A Quantitative Comparison of Multiple Access Control Protocols for Integrated Voice and Data Services in a Cellular Wireless Network

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Abstract— **The multiple access control (MAC) problem in a wireless network has intrigued researchers for years. An effective MAC protocol is very much desired because efficient allocation of channel bandwidth is imperative in accommodating a large user population with satisfactory quality of service. MAC protocols for integrated data and voice services in a cellular wireless network are even more intricate to design due to the dynamic user population size and traffic demands. Considerable research efforts expended in tackling the problem have resulted in a myriad of MAC protocols. While each protocol is individually shown to be effective by the respective designers, it is unclear how these different protocols compare against each other on a unified basis. In this paper, we quantitatively compare six recently proposed TDMA-based MAC protocols for integrated wireless data and voice services. We first propose a taxonomy of TDMA-based protocols, from which we carefully select six protocols, namely CHARISMA, D-TDMA/VR, D-TDMA/FR, DRMA, RAMA, and RMAV, such that they are devised based on rather orthogonal design philosophies. The objective of our comparison is to highlight the merits and demerits of different protocol designs.**
Keywords: Multiple access protocols, cellular wireless networks, adaptive channel coding, TDMA, integrated voice and data.

I. INTRODUCTION

The problem of allocating channel bandwidth to uncoordinated, geographically distributed, and possibly mobile users in a TDMA-based wireless network, called the *multiple access control* (MAC) problem, has intrigued researchers for quite some time. Due to its real-time and statistical nature, obtaining a deterministically optimal allocation is intractable, and thus, heuristic techniques are commonly sought in MAC protocol design. Furthermore, because efficient utilization of the channel bandwidth is imperative for accommodating a large number of distributed and/or mobile users, the MAC problem continues to spur interests among the research community. Thus, considerable research efforts expended in tackling the problem have resulted in a myriad of MAC protocols [1], [2], [4], [11] targeted for different environments such as packet radio networks, satellite networks, wired LANs, and cellular wireless networks. While each protocol is individually shown to be effective by the respective designers, it is unclear how these different protocols compare against each other on a unified basis. In this study, we quantitatively compare the performance of a set of TDMA-based MAC protocols for integrated wireless voice and data services. The protocols considered are carefully selected from the literature in that they are devised based on rather orthogonal design philosophies. The major objective of the comparison is to highlight the relative strengths and weaknesses of different protocols.

The classical design of a MAC protocol is to arbitrate and statistically multiplex the transmission requests of multiple uncoordinated users and allocate transmission bandwidth to the users in a fair manner. Notorious examples include the ALOHA protocol for a packet radio network and the CSMA/CD protocol for a wired local area network. The key feature of the classic design is that all users are homogeneous—they have the same traffic characteristics. However, in our study, we consider a wireless communication system for integrated voice (i.e., isochronous traffic) and data services (i.e., bursty traffic), for which an effective and intelligent MAC protocol is particularly desired due to the sharing of the precious bandwidth by a dynamically changing population of users with various traffic demands. In this regard, a plethora of MAC protocols [2], [6], [11] have been suggested in the literature for supporting integrated voice and data traffic. As detailed in Section II, there are four aspects in characterizing these MAC protocols:

- *Request Mechanism*: The mechanism of receiving user requests critically affects the performance of a MAC protocol. For example, in some contention based protocols, too much contention (e.g., a large number of active users) will result in system instability such that users keep on contending without success due to excessive collisions. Under such a *thrashing* situation, most of the information slots are not used. Different protocols employ various techniques

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to combat this problem.

- *Slots Allocation*: In most MAC protocols, information slots are assigned on a first-come-first-basis and can be reserved in subsequent frames if the user is a voice terminal. However, some recently proposed protocols employ more intelligent approaches to further enhance the channel utilization.
- *Frame Structure*: Traditionally, the frame is of a static structure. That is, for example, there is a fixed portion of the frame dedicated for receiving transmission requests, while the remaining portion is for information slots. A major merit of a static frame structure is the ease of implementation and is energy efficient for the mobiles, which do not need to listen to the channel all the time. Some other protocols, however, employ a dynamic frame structure, with the objective to utilize the bandwidth more efficiently.
- *Performance*: The capacity of the network and quality of service (QoS) depend critically on the performance of the MAC protocol in terms of packet dropping rate, delay, throughput, and utilization.

A scrutiny of the above four aspects reveals a large design space for MAC protocols. Indeed, based on these four dimensions, we introduce a simple taxonomy of recent MAC protocols suggested in the literature for integrate wireless voice and data services. With the taxonomy, six MAC protocols, designed based on radically different philosophies, are selected for an extensive performance comparison. The protocols chosen are:

- RAMA [1]: resource auction multiple access, a protocol that employs a collision avoidance approach;
- RMAV [4]: reservation-based multiple access with variable frame, a protocol with a dynamic frame with variable length, designed to achieve a short delay at light load and high throughput at high load;
- DRMA [11]: dynamic reservation multiple access, a protocol with a dynamic frame structure in which the portion of bandwidth designated for user requests is dynamically adjusted, designed to maintain system stability at high load;
- D-TDMA/FR [11]: a traditional dynamic TDMA protocol with a static frame structure;
- D-TDMA/VR [5]: a dynamic TDMA protocol based on a channel-adaptive variable-throughput physical layer;
- CHARISMA [8]: channel-adaptive reservation-based isochronous multiple access, a dynamic TDMA protocol in which the MAC protocol and a variable-throughput physical layer are closely integrated in a fully channel-adaptive manner in order to achieve more judicious bandwidth allocation [7], [9].

We have implemented all the six protocols on a common simulation platform, from which extensive performance results are obtained. Three performance metrics, namely voice packet dropping rate, data delay, and data throughput, are considered. The balance of this paper is as follows. In Section II, we present a detailed scrutiny of the TDMA-based MAC problem, with the help of a simple taxonomy. Section III contains the performance results and our interpretations. The final section provides some concluding remarks.

II. TDMA-Based MAC Protocols

In this section, we first introduce the user models. We then describe a taxonomy of MAC protocols, which serves as a design framework to facilitate the interpretations of quantitative comparisons. As such, with the performance results, the merits and demerits of different protocols can be identified.

A. Models

The wireless system consists of two types of mobile terminals, namely the voice terminal and the data terminal in the system. Voice packets are assumed to be delay sensitive while data packets are assumed to be delay insensitive. Thus, voice packets are labeled with *deadlines*. A voice packet will be dropped by a voice terminal if the deadline expires before being transmitted. Such packet dropping has to be controlled to within a certain limit (e.g., below 1% as indicated in [3]) in order that the quality of service to the voice users is still acceptable. The source and contention models are summarized below.

- **Voice Source Model:** The voice source is assumed to be continuously toggling between the talkspurt and silence states. The duration of a talkspurt and a silence period are assumed to be exponentially distributed with means t_t and t_s seconds, respectively (as indicated by the empirical study in [10], $t_t = 1$, and $t_s = 1.35$). We assume a talkspurt and a silence period start only at a frame boundary.
- **Data Source Model:** The arrival time of data generated by a data terminal is assumed to be exponentially distributed with mean equal to one second. The data size, in terms of number of packets, is also assumed to be exponentially distributed with mean equal to 100 packets. Again we assume that the packets arrive at a frame boundary.
- **Terminal Contention Model:** As in most previous studies, to avoid excessive collisions, even if a voice or data user has some packets awaiting to be sent, the user will attempt to send a request at a request mini-slot only with a certain *permission probability*. The permission probability for voice and data users are denoted by p_v and p_d, respectively.

B. A Taxonomy of TDMA-Based MAC Protocols

Figure 1 depicts a partial taxonomy of TDMA based MAC protocols considered in our study. In a TDMA-based protocol, time is divided into slots, which are grouped into frames. The slots, more specifically the information slots, are for users to transmit information packets. In general, the users contend for information slots on a frame-by-frame basis. There are two types of TDMA-based protocols: pure TDMA and *dynamic* TDMA (D-TDMA). In a pure TDMA protocol, the slots assignment, determined statically, is fixed throughout the communication process without regard to the actual requirements of the users. Thus, even if a user does not have any information packet to send, the assigned time slot is still occupied and, therefore, is wasted. In view of the poor utilization and inflexibility, pure TDMA protocols are not used in the cellular wireless networks considered in this paper, due to the dynamic users population involved. D-TDMA was first introduced for satellite communications and has been proposed recently as a candidate MAC protocol for the third-generation wireless communication systems [11]. There are many variations of D-TDMA based MAC protocols [2], [6]. Despite that these protocols are different in many detailed aspects, they can nevertheless be described by a common framework. Time on the channel is also divided into a contiguous sequence of TDMA frames, which are subdivided into request slots and information slots. The information slots are sometimes further classified into voice and data slots. There are two types of packets being transmitted in the channel, namely the *request packet* and the *information packet*. A request packet is used for the request of information slot (either voice or data slots). It often includes only very small of amount of information, namely the origin and the destination addresses, and is therefore usually much shorter than a information packet. The request subframe is usually operated using the slotted-ALOHA protocol.

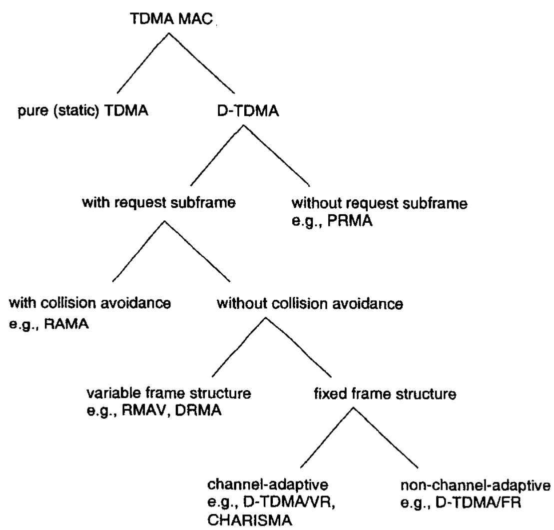


Fig. 1. A taxonomy of TDMA-based MAC protocols.

Goodman et al. [2] pioneered the research in devising effective MAC protocols for combining voice and data services, and suggested the well known PRMA (packet reservation multiple access) protocol, which is TDMA-based scheme designed based on the R-ALOHA protocol. The PRMA protocol works by dividing the uplink TDMA frame into equally spaced information slots, for which the users contend in order to transmit information packets. Voice users enjoy a higher transmission priority in that once a voice user successfully seizes a time slot, he/she can keep on using the same slot in every succeeding frames until the talkspurt ends. Because using information slots for contention can lead to low utilization and system throughput, many researchers then proposed improved variants of the PRMA protocol [6], [10], [11].

A terminal entering a new voice talkspurt or generating a new stream of data packets transmits an appropriate request packet in one of the request slots of the next frame. If there are more than one packet transmitted in the same request slot, collision occurs and none of the requests will be correctly received (we ignore the capture effect in this paper). At the end of each request slot, the successful or unsuccessful request will be identified and broadcast by the base station. Due to the short propagation delay in a cellular network, the mobile terminals can immediately know the request result. An unsuccessful user can retry in the next request slot. On the other hand, a successful user then transmits his/her information packet in the corresponding information slot in the current frame.

The D-TDMA protocols with a request subframe can be further classified into two types: with and without collision avoidance. The objective of collision avoidance is to further optimize the utilization of channel bandwidth. The rationale is that if two requests collide, the request mini-slot in the request subframe may be wasted (if the capture effect is considered, one of the request, with a higher signal power, may be successfully received despite the collision). If the traffic load is too high, thrashing may occurs in that the users keep on contending without success (i.e., too many collisions) and the system becomes unstable. However, collision avoidance also involves signaling overheads. One very well known collision avoidance MAC protocol is the RAMA (resource auction multiple access) protocol [1]. In the RAMA protocol, the channel information slots are "auctioned" to the users. In simple terms, the users bid for information slots using randomly generated IDs—a larger ID wins the auction. At the expense of a larger auction slot and hardware overheads than a request slot, collision is completely avoided. The protocols without collision avoidance can be further divided into two categories: variable frame structure and fixed frame structure. In the former category, the frame structure, in terms of frame length (in the RMAV protocol [4]) or frame format (in the DRMA protocol [11]), is varied over time. The objective is to optimize the bandwidth usage for requesting and information transmission. Finally, in the fixed frame structure category, some recently proposed protocols (e.g., D-TDMA/FR and CHARISMA) use a variable-throughput frame supported by a channel adaptive physical layer.

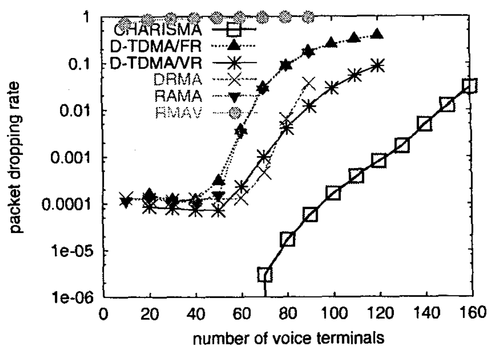
In general, these previous protocols attempt to accommodate more data users, which do not impose constraints on data delay, by exploiting the silence gaps of the voice users, which require bounded-delay packet transmission and hence, enjoy a higher transmission priority than data users in that reservation is allowed for the former but not the latter. However, while sophisticated slot allocation strategies with articulated frame structures are proposed in these methods, most of them considers the effect of burst channel errors on protocol performance (D-TDMA/FR and CHARISMA are exceptions), let alone the investigation of exploiting the error characteristics to enhance performance. Essentially, these previous protocols are designed and analyzed based on the assumption that packet transmission through the wireless channel is error-free. Indeed, because the geographically scattered mobile users inevitably suffer from different degrees of fading and shadowing effects, a common drawback of previous MAC protocols is that they assume the underlying physical layer always delivers a constant throughput, and as such, they may not be able to effectively utilize the precious bandwidth when the channel condition is swiftly varying among different users.

III. Performance Results

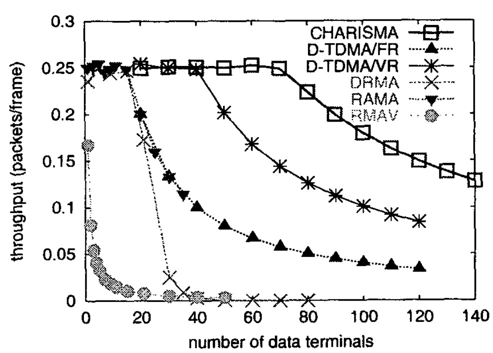
We have implemented the six MAC protocols on a common simulation platform. In our experiments, we assume a transmission bandwidth of 320 KHz for the TDMA frames. Bit rate of the speech terminals is 8 Kbps which conforms to the values in GSM and CDMA systems.

The performance of the six protocols in terms of packet loss rate versus the number of active voice user is shown in Figure 2(a) for cases with and $N_d = 0$ (the case with $N_d = 10$ is not shown here due to space limitations).

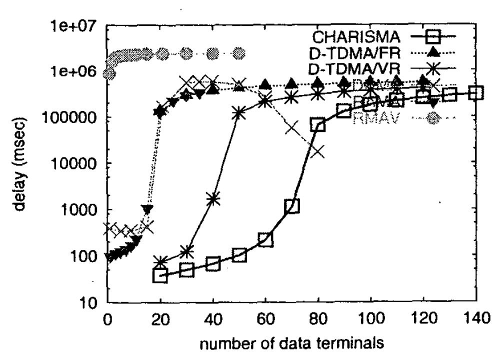
A glance at the results clearly reveals that the CHARISMA protocol outperforms the other five protocols by a considerable margin in terms of voice packet dropping rate, while the relative rankings among the other fives are not very consistent in the six test scenarios. In addition, at low traffic low, the CHARISMA protocol almost incurs no packet loss but the other five protocols still have a certain level of packet loss. A close scrutiny reveals that such low load losses are due to transmission errors. Another general observation is that the RMAV protocol quickly becomes unstable even with a moderate number of voice users (e.g., 10). This demonstrates clearly that providing just one request contention opportunity can easily lead to instability. Specifically, consider the case with $N_d = 0$ (see Figure 2(a)). At the 1% voice packet dropping rate threshold, we can see that CHARISMA can accommodate approximately 160 voice users, while both DRMA and D-TDMA/VR can support only about 100 voice users (the former is slightly better than the latter in this case). Furthermore, the number of voice users supported by both RAMA and D-TDMA/FR is about 60. Thus, for this test scenario ($N_d = 0$), the ranking of the six protocols is: CHARISMA, D-TDMA/VR, DRMA, RAMA, D-TDMA/FR, RMAV. In the case where $N_d = 10$ (not shown here), all the protocols can only accommodate about 80% of the number of voice users compared with the case in which $N_d = 0$. However, the protocol ranking is the same as in the previous case. To summarize, these results indicate



(a) voice packet dropping rate for $N_d = 0$



(b) data throughput for $N_v = 0$



(c) data throughput for $N_v = 0$

Fig. 2. Performance comparison.

the following findings:

- With the intelligent CSI dependent scheduling, the CHARISMA protocol is able to utilize the bandwidth much more effectively. Indeed, because the scheduling process avoids allowing requests with poor channel states to get information slots, packet loss due to transmission errors is greatly reduced. Furthermore, at high load, the CHARISMA protocol can keep the packet dropping due to timeout at a low level.
- Despite that D-TDMA/VR also employs a variable-throughput physical layer, it does not outperform DRMA and RAMA by a great margin (i.e., those with fixed-throughput physical layer). Indeed, by examining the simulation traces, we find that the major benefit of using a variable-throughput physical layer in D-TDMA/VR is that packet loss due to transmission errors is reduced due to the added protection. Thus, it appears that exploiting the synergistic effect between the MAC and physical layer (i.e., the CSI dependent scheduling in CHARISMA protocol) is much more important than using the variable-throughput physical layer alone.
- The RAMA protocol, with its collision avoidance property, exhibits a much more graceful performance degradation compared with CHARISMA, D-TDMA/VR, D-TDMA/FR, and RMAV, when the traffic load becomes very high. Similarly, the DRMA protocol also does not become unstable when system load is high due to its dynamic frame structure, which simply does not allow users to make requests at high load.
- When there are data users in the system, the request contention load becomes much higher because a data user repeatedly transmits requests until information slots are granted, as governed by the data permission probability p_d. Furthermore, as a data burst may consist of a few tens of packets, a data user that successfully gets some information slots may also repeat transmitting requests because reservation is not allowed for data users. Thus, every protocol accommodates less voice users when there are data users in the system.

Figures 2(b) and (c) illustrate the performance of data terminals in terms of throughput and delay, respectively. Again, the CHARISMA protocol outperforms the other five protocols by a great margin and the RMAV protocol very quickly becomes unstable. In addition, the rankings in terms of throughput and delay are quite consistent: CHARISMA, D-TDMA/VR, DRMA, RAMA, D-TDMA/FR, RMAV. When the traffic load is high, the system is in a highly congested state so that the average per-user throughput drops and the average per-user delay also increases dramatically. These adverse phenomena are detrimental to the data users' quality of service (QoS), which depends critically on the parameters pair `(delay, throughput)`. For example, at a QoS level of `(1 sec, 0.25)`, the capacity of the CHARISMA protocol is approximately 1.5 times that of D-TDMA/VR, and 3 times that of RAMA and DRMA. Other results also concur with these observations.

IV. Conclusions

Our quantitative performance study reveals that using a variable-throughput physical layer (in the CHARISMA and D-TDMA/VR protocols) can help reducing voice packet dropping due to transmission errors. In addition, protocols with contention collision avoidance (i.e., the RAMA protocol) and protocols with a controlled requesting process (i.e., the DRMA protocol) can provide a high system stability such that performance degrades gracefully even when the traffic load is very high. Furthermore, request queues generally can help improving system performance because the request contention is greatly alleviated. Finally, in view of the fact that the CHARISMA protocol outperforms the other five protocols by a considerable margin, the knowledge of the channel condition reported to the MAC layer by the physical layer (in the CHARISMA protocol) is indeed a very useful component in achieving even higher performance in a wireless communication system where burst errors are the norm rather than exception.

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