Is Diversity Gain Worth the Pain: Performance Comparison Between Opportunistic Multi-Channel MAC and Single-Channel MAC

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***Abstract*—In this paper we analyze the delay performance of an opportunistic multi-channel medium access control scheme and compare it to that of the corresponding single channel MAC scheme. In the opportunistic multi-channel MAC scheme, we assume that the pair of sender/receiver is able to evaluate the channel quality after a certain amount of channel sensing delay and to choose the best one for data communication. We consider three settings: (1) an ideal scenario where no control channel is needed and no sensing delay is incurred, (2) a more realistic scheme where users compete for access on a control channel using random access, and (3) a scheme similar to (2) but with a Time Division Multiplex (TDM) based access scheme on the control channel. Our analysis show that in terms of delay performance, the random access overhead on the control channel almost always wipe out the channel diversity gain, which is the main motivation behind an opportunistic multi-channel MAC. Using a TDM based access scheme on the control channel can help remove this bottleneck, but only when channel sensing can be done sufficiently fast.**

I. Introduction

Recent advances in cognitive radio technologies have led to a number of dynamic multi-channel MAC schemes (see e.g., [5], [10]) that allow radios to dynamically switch between channels in search of good instantaneous channel condition. The fundamental idea is the exploitation of multi-channel diversity: if a radio is statically assigned a fixed channel, then over time it sees the *average* condition of the channel, and obtains an average rate. In contrast, if a radio is allowed to always pick a better channel (e.g., higher instantaneous received SNR) from a set of channels, then over time it sees a possibly much higher average rate.

While intuitively appealing, in practice for such schemes to work, certain control overhead becomes hard to avoid. First, a control channel is typically needed for purposes including reservation (gaining the right to use one of the data channels), homing (finding an intended destination node), and common communication (broadcasting information like channel selection, completion of transmissions, etc.). This takes away a certain amount of available bandwidth that could have been used for data communication. Secondly, it takes resources to determine which channel has better instantaneous condition. Successive channel sensing consumes energy and time [5]. This takes away time that could have been used for data communication.

The above observation motivates us to examine whether there is indeed an advantage in using dynamic multi-channel MAC, and if so under what conditions. In other words, we are interested in understanding whether the diversity gain in general can sufficiently compensate for the overhead mentioned above.

To achieve this goal, we perform the following sequence of comparisons in terms of delay performance. We start by considering an idealized opportunistic multi-channel MAC, whereby an oracle oversees channel access and has full information on the instantaneous conditions of all data sub-channels. It automatically assigns an arriving user to the best channel among those currently available. This allows us to eliminate the need for a control channel, and fully use the bandwidth for data communication: each of m data sub-channels gets bandwidth B/m. This is compared to a similar, idealized single-channel MAC. As expected, under this scenario, the multi-channel MAC has a clear advantage over the single-channel MAC due to the channel diversity gain.

We then consider a more realistic multi-channel MAC, where users must compete for access to data sub-channels on a control channel first, and this is done using RTS-CTS based random access. Once a user gains access it performs channel sensing before selecting a channel; it then announces its selection on the control channel. We assume each user has two radios, with one dedicated to the control channel so that each user is able to accurately track channel usage. This is therefore a much more efficient use of resources than that proposed in [5]. This is compared to a common random access based single-channel MAC. Under such a scenario, our main finding is that this multi-channel MAC significantly under-performs the single-channel MAC. There are two main reasons. One is that random access on the control sub-channel becomes a bottleneck as the control sub-channel is typically

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a very small portion of the overall bandwidth. The second reason is the overhead in channel sensing.

These observations led us to consider a third multi-channel MAC, similar to the second one but with a TDM type of access scheme on the control channel. The intention is to separate the effect of random access from that of sensing delay. Our finding is that while this does remove the random access on the control channel as a bottleneck, the sensing delay remains an obstacle. As a result, the multi-channel MAC only shows an advantage when channel sensing can be performed much faster than a regular RTS-CTS packet exchange.

The remainder of the paper is organized as follows. After presenting the system model in Section II, we detail the three sets of comparisons in Sections III, IV, and V, respectively. Related work is presented in Section VI and Section VII concludes the paper.

II. System Model and Preliminaries

We assume a set of n active users within a single interference domain. The total amount of bandwidth available is B. Under a single-channel MAC, this whole amount is treated as a single channel for data transmission. Under a multi-channel MAC, the amount B is divided into a single control channel of bandwidth B_c, and m equal data sub-channels each of bandwidth $B_d = (B - B_c)/m$. We will assume that these m data sub-channels are statistically identical. Furthermore, we assume that the dynamics of a channel is such that for a fixed size packet its transmission time (or service time, including retransmissions) is given by an i.i.d. exponential random variable. This models the fact that higher received SNR leads to shorter successful transmission time. These are simplifications for tractability of analysis, but do not affect the qualitative conclusions we draw from the analysis.

Each user is assumed to have two radio transceivers, one for data transmission, the other dedicated to monitoring activities on the control channel. This is an assumption in favor of the multi-channel MACs, as the second radio has no utility in a single channel system. The intention is so that a user has full information on channel occupancy: which data sub-channels are currently being used and therefore can avoid those when performing channel sensing and selection. We assume a user always picks the best of the set of currently available channels as a result of channel sensing. This is again a simplification and an assumption in favor of the multi-channel MAC. In practice a user may not get to sense all available channels.

For a single data sub-channel of bandwidth B_d, its maximum achievable rate is given by $R_d = B_d \cdot \log(1+\text{SNR})$. We will assume that the aggregated single channel has the same SNR as a data sub-channel (e.g., by assuming that users keep the bit error rate at the same level). The transmission rate of the aggregated single channel is thus given by

$$R = B \cdot \log(1 + \text{SNR}) = (B_c + m \cdot B_d) \cdot \log(1 + \text{SNR}) \ .$$

Thus when B_c is zero, the service rate of the single channel is modeled as m times that of a data sub-channel.

III. An Ideal Access Model

In an idealized scenario, an oracle has full information on the data sub-channels and immediately assigns an arriving packet to an available channel. There is also no need for a control channel. Under this scenario, we consider three schemes: the first is a single-channel MAC, the second a multi-channel MAC that does not utilize instantaneous channel information, and the third an opportunistic multi-channel MAC.

A. A single-channel MAC

Under the idealized assumption, the dynamics of a single-channel MAC may be modeled as an $M/M/1+q$ queue, where the aggregate arrival process is Poisson with rate λ, the mean service rate is $m \cdot \mu$ (μ will be taken as the mean service rate of a single data sub-channel in subsequent analysis), and the parameter q denotes a "virtual" queue size that models the fact that packets arriving to a busy channel are forced to wait. This parameter is adjustable, and can easily model an finite-queue and no-queue situation. Denoting by π_i the steady state probability of having i packets in such a system, and by $\rho = \frac{\lambda}{m\mu}$ the utilization factor, elementary queuing analysis suggests

$$\pi_{i+1} = \rho \cdot \pi_i, \ i = 0, 1, ..., q, 1 = \sum_{i=0}^{1+q} \pi_i = \sum_{i=0}^{1+q} \rho^i \pi_0$$

and the packet delay is given by

$$D_s = \frac{\sum_{i=0}^{1+q} i \cdot \pi_i}{\bar{\lambda}}, \tag{1}$$

where $\bar{\lambda} = \lambda \cdot (1 - \pi_{1+q})$.

B. Multi-channel MAC, no opportunistic access

Similarly, under this ideal scenario, we model the multi-channel MAC as an $M/M/m/m+q$ queue with an aggregate arrival rate of λ and service rate μ per server/channel. For this system the packet delay D_m is given by

$$N_q = \sum_{i=0}^{q} i \cdot \pi_{m+i}, D_m = \frac{1}{\mu} + \frac{\sum_{i=0}^{q} i \cdot \pi_{m+i}}{\bar{\lambda}} \tag{2}$$

where $\bar{\lambda} = \lambda \cdot (1 - \pi_{m+q})$. Note that we have reused the same notation π_i to denote the steady state probability in this system:

$$\pi_i = \begin{cases} \pi_0 \frac{(m\rho)^i}{i!}, & i \le m \\ \pi_0 \frac{m^m \rho^i}{m!} & m < i \le m+q. \end{cases} \tag{3}$$

C. Multi-channel MAC, opportunistic access

Under an ideal opportunistic multi-channel MAC, an arriving packet is immediately assigned to the best sub-channel among all those currently available. A packet finding all sub-channels busy will be put in a queue. We will again model this system as an $M/M/m/m+q$ queue. However, since a packet is always assigned the "best" channel among all those available, we can no longer model the service rate of a single data sub-channel as a constant μ. Indeed the characterization of the service rate is much more complicated: a particular sub-channel's service rate is strictly speaking a function of the number of available sub-channels when this sub-channel was selected. In this sense the evolution of the system state, the number of packets in the system, is no longer Markovian.

To address this difficulty, we will adopt the following approximation. We will first characterize the *average per sub-channel service rate* under such an opportunistic MAC, $\bar{\mu}$, and then use $\bar{\mu}$ as the service rate in a standard $M/M/m/m+q$ system. When there are k sub-channels available and the best one is chosen, the service rate of the chosen sub-channel has a mean of $k\mu$. And

$$\bar{\mu} = \sum_{j=0}^{m-1} (m-j) \cdot \mu \cdot \frac{\pi_j}{\sum_{i=0}^{m-1} \pi_i} \ . \tag{4}$$

Here again we have reused the notation π_i to denote the steady state probability of having i packets in this system.

Note that $1 \leq m-j \leq m$ when $j = 0, 1, \cdots, m-1$. Applying this to Equation (4), we have $\mu \leq \bar{\mu} \leq m\mu$, thus the opportunistic strategy clearly improves the service rate.

Define the utilization factor for this $M/M/m/m+q$ model as $\rho = \frac{\lambda}{m\bar{\mu}}$. Combined with the steady-state distribution of $M/M/m/m+q$ given in (3), we can solve $\bar{\mu}$ and the steady-state distributions simultaneously through the set of fixed point equations formed by (3) and (4). Define $F(\bar{\mu}) = \mu \cdot \sum_{j=0}^{m-1} \frac{\pi_j}{\sum_{i=0}^{m-1} \pi_i} \cdot (m-j)$. We have the following results.

Lemma 1. $F(\bar{\mu})$ is an non-decreasing function and concave function with respect to $\bar{\mu}$.

Lemma 2. There is only one unique fix point solution to $\bar{\mu} = F(\bar{\mu})$.

Having obtained $\bar{\mu}$, the rest of the delay analysis is similar to Section III-B, from which packet delay $D_{\bar{m}}$ is derived.

D. Delay comparison

First as $m\bar{\mu} \geq m\mu$, and D_m and $D_{\bar{m}}$ are derived from the same model, we have $D_m \geq D_{\bar{m}}$. Intuitively, for $M/M/m/m+q$ queues, the one with faster service rate experiences less delay. Consider D_s and D_m. When the traffic is light, i.e., λ is small, the delay is dominated by the service rate in which case $D_s \leq D_m$; when λ gets large, as the stability region of the single channel case is much less than the multi-channel case, the delay of single channel grows quickly; thus it is expected that $D_s \geq D_m$.

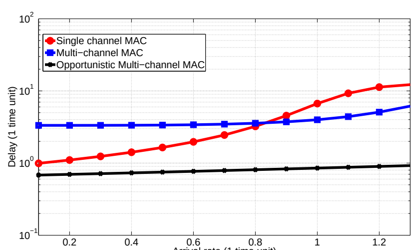


Fig. 1: Delay performance comparison for idealistic model

Analytical and simulation results shown in Fig. 1 confirm the above comparisons. Simulation parameters are: $m = 5, q = 5$ (the queue length does not have significant impact on the general results), packet length $L_d = 1024$ bits, and the same set is used throughout the paper. These results show quite clearly the benefit of exploiting multi-channel diversity when no other overhead is associated.

IV. Random Access

In this section, we turn to a more practical setting, where a control sub-channel is allocated for the users to compete for access to the data sub-channels, and the competition is through an RTS-CTS based random access scheme. This setting is close to the protocol MOAR proposed in [5], but has higher channel utilization due to the two-radio assumption.

A. An opportunistic multi-channel MAC

This prototype MAC operates in the following steps. (1) Any user having packets to send first competes on the control channel for the right to access the data sub-channels, through carrier sensing, random backoff followed by RTS-CTS packet exchange, very much like in IEEE 802.11b. (2) After the completion of RTS-CTS exchange, the pair of users enters a sensing period, where they successively probe the set of currently available data sub-channels. Exactly how this is done is left unspecified; we simply assume that certain channel sensing packets need to be exchanged between the pair, and ultimately they are able to select the sub-channel with the best current condition. (3) Upon this decision the pair sends an ACK on the control channel announcing its channel selection as well as the duration of occupancy. This serves the purpose of letting all other users accurately track which sub-channels are current busy. From this point on the reservation on the control channel and all available data sub-channels is released by the pair and other users can resume competing for access. (4) In the meantime, the pair returns to the sub-channel of their selection and perform data transmission. Note that due to the two-radio assumption, a user can continue to monitor traffic on the control channel even as it is engaged in data transmission on a data sub-channel. By contrast, under MOAR the control channel is not released until the pair has completed data transmission on a sub-channel.

The types of delays experienced by a user under this MAC are as follow. (1) D_1: time between a packet arrival till the completion of the current RTS-CTS exchange (if any). (2) D_2: time between the start of competition and when it successfully obtains the right to transmit. (3) D_3 (included in D_2): time for RTS-CTS exchange on the control channel and channel sensing. (4) D_4: time for data transmission. We have ignored the acknowledgment to release the control channel as it's typically a much smaller packet.

The derivation of D_1 and D_2 is essentially the same as in a non-opportunistic multi-channel system, and will be taken from [3]. In computing D_3, we need to reserve all available channels in order to avoid collision. This introduces extra waiting time. For a ready packet, we have $E[D_3] =$

$\sum_{i=0}^{m+q} E[D_3|i] \cdot \pi_i$. We assume that the sensing packets are of size L_s, and no larger than the RTS-CTS pair, denoted as L_c. Denote the ratio of the two: $r_{cs} = L_s/L_c$, $0 < r_{cs} \leq 1$. Also denote the ratio between the average rates of the control channel and a data sub-channel: $r = R_c/R_d$. We normalize the time to transmit one pair of RTS/CTS on the control channel to be 2 units[1]. Consider now $E[D_3|i]$ in terms of the same time unit, for $i = 0, 1, ..m-2$. As there are i busy sub-channels,

$$E[D_3|i] = \lceil \frac{m-i}{2} \rceil \cdot \frac{L_s}{R_d} / \frac{L_c}{R_c} \cdot 2 = 2 \lceil \frac{m-i}{2} \rceil \cdot r_{cs} \cdot r \ . \quad (5)$$

In the above calculation the number of sensing packets (pairs) is taken to be $\lceil \frac{m-i}{2} \rceil$ rather than $m-i$ as the two radios can potentially both be used during the sensing phase. We thus have $E[D_3|j] = 0$. Following the results in [2], the average completion rate is given by

$$\lambda = \frac{Ge^{-2G}}{1 + (1 + r \cdot r_{cs} \cdot E[cs])Ge^{-2G}} \ , \quad (6)$$

where G is the aggregated arrival (including retransmission) on the control channel in one time unit, and $E[cs]$ is the expected number of channel sensing performed: $E[cs] = \sum_{i=0}^{m-2} \lceil \frac{m-i}{2} \rceil \pi_i$ (in time units). Subsequently D_2 and D_1 are given by [3] as $E[D_2] = E[N] \cdot E[Z]$, where $E[N]$ is the expected retransmission time, while Z is the completion time for one successful RTS/CTS contention.

$$E[Z] = \frac{(e^{2G} - 1)(1/\zeta + 2) + 2 + E[D_3]}{1 - \pi_{m+q}} \ , \quad (7)$$

where $1/\zeta$ is the average delay due to random backoff. The delay caused by an arrival during RTS/CTS transmission is

$$E[D_1] = \frac{1}{\lambda} + \frac{1}{\zeta} - (E[D_3] + 1 + \frac{1}{\lambda} + \frac{1}{\zeta})e^{-(E[D_3]+1)\lambda} \ .$$

Finally, following the earlier model $E[D_4] = \frac{\sum_{j=0}^{m+q} j \cdot \pi_j}{\lambda(1-\pi_{m+q})}$.

B. Delay comparison

The delays of single and multi-channel MACs under random access have been calculated in [3] to be

$$\begin{aligned} E[D_{single}] &= \frac{L_c}{R}\{(e^{2G} - 1)(1/\zeta + 2 + r_d) + 2 + 1/m\mu \\ &\quad + 1/\lambda + 1/\zeta - [r_d + 1 + 1/\lambda + 1/\zeta]e^{-(r_d+1)\lambda}\} \\ E[D_{multi}] &= \frac{L_c}{R_c}\{\frac{(e^{2G} - 1)(1/\zeta + 2) + 2}{1 - \pi_{m+q}} + \frac{\sum_{j=0}^{m+q} j \cdot \pi_j}{\lambda(1 - \pi_{m+q})} \\ &\quad + 1/\lambda + 1/\zeta - [1 + 1/\lambda + 1/\zeta]e^{-\lambda}\} \ . \end{aligned}$$

For the opportunistic multi-channel MAC we have

$$\begin{aligned} E[\bar{D}_{multi}] &= \frac{L_c}{R_c}\{\frac{(e^{2G} - 1)(\frac{1}{\zeta} + 2) + 2 + 2rr_{cs}E[cs]}{1 - \pi_{m+q}} + \frac{1}{\lambda} \\ &+ \frac{\sum_{j=0}^{m+q} j \cdot \pi_j}{\lambda(1 - \pi_{m+q})} + \frac{1}{\zeta} - [E[D_3] + 1 + \frac{1}{\lambda} + \frac{1}{\zeta}]e^{-(E[D_3]+1)\lambda}\} \ . \end{aligned}$$

[1]The actual quantity is unimportant as all other quantities will simply get scaled.

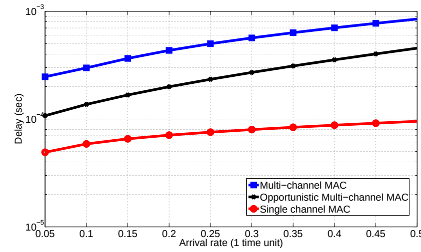


Fig. 2: Delay performance comparison for random access

Define $r_d = \frac{L_d}{L_c}$. The following set of results compare the delay of these three systems quantitatively.

Theorem 1. When r_d gets large, $E[\bar{D}_{multi}] \geq E[D_{single}]$.
Theorem 2. When r_d gets large, $E[D_{multi}] \geq E[D_{single}]$.
Theorem 3. For r_{cs} close to 0, $E[\bar{D}_{multi}] \geq E[D_{single}]$.

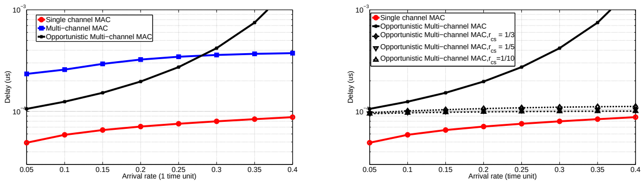
The numerical results are shown in Fig. 2. In the simulations the control packet length is set to $L_c = 48$ bits. We also assume that channel sensing is performed using RTS-CTS packet exchanges, i.e., $r_{cs} = 1$. The overall channel data rate is 35 Mbps; the back-off parameter $1/\zeta$ is set to 37 time units. Similar parameters are used in Section V. We see from Fig. 2 as well as our analytical results that even though the opportunistic strategy helps improve delay performance, the random access on the control channel eliminates any potential gain from channel diversity. This holds even when the channel sensing overhead is significantly lowered or eliminated.

V. Time-Division Multiplexing (TDM) Access

The observation that the random access on the control channel poses a significant bottleneck to the system performance motivated us to consider an alternative access scheme on the control channel. We now consider a TDM based access scheme on the control channel while keeping other features unchanged. Again we assume the total arrival rate on the control channel is given by λ (including retransmission). Also for simplicity, we assume all users have the same arrival rate (λ/n).

A. TDM-based non-opportunistic multi-channel MAC

We identify two types of delays in a TDM-based multi-channel system: (1) D_1, time between the arrival of a packet and when it gains right to transmit; (2) D_2, time for data transmission. We normalize the time for transmitting one pair of control packets to 2 and in this case $\mu = 1$ (for serving one control packet). For D_1, standard results on TDM yield the following delay on a single attempt: $\frac{n}{\mu - 2\lambda} = \frac{n}{1-2\lambda}$. The expected number of transmission times N on the control channel is given by $E[N] = 1/(1 - \pi_{m+q})$. Thus we have $E[D_1] = E[N] \cdot E[T_1] = \frac{n}{(1-2\lambda)\cdot(1-\pi_{m+q})}$. Note that the rate of completing RTS/CTS exchange on the control channel is also λ. Following earlier analysis we have $E[D_2] = \frac{\sum_{j=0}^{m+q} j \cdot \pi_j}{\lambda(1-\pi_{m+q})}$ and $E[D_{multi}] = \frac{L_c}{R_c}\{E[D_1] + E[D_2]\}$.



(a) $r_{cs} = 1$ (b) different r_{cs}

Fig. 3: Numerical results for delay performance comparison

B. TDM-based Opportunistic Multi-Channel MAC

Under a TDM-based opportunistic multi-channel MAC scheme, the pair of users first performs RTS/CTS exchange on the control channel followed by channel sensing; they then announce their decision on the control channel, all within the same TDM time slot. They then perform data communication in the selected sub-channel while other users continue on the control channel. As before we normalize the RTS-CTS exchange on the control channel to be 2. The time till the completion of channel sensing is thus $2 + 2 \cdot r \cdot r_{cs} E[cs]$.

We define and compute delay for TDM-based opportunistic multi-channel MAC the same as TDM-based multi-channel MAC in Section V-A, the only difference lies in $E[D_1]$:

$$E[D_1] = \frac{n}{[1 - 2 \cdot (1 + r \cdot r_{cs} \cdot E[cs]) \cdot \lambda] \cdot (1 - \pi_{m+q})} . \quad (8)$$

C. Delay comparison

Consider first the results shown in Fig. 3a, where we have set $n = 5$. We see that the two TDM based multi-channel schemes continue to under-perform their single-channel counterpart. The TDM scheme's advantage starts to emerge as we lower the sensing delay by using a smaller r_{cs}. This is shown in Fig. 3b as we repeat the same experiment with even smaller r_{cs}. Specifically, this advantage is shown at high arrival rates, when the amount of collision increases under the random access scheme (in the single-channel MAC). These results show that the bottleneck in the TDM-based opportunistic multi-channel scheme lies in the inefficiency of channel sensing. Unless the sensing overhead can be reduced to 1/5 or less of the size of RTS-CTS transmission, the opportunistic multi-channel MAC scheme significantly under-performs the single-channel MAC scheme.

VI. Related works

For performance improvement consideration, researchers proposed to split single channel into multiple sub channels with one used as control channel and the others used as data channels. Related works on split channel can be found in [8], [11], [13]. RTS/CTS exchanges are then performed on the control channel [4], [6]. In [7], a multi-channel CSMA/CD protocol was investigated. Marsan and Neri concluded that multi-channel may improve the delay performance compared to single channel. Xu et al. suggested the use of multiple receivers on a single node [12]. With the help of improvement on hardware implementation efficiency, multiple receivers scheme becomes more practical. In [2], [3], Deng et al. presented a queue model for analyzing random access multi-channel MAC scheme (without diversity gain) and concluded that multi-channel MAC scheme would not improve either delay or throughput performance compared to single channel MAC. In [1], [5], [9], opportunistic channel selection algorithms were investigated with system performance evaluated experimentally and mathematically. There however lacked a general model for analyzing the delay performance of these strategies.

VII. Conclusion

We analyzed the delay performance of opportunistic multi-channel MAC and their single-channel counterparts. Our general conclusion is that while there is significant channel diversity gain in using the former, the overhead is also significant, in the form of a much slower access rate on the control channel and the cost in channel sensing. Using a TDM based access scheme on the control channel can help remove the first bottleneck, but only when channel sensing can be done sufficiently fast.

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