is the adaptive, variable-window version of pure $p$-CSMA commercially implemented in MAC sublayer of LonTalk protocol (LonTalk Protocol Specification, 1995) and exploited in Local Operating Networks (LonWorks) technology for communication between intelligent sensors and actuators (Dietrich, et al., 2001). The probability $p$ is variable and dynamically adjusted to the expected traffic load using the additive increase/additive decrease scheme. Several papers deal with the performance analysis of the predictive $p$-persistent CSMA protocol including the simulation analyses (Miśkowicz, et al., 2002; Chen, and Hong, 2002a), and the analytical approaches (Miśkowicz, 2006; Buchholz, and Plönnigs, 2004; Chen, and Hong, 2002b). The present study is a continuation of the author’s work (Miśkowicz, 2006) where the Markov analysis for the generalized load scenario is reported. The contribution of this paper is to highlight the fundamental tradeoff of the predictive $p$-persistent CSMA operation. Namely, it is shown that the maximization of the channel bandwidth utilization is
obtained at the cost of the minimization of the fraction of bandwidth devoted to transmission of the messages carrying application data. In other words, if the probability of a successful transmission becomes high, most of packets transmitted through the channel are acknowledgements.

2. PROTOCOL PERFORMANCE

2.1 Protocol Specification.

A node contending for the channel according to the predictive p-persistent CSMA delays a random backoff expressed as a random number of slots drawn from the uniform distribution between 1 and W, where W is the size of the contention window. 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 chooses the same slot number, and where that slot has the lowest number selected by any node with a packet to send, then a collision happens. All the packets involved in a collision are corrupted.

The size of the contention window is dynamically adjusted to the expected channel load. If the channel is idle for a long time, the randomizing window becomes steady at sustained levels depending on the number of contending nodes. Thus, the number of contending nodes is constant in time.

Each node is a source of messages unless it receives an acknowledged message. Then, it generates acknowledgement packet and switches its status to the source of acknowledgements. If the acknowledged message is received by a recipient that is currently the source of acknowledgements, the node queues a new acknowledgement. The probability of a successful transmission of message/acknowledgement is proportional to the number of sources of messages/acknowledgements in the steady state of the network. Every node generates the same traffic according to assumed load scenario.

A key assumption we make is that the destination address(es) of transmitted messages are distributed rather than concentrated on particular nodes. The simulator distributes destination addresses of messages by selecting at random the addresses of recipients only from the set of nodes that are currently the sources of messages. Simulation outputs interesting from the point of view of the present study are the relative frequencies of successful/unsuccessful transmissions of messages and acknowledgements which are the experimental equivalents of the appropriate probabilities of successful/unsuccessful transmission.

2.2 Performance Evaluation Model.

To introduce the problem of performance limits of the predictive p-CSMA we present first the simulation results. The simulation model has been implemented in LabView. In order to stimulate a channel with heavy load we choose the saturation conditions for protocol analysis where all nodes have always packets ready to send. Thus, the number of contending nodes is constant in time.

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2.3 Simulation Results

In 1/16-persistent CSMA, the contention window consists of 16 slots in each packet cycle. The predictive p-CSMA reduces to 1/16-persistent CSMA if the collisions detection is not provided and no multicast messages are transmitted through the channel. Moreover, as follows from Fig. 1, under light traffic load the predictive CSMA operates closely to 1/16-persistent CSMA regardless of the load scenario since even occasional multicast messages do not increase the long-term mean randomizing window over 16 slots considerably. Hence, the predictive p-CSMA might be approximated by 0.0625-persistent CSMA for any load scenario if the traffic is light.

Comparing to 0.0625-persistent CSMA a fundamental difference in predictive CSMA operation appears for overload situations when the number of active nodes is large.

The relative frequency of a successful transmission, which is the simulative approximation of the success probability \( p_{suc} \) with a number of \( n \) contenders, decreases with growing number of nodes, \( n \), for a network containing dozens of devices (Fig. 1). Next, for the number of about 70 contending nodes, it becomes steady at sustained levels depending on the load scenario.
is a superposition of the traffic of messages and acknowledgements. The specification of a load scenario describes the structure of the primary traffic generated to the network (i.e. a percentage of particular message types). Each original message is characterized as regards its contribution to derivative traffic that will be generated in case of its successful reception. Therefore, a specification of a message type has to include the message service (acknowledged or unacknowledged one), and the addressing (unicast, or multicast).

Let the load scenario be specified by a set of numbers $0 \leq \alpha_i \leq 1$ representing percentages of multicast($i$) messages in the primary traffic. Thus:

$$\sum_{i=0}^{M} \alpha_i = 1$$  \hfill (1)

Let us transform the numbers $\alpha_i$ to the set of relative coefficients $\gamma_j = \alpha_j : i=0,...,M$ denoted as the scaling factors. The transformation relies on the normalization of a set of $\alpha_i$ to their minimum. Assume that the multicast($j$) messages, $j \in \{0,...,M\}$, are the smallest non-zero component in the primary traffic of original messages. Then, the scaling factors are simply defined as:

$$\gamma_j = \alpha_j : i=0,...,M$$ \hfill (2)

where by the assumption $\alpha_j = \min_{i=0,1,...,M} \{\alpha_i; \alpha_i \neq 0\}$.

By the definition: $\gamma_i \geq 1, i \neq j$, and $\gamma_i = 1, i = j$. Note that the scaling factors $\gamma_0,...,\gamma_M$ provide a complete specification of the traffic in the channel: the index of $\gamma_i$ defines a size of a backlog change in case of a successful transmission of the multicast($i$) message, and the value of $\gamma_i$ determines the probability of a successful transmission of that message. The traffic description by the set of $\alpha_i$, $0 \leq \alpha_i \leq 1$ coefficients is equivalent to the specification by scaling factors $\gamma_i$, $\gamma_i \geq 1$. However, a definition of a particular load scenario by $\gamma_i$ requires a specification of all $M+1$ corresponding scaling factors, whereas in case of the use of $\alpha_i$, only non-zero coefficients may be listed.

3.2 Equilibrium Analysis.

Asymptotic probability of a successful transmission of any packet. The following lemma provides a closed-form formula to calculate the asymptotic probability of a successful transmission (both messages and acknowledgements) in the channel for the predictive $p$-persistent CSMA protocol.

**Lemma 1.** The asymptotic probability of a successful transmission of any packet in a channel defined as $p_{\text{succ}} = \lim_{n \to \infty} p_{\text{succ}}^{(n)}$, where $p_{\text{succ}}^{(n)}$ is the probability of a successful transmission for a number of $n$ contending nodes, is given by the following formula:

$$p_{\text{succ}} = \frac{\sum_{i=0}^{M} [(i+1)\gamma_i]}{\sum_{i=0}^{M} [(i+2)\gamma_i]}$$ \hfill (3)
**Furthermoe,** \( p_{\text{suc}} \) **is the worst-case probability of successful transmission for a specified load scenario, and is independent of the number of contenders.**

**Proof:** Since a successfully transmitted acknowledged multicast(l) message generates a number of \( i \) acknowledgments, the total traffic in the channel is a superposition of the traffic of messages and traffic of acknowledgements. Applying the assumption about distribution of message recipient addresses, the total traffic in the channel might be described as follows:

\[
\alpha_j' (\gamma_0 + \gamma_1 + \gamma_2 + 2\gamma_M + M\gamma_M) = 1 \quad (4)
\]

where \( \alpha_j' \) represents a percentage of multicast(l) messages in the total traffic. Solving the equation (4) for \( \alpha_j' \):

\[
\alpha_j' = \frac{1}{\gamma_i} \sum_{i=0}^{M} [(i+1)\gamma_i] \quad (5)
\]

Next, the percentage \( \alpha_i' \) of the multicast(l) messages in the total traffic:

\[
\alpha_i' = \gamma_i \alpha_i' = \frac{\gamma_i}{\sum_{i=0}^{M} [(i+1)\gamma_i]}, \quad \forall l = 0, \ldots, M \quad (6)
\]

**Probabilities of a successful transmission of messages/acknowledgements.** Since the number of contending nodes \( n \) is large by the assumption, the probability of a successful transmission of any packet in the steady state of the network equals

\[
p_{\text{suc}} = \lim_{n \to \infty} p_{\text{suc}}^{(n)}
\]

which is the searched variable.

The probability of a successful transmission of the multicast(l) message is simply equal to \( \alpha_i' p_{\text{suc}} \). Finally, the probability of a successful transmission of an acknowledgement packet is \( p_{\text{suc}} \sum_{i=1}^{M} i\alpha_i' \) since each of the primary traffic components \( \alpha_i' \) contributes as \( i\alpha_i' \) to the traffic of acknowledgements.

**Transition probabilities between backlog stages.** Assume the channel backlog BL equals \( k \) at a certain instant. Note that \( k \gg 1 \) if the number of nodes \( n \) is assumed to be large. Denote by \( p_{k, k+l-1} \) the probability of the channel backlog increase by \( l-1 \) from the state \( k \) to \( k+l-1 \). As follows from the predictive CSMA protocol specification, for \( l = 1 \) or \( 3 \leq l \leq M \), \( p_{k, k+l-1} \) equals the probability of a successful transmission of the multicast(l) message, which simply amounts \( \alpha_i p_{\text{suc}} \) (Eq. (7a), (7c)). The probability \( p_{k, k+1} \) of incrementing the backlog by one is the sum of \( \alpha_i' p_{\text{suc}} \) and the probability of a collision that equals \( (1 - p_{\text{suc}}) \) (Eq. (7b)). Finally, the probability \( p_{k, k-1} \) of decrementing the backlog by one is the sum of the probability of a successful transmission of the unacknowledged message \( \alpha_0 p_{\text{suc}} \) and the probability of a successful transmission of the acknowledgement packet \( p_{\text{suc}} \sum_{i=1}^{M} i\alpha_i' \) (Eq. (7d)). The other transitions of backlog are prohibited. Summarizing, the transition probabilities are given by:

\[
\begin{align}
p_{k, k+l-1} &= \alpha_i' p_{\text{suc}}, \quad M \geq l \geq 3 \\
p_{k, k+1} &= \alpha_i' p_{\text{suc}} + (1 - p_{\text{suc}}) = (\alpha_2' - 1)p_{\text{suc}} + 1 \\
p_{k, k} &= \alpha_1' p_{\text{suc}} \\
p_{k, k-1} &= \alpha_0' p_{\text{suc}} + p_{\text{suc}} \sum_{i=1}^{M} i\alpha_i' = p_{\text{suc}} \sum_{i=0}^{M} i\alpha_i'
\end{align}
\]

Setting the expression (6) to a set of the formulas (7a)-(7d), the probabilities of switching the backlog states are given by the following set of equations:

\[
\begin{align}
p_{k, k+l-1} &= \frac{\gamma_i p_{\text{suc}}}{\sum_{i=0}^{M} [(i+1)\gamma_i]} \\
p_{k, k+1} &= \frac{\gamma_i p_{\text{suc}}}{\sum_{i=0}^{M} [(i+1)\gamma_i]} - p_{\text{suc}} + 1 \\
p_{k, k+l-1} &= \frac{\gamma_i p_{\text{suc}}}{\sum_{i=0}^{M} [(i+1)\gamma_i]}, \quad 3 \leq l \leq M \\
p_{k, k-1} &= p_{\text{suc}} \left[ 1 - \frac{\sum_{i=0}^{M} \gamma_i}{\sum_{i=0}^{M} [(i+1)\gamma_i]} \right]
\end{align}
\]

The asymptotic probability of a successful transmission \( p_{\text{suc}} \) establishes at the equilibrium state where the expected value of backlog random changes equals zero (i.e. a probability of backlog increase is equal to a probability of backlog decrease):

\[
\sum_{i=0}^{M-1} p_{k, k+i} = 0
\]

Setting appropriate transition probabilities (8) to (9), and solving the equation with respect to \( p_{\text{suc}} \) we obtain the formula (3). Thus, the proof is completed.

As follows from Lemma 1, \( p_{\text{suc}} \) is determined by the structure of the traffic transmitted through the channel so it is forced “from outside” of the protocol (i.e. by the input traffic to the channel).

Paradoxically, \( p_{\text{suc}} \) is independent of the number of contenders. However, the price for keeping \( p_{\text{suc}} \) constant is an increase in access delay (Miśkowicz, \textit{et al.}, 2002). The next interesting issue is the range of \( p_{\text{suc}} \) achievable for various load scenarios.

**Remark 1.** The sustained probability of a successful transmission \( p_{\text{suc}} \) reaches its maximum and minimum that are equal respectively to:

\[
\begin{align}
\max_{\gamma_0 \to \gamma_a} p_{\text{suc}} &= (M + 1)/(M + 2) \\
\min_{\gamma_0 \to \gamma_M} p_{\text{suc}} &= 1/2
\end{align}
\]

The maximum of \( p_{\text{suc}} \) is obtained for the homogenous traffic of multicast(M) messages (i.e. for \( \alpha_M = 1 \)), and is close to one if a group of message recipients (M) is large. The prediction efficiency is the best achievable then. On the other hand, \( p_{\text{suc}} \) reaches its minimum equal to \( 1/2 \) if the homogenous unacknowledged traffic is sent via the channel (i.e. if \( \alpha_0 = 1 \)).
Global reliability versus end-to-end reliability. The acknowledgement packets constitutes control packet overhead and do not carry application data. If collision detection is not provided, sending an acknowledgement by a destination node is the only way to notify the sender of a successful message reception. However, a transmission of acknowledgments increases the collision rate, the mean access delay, and in fact degrades the global reliability of packet delivery. This is a price for back information about a result of successful completing a transaction. Thus, acknowledgement message service improves the end-to-end reliability of individual transactions, but degrades the global reliability of packet delivery.

Asymptotic probability of a successful transmission of messages and acknowledgements. Lemma 1 deals with the probability of a successful transmission of packets, i.e. both messages and acknowledgements. The next interesting issue is a distribution of this probability among messages which carry application data, and acknowledgement packets, which form only the control traffic overhead.

Remark 2. The sustained probability of a successful transmission of messages in the channel, \( p_{\text{succ mes}} \), and the sustained probability of a successful transmission of acknowledgement packets, \( p_{\text{succ ack}} \), are given by the formula:

\[
p_{\text{succ mes}} = \frac{\sum_{i=0}^{M} \gamma_i}{\sum_{i=0}^{M} (i+2) \gamma_i} \quad (11)
\]

\[
p_{\text{succ ack}} = \frac{\sum_{i=0}^{M} i \gamma_i}{\sum_{i=0}^{M} (i+2) \gamma_i}
\]

**Proof:** As was explained, each of primary traffic components is represented by \( \gamma_i, i=0,...,M \), and contributes by \( i \gamma_i \) to the traffic of acknowledgements. To calculate the contribution of primary messages to the total traffic, each total traffic component \( \gamma_i \) has to be divided by \( 1/(i+1) \). The formula (11) might be derived directly from the equation (3) if each element of the sum in the numerator is scaled by \( 1/(i+1) \). Obviously, \( p_{\text{succ mes}} + p_{\text{succ mes}} = p_{\text{succ}} \). In particular, if the traffic transmitted via the channel is homogeneous and comprised of multicast(\( k \)) messages (\( \alpha_k = 1 \)), then \( p_{\text{succ mes}} = 1/(k+2) \). Furthermore:

\[
\max_{\gamma_0,...,\gamma_M} p_{\text{succ mes}} = 1/2 \quad (12)
\]

\[
\min_{\gamma_0,...,\gamma_M} p_{\text{succ mes}} = 1/(M + 2)
\]

The maximum of \( p_{\text{succ mes}} \) is achieved for the homogenous unacknowledged traffic (\( \alpha_0 = 1 \)), and \( p_{\text{succ mes}} \) reaches its minimum if the traffic is comprised of multicast(M) messages (\( \alpha_M = 1 \)).

Remark 3. The sustained probability of a successful transmission of messages, \( p_{\text{succ mes}} \), equals the sustained probability of a collision \( p_{\text{coll}} \):

\[
p_{\text{succ mes}} = p_{\text{coll}} \quad (13a)
\]

or equivalently

\[
p_{\text{succ mes}} + p_{\text{coll}} = 1. \quad (13b)
\]

The formula (13a) can be found directly if (3) is set to (11a) taking into account that \( p_{\text{succ}} = 1 - p_{\text{coll}} \).

Remark 4. The sustained probability of a successful transmission of control packets (acknowledgements) equals:

\[
p_{\text{succ ack}} = 2p_{\text{succ}} - 1 \quad (14a)
\]

or equivalently

\[
p_{\text{succ ack}} = 1 - 2p_{\text{succ mes}} \quad (14b)
\]

The formulas (14a), (14b) are obtained if the equation (13b) and the formula \( p_{\text{succ ack}} = p_{\text{succ mes}} = p_{\text{succ}} \) are taken into account.

Remarks 3 and 4 explicitly display the fundamental tradeoff of the predictive \( p \)-persistent CSMA operation: a maximization of \( p_{\text{succ}} \) is obtained at the cost of a minimization of \( p_{\text{succ mes}} \). In other words, \( p_{\text{succ}} \) is high if most of packets transmitted through the channel are acknowledgements.

### Table 1. Numerical results of \( p_{\text{succ}}, p_{\text{succ mes}}, p_{\text{succ ack}} \) for selected load scenarios.

<table>
<thead>
<tr>
<th>Load scenario</th>
<th>( p_{\text{succ}} )</th>
<th>( p_{\text{succ mes}} )</th>
<th>( p_{\text{succ ack}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% of UNACK:</td>
<td>( \alpha_0 = 1 )</td>
<td>1/2</td>
<td>1/2</td>
</tr>
<tr>
<td>50% of UNACK:</td>
<td>( \frac{1}{4} )</td>
<td>2/5</td>
<td>2/5</td>
</tr>
<tr>
<td>50% of unicast/ACK:</td>
<td>( \alpha_0 = 0.5 ), ( \alpha_1 = 0.5 )</td>
<td>( 2/5 )</td>
<td>( 1/3 )</td>
</tr>
<tr>
<td>100% of unicast/ACK:</td>
<td>( \alpha_0 = 1 )</td>
<td>( 5/7 )</td>
<td>( 2/7 )</td>
</tr>
<tr>
<td>50% multicast(2)/ACK:</td>
<td>( \alpha_0 = 0.5 ), ( \alpha_2 = 0.5 )</td>
<td>( 1/4 )</td>
<td>( 1/4 )</td>
</tr>
<tr>
<td>100% of multicast(2)/ACK:</td>
<td>( \alpha_0 = 1 )</td>
<td>( 8/11 )</td>
<td>( 3/11 )</td>
</tr>
<tr>
<td>33.3% of UNACK:</td>
<td>( \alpha_0 = 1 )</td>
<td>( 33.3% )</td>
<td>( 33.3% )</td>
</tr>
<tr>
<td>33.3% of unicast/ACK:</td>
<td>( \alpha_0 = 1 )</td>
<td>( 10/12 )</td>
<td>( 1/12 )</td>
</tr>
</tbody>
</table>

Comparing results of the asymptotic probability \( p_{\text{succ}} \) from Table 1, we conclude that they are consistent with simulation results presented in Fig. 1. In particular, \( p_{\text{succ}} \) equals 0.5 for UNACK messages, 0.67 for ACK/unicast traffic, 0.75 for ACK/multicast(2), and about 0.73 for mixed scenario defined in Fig. 1 caption. The results of \( p_{\text{succ mes}} \) and \( p_{\text{succ ack}} \) will be further verified via simulation in Sect. 3.4.
3.3 Analytical Approach Based on Markov Chains.

Now, we compare the results of the equilibrium analysis derived in the previous section to the results obtained using Markov chains reported in (Miškowicz, 2006). The appropriate transition probabilities are calculated as follows:

\[ p_{k,k+1} = p_{\text{succ}}^{(n)}(16k) \frac{\gamma_{i}}{\gamma_{i-1}} \], \quad l = 1 \text{ or } 3 \leq l \leq M

\[ p_{k,k+1} = 1 + p_{\text{succ}}^{(n)}(16k) \frac{\gamma_{i}}{\gamma_{i-1}} \] \quad (15)

\[ p_{l,1} = p_{\text{succ}}^{(n)}(16k) \left[ 1 + \frac{\gamma_{i}}{\gamma_{i-1}} - \sum_{i=0}^{M} \frac{\gamma_{i}}{\gamma_{i-1}} \right], \quad k \geq 2 \]

where \( \gamma = \sum_{i=0}^{M} [(i+1)\gamma_{i}] \), and \( p_{\text{succ}}^{(n)}(16k) \) is the probability of a successful transmission if the number of nodes competes for 16k slots. The \( p_{\text{succ}}^{(n)}(16k) \) can be expressed by the formula:

\[ p_{\text{succ}}^{(n)}(16k) = n \sum_{i=1}^{16k} \left( \frac{16k - s}{16k} \right)^{i-1} \] \quad (16)

The probability of a successful transmission \( p_{\text{succ}}^{(n)} \) might be found as the expectation:

\[ p_{\text{succ}}^{(n)} = \sum_{k=1}^{\infty} \pi_{k} p_{\text{succ}}^{(n)}(16k) \] \quad (17)

where \( \pi = [\pi_{1}] \) is the backlog stationary distribution calculated using standard methods. The asymptotic probability \( p_{\text{succ}} \) is simply approximated by \( p_{\text{succ}}^{(n)} \) if a number of nodes is large (e.g. more than 100). The obtained results of \( p_{\text{succ}}^{(n)} \) approximation are with the computational accuracy equal to results based on equilibrium analysis listed in Table 1, and simulation results for large number of nodes shown in Fig. 1.

3.4 Verification of \( p_{\text{succ\_msg}} \) and \( p_{\text{succ\_ack}} \).

Fig. 2 shows the simulation results of the relative frequencies/probabilities of collisions and successful transmissions of messages and acknowledgements for the mixed scenario. Note that \( p_{\text{succ\_msg}} = p_{\text{rat}} = 27\% \), and both measures are consistent with the analytical results for the mixed scenario listed in the sixth row in Table 1.

All these measures are the experimental equivalents of the appropriate probabilities defined in the sixth row of Table 1. Fig. 2 shows that the successful transmissions of acknowledgements are about 5/3 times more frequent than transmissions of messages. The asymptotic frequency of collisions read from Fig. 3 equals about 27\%, which corresponds to the asymptotic frequency of successful transmission shown in Fig. 1 (equal to about 73\%).

CONCLUSIONS

The simple and closed-form formula based on the equilibrium analysis to find the asymptotic channel utilization for the predictive p-CSMA is formulated and verified. The validation both by the analytic approach based on Markov chains, and via simulation is provided. It is also shown that the maximization of the channel bandwidth is obtained at the cost of minimization of the bandwidth fraction devoted for a transmission of application data. This is a fundamental tradeoff of the predictive p-persistent CSMA operation displayed by the present study.

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