Channel Utilisation for Contention MAC Protocols Using Control Frames Exchange

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Abstract: Contention medium access protocols based on control frames exchange with optional carrier or busy tone sensing, designed for efficient operation in wireless ad-hoc networks, have been compared for their efficiency in a wireless network. As the efficiency measure, channel utilisation as a function of total channel load has been accepted. The comparison is based on relations derived using probability calculus. The protocols analysed are designed to operate in a typical wireless network where hidden and exposed stations exist and carrier sensing is often not sufficient method of collision avoidance. The analysis considers MACA, FAMA and DBTMA protocols and compares them to CSMA and CSMA/CD.

Keywords: MAC protocols, wireless networks

1. Introduction

The medium access protocols are one of the most important issues of network design [10]. If a protocol is not suitable for a specific application, the network may work not efficiently enough to provide the necessary parameters like throughput or QoS support.

In wireless networks, several problems appear that correspond to the medium access design. These problems include hidden and exposed stations phenomena as well as capture effect [13] and they are not known from wired networks. They are especially visible when contention MAC protocols based on carrier detection are used in wireless ad-hoc networks (but not only in them), because of their rapidly changing structure and lack of general control information [9]. Such networks have therefore their own requirements that must be fulfilled by a medium access protocol, thus new collision avoidance and detection methods are necessary [13].

The first medium access protocols for wireless networks used collision avoidance methods like carrier or busy-tone detection [12]. However, they have some disadvantages. Carrier sense is a good collision avoidance method only if there are no hidden or exposed stations in the network, i.e., all the stations can communicate with
each other directly. Busy tone, in turn, is not as easy to implement as carrier sense, because it requires two- or even three-channel transceivers. Therefore, typical wireless network needs other collision avoidance methods, like for example control frames exchange [12]. It is interesting how these methods behave in different environments. One of several methods to estimate this is theoretical analysis based on probability calculus.

2. A comparison of protocols efficiency

There are several measures of MAC protocols efficiency [7,11]. One of them is channel utilisation as a function of total traffic offered to the channel. The traffic is defined as number of frames generated within the transmission time of a single frame. Using this relation one can calculate maximum channel utilisation taking into account all possible collisions and protocol overhead.

The formulas presented are derived under following assumptions:

- frame generation forms a Poisson process with intensity of \( g \) frames per second,
- frame transmission time is constant and equal to \( T \) seconds,
- acknowledges of correctly received frames are sent immediately at no cost (e.g., in a separate transmission channel),
- number of stations in the network is infinite,
- there are no transmission errors, therefore frames can be lost because of collisions only,
- capture effect does not exist (i.e., none of colliding frames is received correctly).

To simplify the formulas, normalised frame generation intensity \( (G = gT) \) is used, showing how many frames are generated within transmission time of a single frame.

It is worth notice that the formulas consider MAC algorithm only. Protocol overhead resulting from frame formats and frame exchange rules remains beyond the scope of this article.

The network model assumed for these comparisons is such that there is only one station, to which all frames are addressed. This is typical situation in wired networks, where there is only a single communication channel shared by all the stations, no matter which station is a sender and which is the addressee of a frame. However, in wireless environments, especially in decentralised ones (e.g., ad hoc networks), several concurrent transmissions are possible without any collision. This is possible, when the addressees are within the transmission range of their senders only, and not within the range of any other transmission (addressees are hidden from any transmitter other than the sender). This conclusion is especially important when calculating a collision-free schedule in TDMA-based ad hoc networks, e.g. [8], because it can significantly raise up the channel utilisation (up to several hundred percent). Calculation results obtained for such a network would be, however, incomparable to
those achieved for a wired one, when only a single station can transmit at the time without a collision. Therefore, the only proper model for the wireless network is a centralized one, as shown on fig. 1.

Efficiency of protocols using control frames exchange – not unlike CSMA – depends upon some transmission parameters accepted for a given network. They include transmission rate and range as well as data frame length. This relation can be explained by the following formula:

\[ a = \frac{\tau}{\delta} = \frac{D_{\text{max}}/c}{l_d/v} = \frac{v \cdot D_{\text{max}}}{c \cdot l_d}, \]

where \( \delta \) – frame transmission time [s], \( \tau \) – channel propagation delay [s], \( v \) – transmission speed [b/s], \( D_{\text{max}} \) – transmission range [m], \( l_d \) – data frame length [in bits or bytes] and \( c \) – signal propagation speed [m/s]. The signal propagation speed is usually assumed equal to the speed of light, although this is true for free-space propagation only. Calculated value of \( a \) may be interpreted as relation between frame transmission time and time necessary to detect carrier by other stations. It specifies, how much of the frame is sent before all the stations find channel busy (in other words, how much of a frame is not protected by carrier detection mechanism). The value of \( a \) ranges from 0 (perfect conditions – no propagation delay, entire frame protected by carrier sense mechanism) to 1 (worst conditions – entire frame is not protected). Typically, \( a = 1 \) is also assumed for networks containing hidden stations, where carrier detection based protection is not effective. This parameter is very important for protocol performance, because the larger part of a frame is protected by

![Fig. 1. The network model accepted for considerations](image)
carrier sensing mechanism, the smaller is the collision probability and – what follows – the higher efficiency.

However, due to the usage of control frames, efficiency of control frames exchange based protocols depends also upon the relation between the length of control and data frames. It can be explained by the following equation:

\[ b = \frac{\gamma}{\delta}, \]

where \( \gamma \) and \( \delta \) are transmission times of control and data frames, respectively [8]. The value of \( b \) is usually between \( 10^{-1} \) and \( 10^{4} \); the smaller it is, the better protocol performance can be achieved, because protocol overhead is smaller. As the value of \( b \) depends on protocol properties, in some networks it may exceed this range (example values of \( b \) for few cases of wireless networks are collected in table 1). Sometimes \( b \) may be calculated in a simplified form:

\[ b = \frac{l_c}{l_d}, \]

where \( l_c \) and \( l_d \) – length of control and data frames, respectively [bits or bytes]. However, this is true only if control and data frames are transmitted at the same transmission rate. This condition is not always fulfilled. For example, in IEEE 802.11 wireless LAN standard, control frames are usually transmitted at lower rates than data. Additionally, the relation assumes that the length of all control frames (especially RTS and CTS) are equal, while in the IEEE 802.11 standard RTS lasts few bytes longer than CTS. By the way, it is worth notice that in order to improve effectiveness of RTS-CTS mechanism, CTS should be longer than RTS. Detailed analysis of this issue may be found in [2].

2.1. MACA protocol

CSMA and CSMA/CD family of protocols, quite efficient in wired and in some wireless networks, do not work well when hidden or exposed stations are present in the network. Thus, it was proposed [5] to replace carrier sensing with control frames exchange, which resulted in definition of MACA (Multiple Access with Collision Avoidance) protocol. According to [3], its efficiency may expressed as

\[ S_{\text{MACA}} = \frac{1}{e^{G(2b+a)}(b+a+\frac{1}{G}+F)+e^{Gb}(b+\frac{2}{G}+P(a-F))+1+\frac{3a}{2}+F+P(a-F)}, \]

while in the slotted version

\[ S_{s,\text{MACA}} = \frac{1}{1+4(a+b)+\frac{1}{G}e^{G(b+a)}}, \]

where \( F \) and \( P \) are defined as:
These relations are illustrated on fig. 2.

\[
F = \frac{e^{Gb} - 1 - Gb}{Gb(1 - e^{-Gb})}, \quad P = \frac{e^{-Gb} - e^{-G(b+a)}}{1 - e^{-G(b+a)}}.
\]

From the presented graph, one can say that properties of slotted and unslotted MACA visibly differ, although slotted one always outperforms the latter. While for the slotted variant, decreasing one of \(a\) or \(b\) parameters always increases throughput, regardless of the other parameter, for the unslotted variant the best throughput is usually achieved when \(a = b\). Indeed, for a given value of \(a\) (or \(b\)), both decreasing and increasing the other parameter degrades the throughput. Slotted variant shows the best performance (both efficiency and stability) for the smallest values of both parameters. In contrast, the unslotted variant shows the best stability for other set of parameters \((a = 0, b = 10^{-6})\) than the best throughput \((a = 10^{-2}, b = 10^{-4})\). The graphs also show that for the unslotted variant, decreasing \(b\) is much more important than \(a\). For the slotted variant this property is not that obvious. When network parameters are worst \((a = 1, b = 1)\), the efficiency of both variants is even much worse than of Aloha protocol. When only one of the parameters equals to 1, the efficiency slightly improves, but never higher than about 15%, which is still worse than Aloha.
2.2. FAMA protocol

FAMA (Floor Acquisition Multiple Access) protocol may be considered as superposition of MACA and CSMA as it uses both control frames exchange and carrier sense mechanisms. Its efficiency in unslotted and slotted versions is given by following equations, respectively [3]:

\[
S_{\text{FAMA}} = \frac{1}{b+1 + \frac{1}{a} (2 - e^{-4G}) + e^{4G}(b+4a)},
\]

and

\[
S_{s\text{-FAMA}} = \frac{Gae^{-Ga}}{Gae^{-Ga}(b + a + 1) + (1 - e^{-Ga})(b + 3a) + a}.
\]

These relations are illustrated on fig. 3.

![Fig. 3. The efficiency of unslotted (u) and slotted (s) FAMA protocol](image)

From the presented graph, one can see that supporting control frames exchange with carrier sense brings advantages – the resulting protocol is more efficient and more stable than without carrier detection. Thus, protection of control frames helps reduce number of collisions, which in turn results in higher throughput due to higher probability of successful transmission. Although MACA and FAMA seem quite
similar (both use the same control frames exchange method), the difference between slotted and unslotted variant in FAMA is much smaller than in MACA.

For every value of \( b \), decreasing \( a \) increases both channel utilisation and protocol stability. This can be especially observed for \( b = 1 \). When \( a = 1 \), protocol behaves much worse than Aloha (maximum channel utilisation less than 10%). Decreasing \( a \) to 0.01 helps achieve better efficiency (about 32%), which is however still lower than for slotted Aloha. Further decreasing of \( a \) (to 0.0001) does not significantly increase throughput, but improves protocol stability instead. When any of the parameters is no larger than 0.01, protocol in both versions is capable of achieving more than 90% channel utilisation for high traffic offered to the channel. In general, one can say that decreasing \( b \) improves efficiency, while decreasing \( a \) – stability.

### 2.3. DBTMA protocol

DBTMA (Dual Busy Tone Multiple Access) protocol may be considered as superposition of MACA and BTMA as it uses control frames exchange as busy-tone mechanisms. There are two versions of DBTMA protocol [1,4]. The efficiency of the initial version may be expressed as [4]:

\[
S_{DBTMA} = \frac{P_d \cdot \delta}{P_s (2 \gamma + 3 \tau + \delta) + (1 - P_s) \cdot 1.5 \gamma + 1/g},
\]

while for the modified version [1]:

\[
S_{DBTMA_m} = \frac{P_d \cdot \delta}{P_s (\delta + \gamma + t_d + 6 \tau) + (1 - P_s) \cdot 1.5(\gamma + \tau + t_d/2) + 1/g},
\]

where \( P_s = e^{-\gamma_{t}} \). In these formulas, \( \gamma \) is control frame transmission time [s], \( \delta \) – data frame transmission time [s], \( \tau \) – propagation delay [s] and finally \( t_d \) – busy tone detection time. It is worth notice that carrier detection time in CSMA protocol may be much shorter than \( t_d \) because carrier makes use of entire data channel, while busy tone must fit in narrow subchannel. Thus, detection of busy tone needs more time than of carrier. As a result, in CSMA analysis this time is usually neglected while in general case of busy-tone-based protocols it must be considered.

These relations are illustrated on fig. 3.

From the presented graph one can see, that – similarly to carrier sense – supporting control frames exchange with busy tone detection improves protocol efficiency as well. However, when \( a = 1 \), both versions of protocol behave worse than Aloha – channel utilisation never exceeds 15%. Under such circumstances, modified variant shows better throughput than the initial one. When \( a \) decreases, protocol efficiency rapidly raises even if \( b = 1 \). This efficiency improvement is especially visible for the modified variant, when \( b = 1 \), while \( a = 0.01 \) or \( a = 0.0001 \). When both \( a \) and \( b \) parameters are very small, efficiency of both variants is comparable and it cannot be
determine which one is better – it depends on actual parameter values. For example, when \(a = b = 0.01\), the modified version looks better. Further decreasing of \(a\) improves efficiency of this version more than of the initial one. However, when \(b\) is decreased, the initial version behaves more efficiently. One can therefore say, that the initial version is more sensitive to the actual value of \(b\), while the modified one depends more on the value of \(a\).

Fig. 4. The efficiency of initial (i) and modified (m) DBTMA protocol

3. Efficiency comparison

Using formulas presented above, one can compare the protocols properties under various operating conditions. It is, however, interesting how the protocols behave in typical wireless environment. Thus, few example networks have been chosen for this comparison, namely:

- Packet Radio network, with data frames containing 32 or 256 data bytes, radio transmission rate of 9600 bps and transmission range of 20 km,
- wireless LAN with parameters similar to IEEE 802.11 standard, with frames containing 256 or 2312 data bytes, radio transmission rate of 2, 11 and 54 Mbps and transmission ranges of 50, 20 and 10 metres.

The network parameter values used for this comparison, together with values of \(a\) and \(b\) parameters calculated using these values, are collected in Tab. 1.
It is worth notice, that accepted parameters are not far from real values. In fact, in IEEE 802.11 standard, RTS frame is 20 bytes long, while CTS – only 14 bytes. The largest size of data field equals to 2312 bytes, while the largest frame contains in general 2346 bytes. In Packet Radio network, neither RTS nor CTS frames are used, however, for the calculation a typical size of a control frame in AX.25 or HDLC protocol may be accepted. Using typical address length for Packet Radio (7 bytes), we get control frame size of 20 bytes. Data frames may contain up to 256 data bytes, which is supplemented by 20 bytes of control information. The analysis does not consider preambles and other physical layer mechanisms. For DBTMA, busy tone detection time value used was $t_d = 10^{-4}$ and $t_d = 10^{-6}$.

<table>
<thead>
<tr>
<th>Network type</th>
<th>Transmission rate [kbps]</th>
<th>Transmission range [m]</th>
<th>Data frame length [B]</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Radio</td>
<td>9,6</td>
<td>20000</td>
<td>52</td>
<td>0,00153</td>
<td>0,384</td>
</tr>
<tr>
<td>Packet Radio</td>
<td>9,6</td>
<td>20000</td>
<td>276</td>
<td>0,00028</td>
<td>0,072</td>
</tr>
<tr>
<td>WLAN</td>
<td>2000</td>
<td>50</td>
<td>276</td>
<td>0,00015</td>
<td>0,072</td>
</tr>
<tr>
<td>WLAN</td>
<td>2000</td>
<td>50</td>
<td>2346</td>
<td>0,00001</td>
<td>0,008</td>
</tr>
<tr>
<td>WLAN</td>
<td>11000</td>
<td>30</td>
<td>2346</td>
<td>0,00005</td>
<td>0,008</td>
</tr>
<tr>
<td>WLAN</td>
<td>54000</td>
<td>10</td>
<td>2346</td>
<td>0,00009</td>
<td>0,008</td>
</tr>
</tbody>
</table>

Tab. 1. Network parameters used for protocol efficiency comparison

Results obtained for given set of parameters are presented on figures 5 to 10.
From the presented graphs it is clearly visible, that for any given set of parameters, CSMA/CD shows the best performance. Unfortunately, this method is not applicable to most wireless environments. FAMA and MACA protocols are much more efficient for longer data frames. This is obvious, because if shorter data frames are used, the influence of control frames is stronger, giving more protocol overhead. This is explained by $b$ parameter. In turn, the influence of propagation delay ($a$ parameter) is stronger for higher transmission speeds. However, for given transmission parameters, propagation delay for Packet Radio network plays more

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1 CSMA/CD in a form known from wired networks, like Ethernet, cannot be implemented in most of wireless environments due to the capture effect and half-duplex nature of transmission hardware.
significant role because of much larger transmission range. CSMA without collision
detection is almost as good as CSMA/CD and might be used in any of considered
networks, however, for high speed WLAN’s (11 and 54 Mbps) it is outperformed by
FAMA and, partially, DBTMA. For 54 Mbps WLAN, there are regions where
slotted MACA performs better than CSMA (for \( G \) between 100 and 1000).

From the protocols considered, the worst is almost always unslotted MACA.
When short data frames are used, MACA is even worse than slotted Aloha, however,
with increasing data frame length, its channel utilisation improves up to about 45%.
Under such circumstances, its stability is also better than of slotted Aloha. Another
interesting thing is such that MACA does not depend upon transmission rate or
range, because it does not use carrier or busy-tone sensing.

Fig. 5. Protocols efficiency comparison for Packet Radio with short frames
Fig. 6. Protocols efficiency comparison for Packet Radio with long frames

Fig. 7. Protocols efficiency comparison for 2 Mbps WLAN with short frames
Fig. 8. Protocols efficiency comparison for 2 Mbps WLAN with long frames

Fig. 9. Protocols efficiency comparison for 11 Mbps WLAN with short frames
Generally speaking, the best results are obtained for 2 Mbps WLAN with long frames. Further increasing of transmission rate changes the relations important for carrier sensing, so the performance starts to decrease. However, for most cases, maximum channel utilisation of FAMA and DBTMA is comparable to that of CSMA and only slightly less than CSMA/CD. Additionally, FAMA shows better stability under extremely high channel load (i.e., when \( G \) exceeds 1000) than any other protocol that may be used in wireless networks. Sometimes – especially for 2 Mbps WLAN with long frames – it even behaves more stable than CSMA/CD.

4. Summary

The protocols presented here are more modern than those using only carrier or busy-tone sensing. In optimal conditions, i.e., when no hidden or exposed stations exist, they are a bit less efficient than usual carrier sense protocols due to control frames exchange which reduces time available for data transmission. However, in typical wireless network they are more stable and preserve higher channel throughput due to decreased number of collisions, especially between data frames. Although control frames exchange seems a good idea for wireless networks, it is not sufficient when high throughput is required; hence, they must be supported by either carrier or busy-tone sensing in order to protect from collisions not only data, but also control frames. In general, implementing control frames exchange-based protocol causes higher protocol overhead, a cost of which returns only at high loads. Therefore, one should decide whether it is necessary for a specific application.
The protocols, which use a separate control or busy-tone channel (or even both), seem have interesting properties, especially for mobile ad-hoc networks [14]. However, they are more difficult and expensive to implement than single-channel ones and therefore they are not used in any practical application.

References


Porównanie wydajności rywalizacyjnych protokołów dostępu do łącza, wykorzystujących wymianę ramek sterujących

Streszczenie

Rywalizacyjne protokoły dostępu do łącza, oparte na wymianie ramek sterujących z opcjonalnym wykrywaniem nośnej lub tonu zajętości, a zaprojektowane dla wydajnej pracy w bezprzewodowych sieciach ad-hoc, porównano pod kątem wydajności w sieci bezprzewodowej. Jako miarę wydajności przyjęto stopień wykorzystania kanału w funkcji całkowitego ruchu wprowadzanego do kanału. Porównanie wykorzystuje zależności, wyprowadzone z użyciem rachunku prawdopodobieństwa. Analizowane protokoły są specjalnie zaprojektowane pod kątem wydajnej pracy w typowej sieci bezprzewodowej, zawierającej stacje ukryte i odkryte, w której samo wykrywanie nośnej często nie wystarcza dla skutecznego unikania kolizji. Analiza uwzględnia protokoły MACA, FAMA i DBTMA i porównuje ich osiągi z CSMA i CSMA/CD.