MAC for Dedicated Short Range Communications in Intelligent Transport System

Jing Zhu and Sumit Roy, University of Washington

ABSTRACT

The need for critical improvements to the North American surface transportation infrastructure vis-a-vis alleviation of congestion while enhancing public safety has led to new intelligent transportation system (ITS) infrastructure based on *vehicle-to-vehicle* (v2v) wireless communications. The allocation of 75 MHz in the 5.9 GHz band for dedicated short-range communications (DSRC) may also enable future delivery of rich media content to vehicles at short to medium ranges via *vehicle-to-roadside* (v2r) links. Recently, ASTM Committee E17.51 endorsed a variant of the IEEE wireless LAN standard, denoted 802.11a Roadside Applications (R/A), as the platform for the DSRC link and data link layer. In this article we provide a tutorial overview of DSRC applications and assess IEEE802.11 PHY and MAC layer characteristics in this context. It is anticipated that current 802.11 specifications will need to be suitably altered to meet requirements for DSRC environments of multihop connectivity, high vehicle mobility, and heterogeneous services with a variety of QoS requirements for which the original design was not intended. This article captures the current state of the art of 802.11-based multiple access protocols and highlights open research issues.

INTRODUCTION

Intelligent transport system (ITS) architecture provides a framework for the much needed overhaul of the surface transportation infrastructure. The immediate impacts include alleviation of traffic congestion and improved operations management in support of public safety goals such as collision avoidance. Instrumenting vehicles with onboard sensors of various kinds and vehicle-to-vehicle (v2v) communications capability will allow large-scale sensing, decision, and control actions in support of these objectives. The allocation of 75 MHz in the 5.9 GHz band for licensed dedicated short-range communications (DSRC) use may also enable future delivery of rich media content to vehicles at short to medium ranges via vehicle-to-roadside (v2r) links. The central role of new wireless DSRC technology in meeting the above goals is self-evident and is the focus of this article.

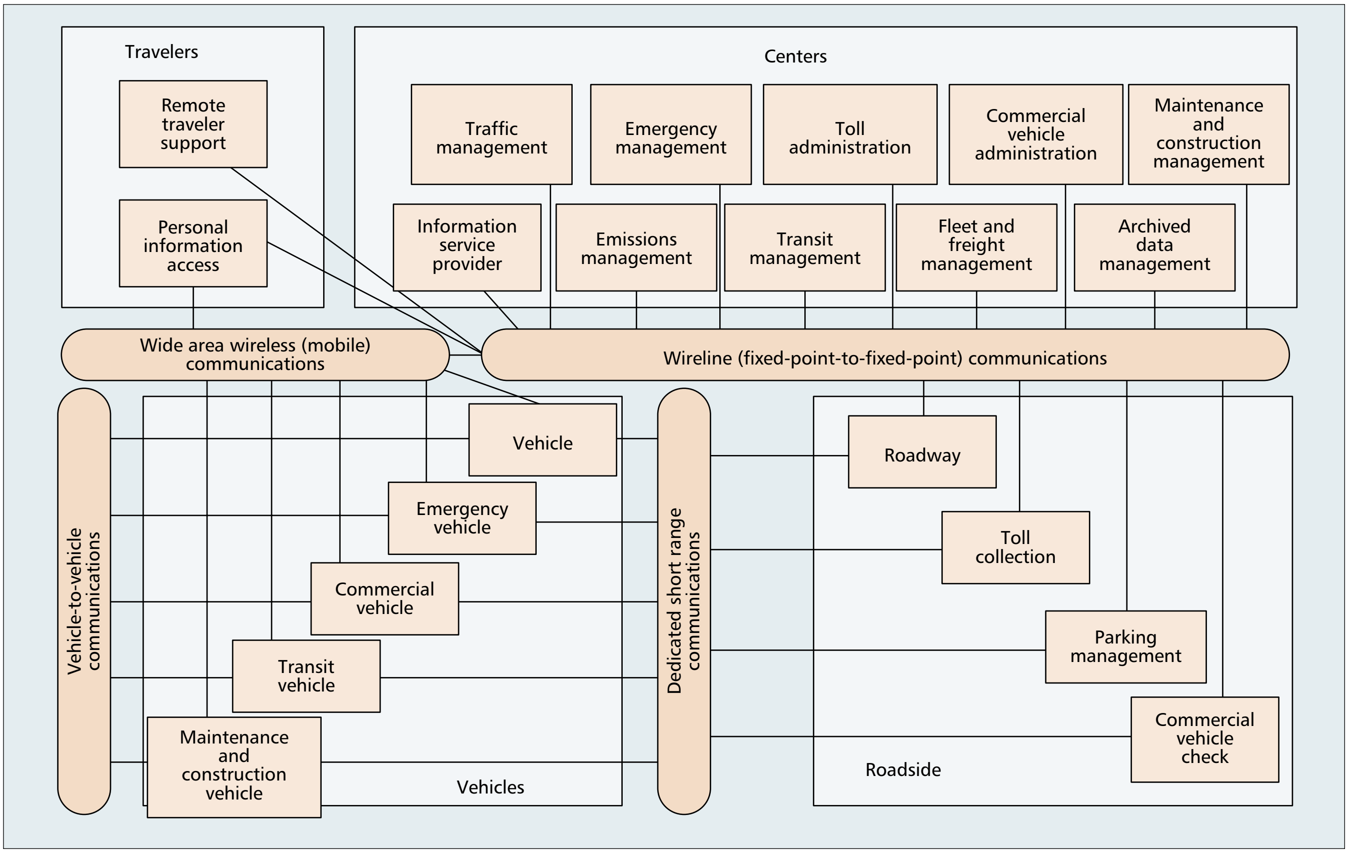
Figure 1 shows a proposed ITS architecture inclusive of DSRC modalities such as v2v and v2r communications in support of various applications. Figure 2 shows the 75 MHz spectrum allocation in the 5.9 GHz band by the FCC in 1999 for DSRC; Fig. 3 outlines the North American DSRC standard structure suggested by the American Society for Testing and Materials (ASTM) Committee E17.51, which endorses a variation of the IEEE wireless LAN standard, denoted 802.11a Roadside Applications (R/A), for the DSRC link and data link layer. There are provisions for three types of channels (Fig. 2) — v2v channel (ch172), control channel (ch178), and v2r service channel (ch174, 176, 180, 182). The control channel is used mainly for broadcast-type traffic, although some sort of unicast communication can be performed by inserting the destination address into a medium access control (MAC) frame. Therefore, the IEEE802.11 MAC protocol primarily supports communication on v2v and v2r service channels, corresponding to two basic scenarios (akin to current 802.11 networks) shown in Fig. 4a: an ad hoc mode characterized by *distributed mobile multihop networking* that allows vehicles in a fleet to communicate peer-to-peer directly; and Fig. 4b: an infrastructure mode characterized by a *centralized mobile one-hop network* for communication between vehicle to fixed roadside hubs.

DSRC APPLICATIONS

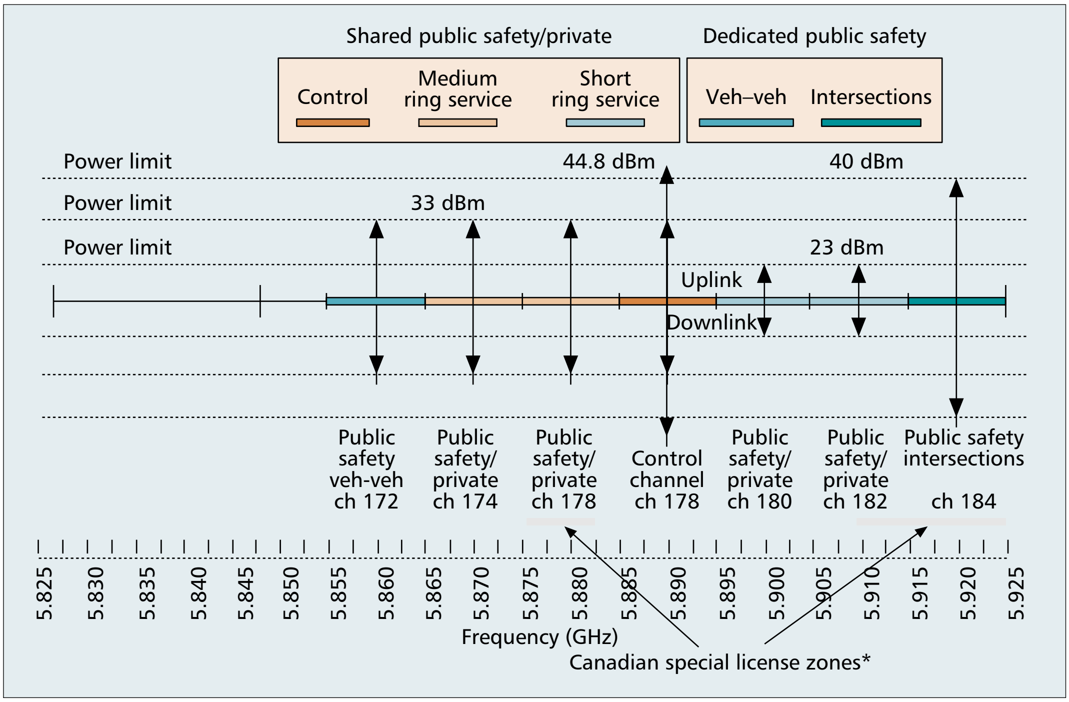
Gigahertz DSRC is a short-to-medium-range communications service that supports both public safety and private operations in v2r and v2v environments. DSRC v2r links must support very

This work was supported by Ford Motor Co. through its Transportation Infotronics Grant. The authors wish to acknowledge helpful discussions with Dr. K. Venkatesh Prasad, Head of Infotronics Research & Adv. Engineering Group, Ford Motor Co.

0163-6804/03/$17.00 © 2003 IEEE



■ **Figure 1.** *ITS architecture (http://itsarch.iteris.com/itsarch/html/entity/paents.htm).*



■ **Figure 2.** *5.9 GHz DSRC band plan with 10 MHz channels and power limit.*

high data transfer rates while minimizing latency in the link over short ranges, much like present-day 802.11 hotspots.

The North American DSRC program is intended to support a wide range of applications, of which only a small subset are presently defined. The following broad classes of applications are envisaged:

- **Public safety** — to reduce traffic accidents
- **Traffic management** — to improve the flow of traffic, reducing congestion
- **Traveler information support** — to provide

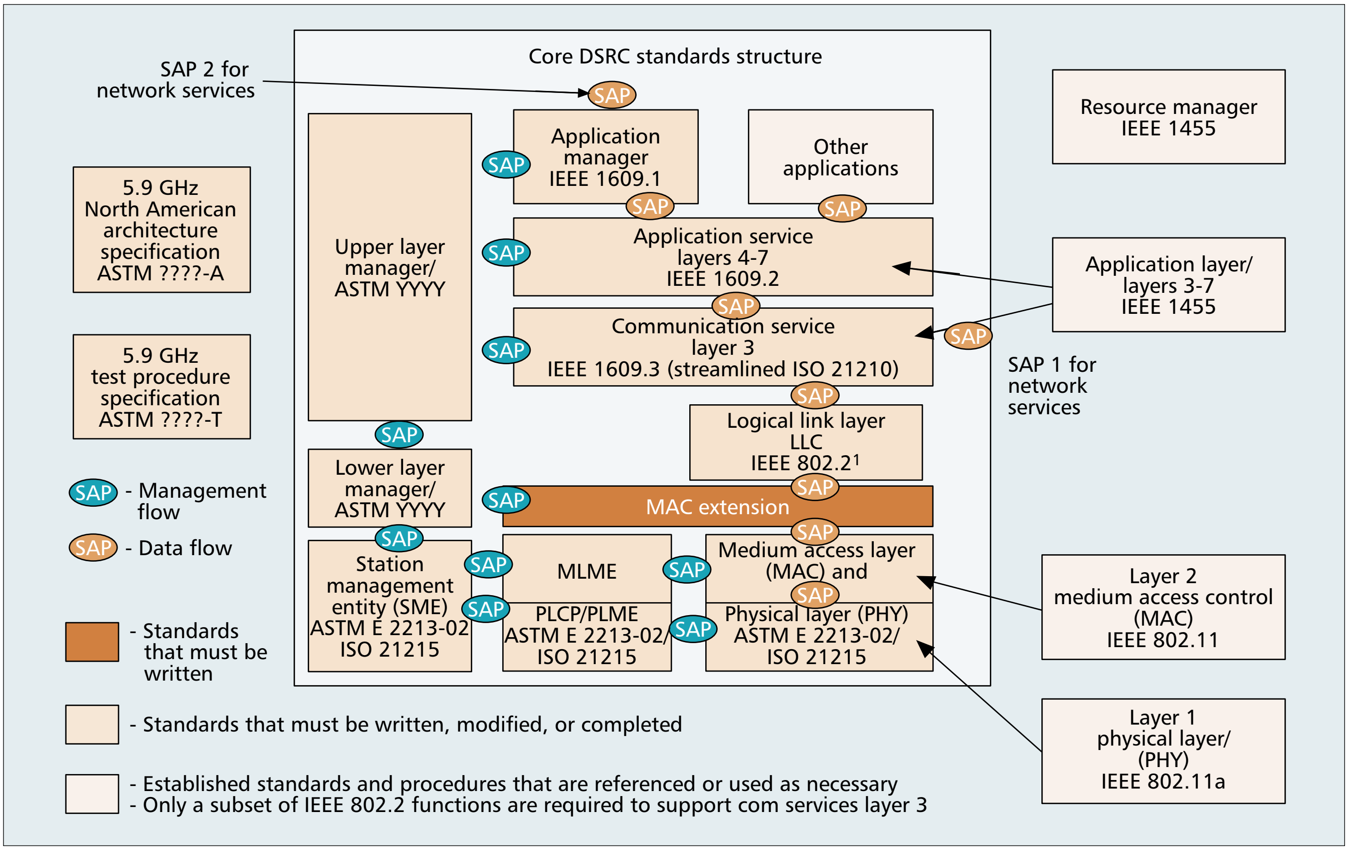


Figure 3. *North American DSRC standards structure.*

a great variety of travel-related timely information, such as electronic maps, and road and weather information

- **Entertainment/rich media content delivery** — Internet access, infotainment (news, sports, movies, etc.) on demand

Three stages in developing DSRC devices and their respective timeframes were identified as follows:

Early adopter device: largely self-contained, minimal interface requirements (for 2003–2005):

- Largely self-contained
- Aftermarket
- Vehicle-powered (a la radar detector)
- One front-end
- Moderate power capability
- No network interface
- Minimal driver display (probably separated)

Second-generation device: good feature set without high-cost components/features (for 2007–2008)

- Built-in and aftermarket versions
- Vehicle-powered
- One or two front-ends
- Moderate power capability
- Possible network interface
- Minimal driver display

Full-blown do-it-all device: 2010

- Built into vehicle
- Vehicle-powered
- Dual front-ends
- High power capability
- High-capability network interface
- Driver interface via network devices

The first-generation device (2003–2005) only supports very few DSRC applications (other than direct v2v communications) due to the lack of mature MAC and network layer techniques suited for this environment and tailored to the intended applications. Nonetheless, the development of a robust and efficient network will be central to third-generation DSRC devices. The article focuses on this issue by first describing the current state of the art in 802.11-based MAC design and examining its capability to support the two basic DSRC scenarios shown in Fig. 4.

IEEE802.11 MAC PROTOCOL

802.11 was approved by IEEE as an international standard for wireless LANs (WLANs) [1], and provides detailed MAC and physical layer (PHY) specifications. In the 802.11 protocols, the fundamental mechanism for medium access is the distributed coordination function (DCF). This is a random access scheme for all associated devices in a cluster (termed the *basic service set*) based on carrier sense multiple access with collision avoidance (CSMA/CA). Proactive collision avoidance was implemented due to the infeasibility of collision detection in a wireless environment.[1] In a multihop network, the so-called *hidden node* and *exposed node* problems greatly impact MAC efficiency. Hence, a virtual carrier sensing mechanism using an initial exchange of request to send/clear to send (RTS/CTS) control packets greatly reduces the chances of collision due to "hidden" terminals. Retransmission of collided

---

[1] *Wireless transceivers are unable to simultaneously transmit and receive.*

packets is managed according to familiar binary exponential backoff rules. DCF is meant to support an ad hoc network without the need for any infrastructure elements such as an access point. If an infrastructure element such as an access point is explicitly recognized within the service set, a centralized MAC protocol, a point coordination function (PCF), can be used to achieve collision-free time-bounded medium access.

LIMITATIONS OF 802.11 IN DSRC ENVIRONMENTS

Earlier, two key scenarios in DSRC applications were described: a *distributed* (without infrastructure) *mobile multihop network* (scenario I) and a *centralized* (with infrastructure) mobile single-hop network (scenario II). In scenario I, only DCF is allowed, while both DCF and PCF are available in scenario II, where the roadside unit can work as either an access coordinator when using PCF or a distributed node equivalent to an onboard unit for DCF. Scenario I corresponds to peer-to-peer communication among vehicles in a fleet where the *relative* speed between vehicles is relatively low despite high absolute speed. Therefore, the effect of mobility on MAC performance can be ignored in scenario I, and we focus on the multihop networking aspect. Scenario II corresponds to v2r communications; consider vehicles moving at speeds of 100 km/h (27 m/s) passing by a roadside unit (RSU) with coverage range of 200 m (radius). This corresponds to the maximum contact duration of 200 × 2/27 ≈ 15 s. Thus, the key attribute necessary for communications in scenario II is the need for very high (bursty) download rates over a short duration. Therefore, the following discussions on limitations of 802.11 in DSRC environments will focus on two aspects: DCF over multihop and DCF/PCF for high-mobility environments.

DCF OVER MULTIHOP

A main problem of 802.11DCF in a multihop scenario is *blocking*, as shown in Fig. 5. As communication between nodes A and B continues, C is blocked because of CSMA/CA and the network allocation vector (NAV). If D sends an RTS to C at this time, there will be no response from C even if the RTS is successfully received. Due to exponential backoff in IEEE 802.11, D quickly enters into a long inhibition period that leads to underutilization of network capacity. If other nodes exist that want to communicate with D, an even more severe problem, *blocking propagation*, will occur, resulting in occasional deadlock [2]. T. Saadawi *et al.* presented a thorough discussion of this problem in [3] and suggested limiting the data transmission duration on one link by using a small maximum TCP window size (4 in [3]). However, the transport layer solution suggested in [3] ignores the fact that the problem is rooted at the MAC layer. We suggest some MAC layer approaches to this "fairness" problem later.

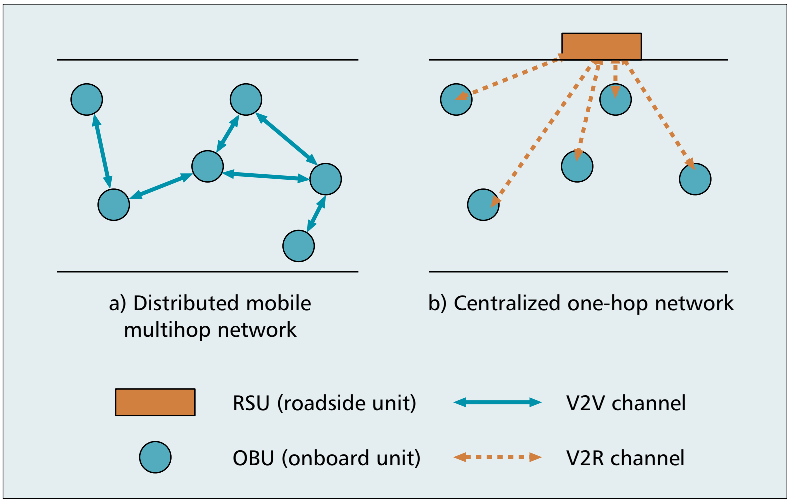


Figure 4. *Two basic scenarios of a DSRC system.*

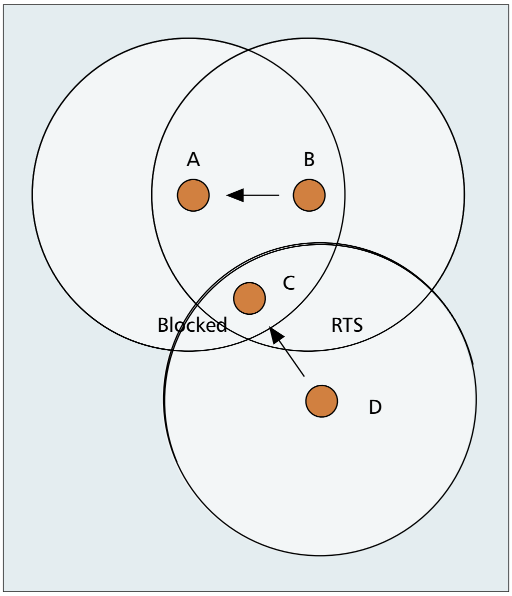


Figure 5. *The blocking problem of 802.11 DCF in a multihop scenario.*

DCF/PCF OVER HIGH MOBILITY

As already noted, a by-product of fast movement is dramatically shortened connection time for v2r links. Therefore, the system is unable to reach a steady state, and hence operates mostly in transient state, implying lower efficiency and potential for instability. Thus, a very efficient protocol with low overhead is preferred in such environments, which conflicts with RTS/CTS handshaking preceding every DATA packet. Furthermore, in PCF mode the point controller (PC) must maintain a list of all active nodes in its coverage area. Continuing with the above example where each node (car) remains in coverage for only 15 s leads to a frequency of list updating of 2/s (i.e., one addition and deletion each per second) for 15 cars within the 200 m coverage radius. Another side-effect of high node mobility is the resulting multirate nature of any short-lived connection since the IEEE802.11 protocol supports variable rates as

A practical difficulty with these algorithms in the DSRC environment is that the estimation must be performed in a highly dynamic environment due to multi-hop and mobility, and algorithms tailored for low-mobility scenarios are unlikely to be effective.

a function of distance. Thus, a node moving through the PC's coverage area will experience variable data rates during the connection period. This leads to potential problems such as overestimation or underestimation of the NAV used in future virtual sensing since it is based on the current transmission rate. These problems are new and remain to be effectively solved.

STATE OF THE ART

We next summarize the progress achieved to date concerning the modeling and analysis of 802.11 MAC in the following key areas: *DCF modeling*, *achieving fairness*, *quality of service* (*QoS*) *support*, and *high-efficiency data transmission*.

DCF MODELING

Most modeling and performance evaluation work to date [4, 5] on DCF multiple access has been based on the assumption of ideal channel conditions and a finite number of terminals. Among them, [5] provides the most accurate model to date, which accounts for all the exponential backoff details in 802.11 DCF, and computes the saturation (asymptotic) throughput for heavy offered loads. A two-dimensional Markov chain was used to model the backoff process using the key assumption that the probability that a transmitted packet collides is constant and independent of the number of retransmissions. Reference [5] showed that this assumption leads to accurate results when the number of active terminals is reasonably large (> 10).

The key conclusions drawn in [5] are:

- Using RTS/CTS, 802.11DCF throughput is not very sensitive to system parameters such as the minimum contention window CW min, maximum backoff stage m, and number of terminals n.
- Maximum saturation throughput is practically independent of the number of terminals, which can be achieved with the optimal backoff value

$$CW\,\min_{opt} \approx n\sqrt{2T_c / s}.$$

(n: total number of active terminals; T_c: the collision duration; s: slot time [20 µs in IEEE802.11b DSSS and 50 µs in IEEE802.11b FHSS]).

- Using RTS/CTS, collision occurs only on RTS frames, so $T_c = RTS + DIFS + \sigma$, where σ is propagation delay (about 1 µs in WLAN).

ACHIEVING FAIRNESS

Notions of fairness in multihop networks [6] can be classified into two kinds: *per-terminal* and *per-stream*. The concept of per-stream fairness was first introduced in multiple access with collision avoidance for wireless (MACAW) [7] — each stream, irrespective of its originating station, is given an equal share of the channel capacity. This is different from per-terminal fairness, which accords shares of channel capacity to individual terminals instead of individual streams. Since it is difficult to implement per-stream fairness in a real system, we only focus on per-terminal fairness in the following discussions.

MACAW — Bharghavan *et al.* [7] pioneered an approach to addressing the fairness problem in the wireless MAC protocol. It was concluded that the key problem is the lack of synchronization information about contention periods, especially in a multihop environment. To propagate such synchronization information, MACAW introduces two new packet types: data-sending (DS) and request for RTS (RRTS). To further improve the fairness, MACAW provides a method of "copying" the backoff parameters such as contention window from overheard packets to make sure that all neighboring terminals use the same contention window. MACAW also adopts a more conservative backoff algorithm than BEB: Multiplicative Increase and Linear Decrease (MILD), by which the contention window is reduced by only one unit if the data packet is successfully transmitted (while the binary exponentially backoff, BEB, reduces the contention window to the minimum value). While improving fairness, MACAW does not provide a solution in all conditions; a necessary condition for MACAW to be effective is that RTS must be correctly received or collide with only RTS or CTS packets. However, RTS may collide with data in some scenarios, where MACAW is not very useful. A possible solution is to decouple the RTS/CTS handshaking with data transmission sequence DATA-ACK by using two channels, one for RTS/CTS and the other for DATA-ACK transmission, implying that RTS never collides with data.

Estimation-Based Fairness Approaches — These approaches rely on real-time estimation of current channel status and other local network information, such as the number of active neighboring terminals [8] and the bandwidth share [9], which is used to adjust the contention window. Priority-based medium access control (P-MAC) [8] adopts a uniform backoff scheme in which only one parameter is suitably selected to reflect the relative weights among data traffic flows to achieve weighted fairness, and the number of terminals contending for the wireless medium to maximize aggregate throughput. Wang *et al.* [9] proposed a scheme based on the estimated bandwidth share of "self" and all "other" stations. However, a practical difficulty with these algorithms in the DSRC environment is that the estimation must be performed in a highly dynamic environment due to multihop and mobility, and algorithms tailored for low-mobility scenarios are unlikely to be effective.

QUALITY OF SERVICE

Obviously, in infrastructure networks with an access point (AP) as a coordinator, providing QoS guarantees is much easier by using PCF than in Scenario I where only DCF can be used. We next discuss various recent proposals for QoS support [10–14] for ad hoc networks. All these schemes are fundamentally based on the

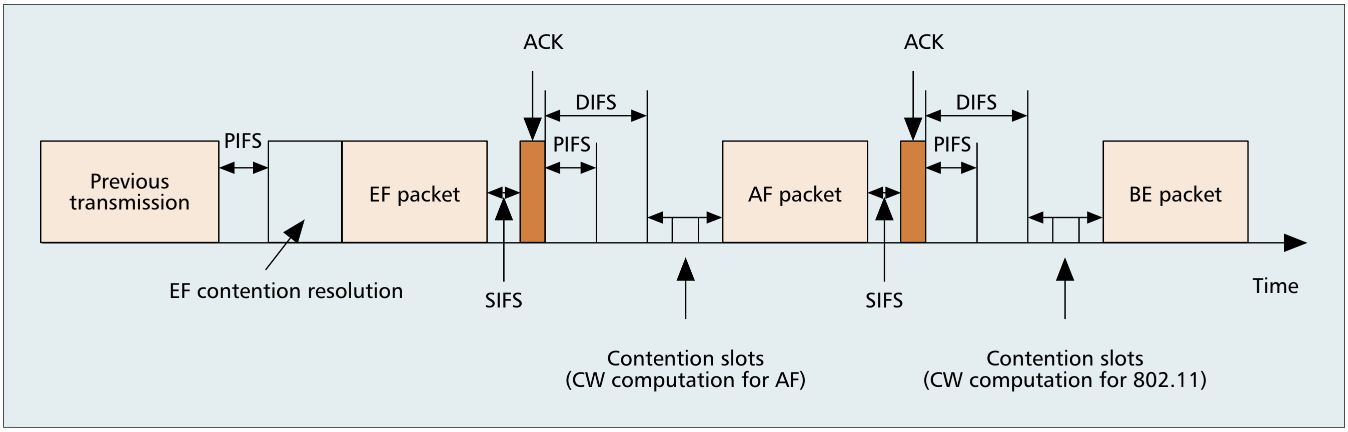


Figure 6. *Protocol operation of DIME.*

idea of modifying the backoff window algorithm in the 802.11 standard to provide service differentiation.

Real-Time Support — In [10], the backoff time computation is modified by assigning a shorter CW to low-delay real-time service. However, the scheme proposed in [10] does not decouple real-time traffic from data traffic; as a consequence, the service quality of real-time traffic in [10] is sensitive to changes in data traffic. The Blackburst scheme in [15] introduces a distributed solution to support real-time sources over 802.11, by modifying the MAC for real-time sources by assigning priority for bursty traffic. While this method can offer bounded delay, a disadvantage is that it is optimized for isochronous sources with equal data rates, which can be a significant limitation for applications comprising variable rate flows.

Differentiated Service — Reference [11] proposes the use of different CWs and backoff increase parameters, respectively, for different priorities in data traffic. However, the use of fixed parameters in [11] negatively impacts the throughput of stations with higher QoS requirements. The Distributed Fair Scheduling (DFS) approach [12] proposes a *dynamic* algorithm for backoff time computation at different stations proportional to their weights. One drawback of DFS is that each terminal has to monitor *all* transmitted packets and read the "finish tag" of each packet. In addition, DFS requires the header format of 802.11 to be modified to include this finish tag in the packet header. Reference [13] provides relative priorities for delay and throughput in a multihop wireless network. This approach piggybacks scheduling information onto RTS/data packets and then uses this information to modify the computation of the backoff times. Reference [13] has the same drawbacks as DFS, since it requires all nodes to monitor all transmitted packets in order to extract the scheduling information. It also requires modification of the 802.11 header format, and hence does not provide backwards compatibility.

DIME (DiffServ MAC Extension) — A MAC Framework for QoS Support — Two optional modules, expedited forwarding (EF) and assured forwarding (AF), are introduced in DIME [14]. DIME-EF reuses the interframe space (PIFS) of the point coordination in a distributed manner, while DIME-AF relies on DCF with a modified algorithm for the computation of the CW. Best effort (BE) is supported by the functionality of the current 802.11 standard in such a way that legacy IEEE 802.11 terminals behave as BE terminals in the DIME architecture. The combination of the EF, AF, and BE mechanisms in the DIME architecture leads to the protocol operation shown in the example of Fig. 6. In this example, after the end of the previous transmission, a station with an EF packet to transmit accesses the channel at the end of the PIFS. After the end of the transmission, the receiver answers with an acknowledgment after a SIFS. In the next access cycle, there is no EF traffic to be transmitted, so the channel can be accessed by AF and BE; in the example shown, the AF packet first accesses the channel since it has a smaller CW. The last packet is a BE packet, which uses a CW calculated according to the IEEE 802.11 standard.

Most of the above schemes can be used to support QoS in scenario I of DSRC systems. Considering backward compatibility, DIME [14] is preferable; furthermore, it supports differentiation not only between data and real-time service but also in data service itself, which is needed for DSRC environments. Other CW adjustment algorithms to support QoS and DiffServ can be integrated into DIME architecture to further enhance performance. The problem with DIME is that since PIFS has been reused by EF, integration of the 802.11 PCF protocol is not feasible in this architecture. One solution is to prohibit the EF module in an infrastructure environment where PCF is usually used, and let 802.11 PCF take control of EF related traffic accessing.

HIGH-EFFICIENCY DATA TRANSMISSION

It has been concluded in [5] that RTS/CTS should be used in the majority of the practical cases because of its capability to cope with hidden terminals. However, in IEEE 802.11 standard, using RTS/CTS on a per-packet basis introduces too much overhead especially when burst traffic predominates. Reference [16]

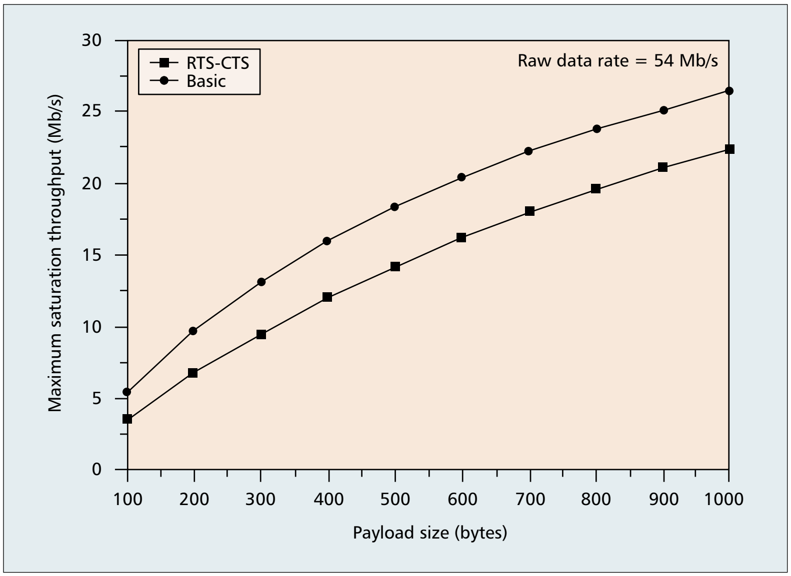


Figure 7. *Maximum saturation throughput comparison of IEEE802.11a with RTS-CTS to basic access scheme.*

showed that simply increasing the link layer date rate without reducing overhead does not result in a proportional increase in MAC throughput, which typically reaches a saturation level. The results in [16] were derived with respect to the basic CSMA/CA scheme of 802.11 DCF without considering RTS/CTS and hence may not be accurate for a real system. However, Bianchi's model [5] includes details of the backoff process and RTS/CTS exchange, and leads to a more accurate theoretical estimate for IEEE 802.11 saturation throughput with and without RTS/CTS exchanges; it was shown in [5] that the maximum saturate throughput is approximately 80 percent at data rate of 1 Mb/s. Figure 7 shows the maximum saturation throughput of IEEE 802.11a at highest data rate 54 Mb/s using Bianchi's model [5]. It is clearly observed that even with the payload size of 1000 bytes, the effective bandwidth utilization ratio of IEEE 802.11a is less than 50 percent. Furthermore, the basic access scheme without RTS/CTS handshaking has higher maximum saturation throughput than the scheme with RTS/CTS enabled. It is reasonable since RTS/CTS handshaking is an extra overhead for the IEEE 802.11 MAC layer. Please note that Fig. 7 is obtained by setting CWmin with the optimal value, which is a function of the total number of active terminals (denoted as n) so that the results are independent of n. Generally, for a fixed CWmin, the saturation throughput degrades as n increases.

Currently, several modifications have been proposed in the literature to reduce the overhead of IEEE802.11 based on two main ideas:

- An RTS/CTS handshake followed by *multiple* data packets [17]
- Reducing the overhead in a RTS/CTS handshake itself [18]

RTS/CTS Solutions — Data Flushing Data Transfer Protocol (DFDT) [17] sends out multiple data packets from the upper layer by using a compiled MAC protocol data unit (cMPDU) after acquiring channel access via a successful contention. The main difference between MPDU and cMPDU is that an MPDU carries data for one destination whereas a cMPDU could carry data for multiple destinations. DFDT takes as much data from the transmission queue at the upper layer limited only by the compilation threshold (CT) (whose function is similar to the fragmentation threshold [FT] in IEEE802.11) to prevent excessively long cMPDU frames. The key assumption used by DFDT is that one CTS associated with the first destination address in cMPDU is enough to reserve the radio channel. This is only valid in a mesh-connected environment (i.e., all terminals can hear each other); thus, DFDT has very limited application in the DSRC environment, where multihop routing is the most common scenario.

Header Efficiency — A Robust ACK-driven Media Access Protocol for Mobile Ad Hoc Networks (ROADMAP) [18] proposes to reduce the number of control handshake messages (e.g., RTS and CTS), especially for a multihop network. By overhearing the ACK message sent by the upstream node, a node can gain advance knowledge that data *might* be arriving and hence need only initiate a CTS after ACK transmission without the need to wait for an RTS handshake from the *potential* sender. Therefore ROADMAP belongs to receiver-initiated MAC scheme. However, the problem is that if a node that is invited to transmit (by receipt of CTS) has no packets for the destination, the transmission of CTS is useless. Consequently, while the traffic due to RTS packets is reduced, the unnecessary CTS transmissions still have an adverse impact on system efficiency. Also, the collision of ACK packets will have an impact on the operation of ROADMAP, although a timer can be set up by the sender to initiate an RTS transmission, as suggested in [18].

CONCLUSIONS

The DSRC environment (high mobility and multihop) poses new challenges to MAC design, requiring consideration of significant changes to the current IEEE802.11 standard. This article presents a summary of the state of the art in 802.11 MAC features, focusing on new challenges introduced by DSRC. The main conclusions drawn in this article are as follows:

- Most current research on multihop networks assumes fixed or very slowly varying network topology. The protocol is optimized by adjusting the CW dynamically to meet predefined requirements, such as maximum saturation throughput, weighted fairness, bounded delay, and differentiated QoS. The challenge is *to design an enhanced .11 MAC layer with open interfaces to integrate new solutions*.
- The effect of high mobility in ad hoc networks has been scarcely investigated. New challenges to MAC design include a *multirate environment, shortened connection time and frequent updating of stations in the coverage area*.

- Due to shortened connection time, burst download speeds in DSRC systems should aim for higher rates than current WLANs. However, it has been shown that simply increasing the data rate without reducing overhead leads to bounded throughput.

In conclusion, design of a wireless MAC protocol that incorporates pragmatic solutions to all the above issues in support of DSRC systems (multihop operation and high mobility) is a ripe area for continuing research.

REFERENCES

[1] IEEE Std., Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Nov. 1997.

[2] S. Ray, J. B. Carruthers, and D. Starobinski, "RTS/CTS-Induced Congestion in Ad Hoc Wireless LANs," *IEEE WCNC 2003*, New Orleans, LA, Mar. 2003, pp. 1516–21.

[3] S. Xu and T. Saadawi, "Does the IEEE802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks," *IEEE Commun. Mag.*, June. 2001.

[4] F. Cali, M. Conti, and E. Gregori, IEEE 802.11 Wireless LAN: Capacity Analysis and Protocol Enhancement," *INFOCOM '98*, San Francisco, CA, Mar. 1998.

[5] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE JSAC*, vol. 18, no. 3, Mar. 2000.

[6] N. H. Vaidya and P. Bahl, "Fair Scheduling in Broadcast Environments," Tech. rep. MSR-TR-99-61, Microsoft Research, Dec. 1999.

[7] V. Bharghavan *et al.*, "MACAW: A Media Access Protocol for Wireless LANs," *Proc. ACM SIGCOMM '94*, 1994.

[8] D. Qiao and K. G. Shin, "Achieving Efficient Channel Utilization and Weighted Fairness For Data Communications in IEEE802.11 WLAN under the DCF," *10th IEEE Int'l. Wksp. QoS*, 2002, pp. 227–36.

[9] Y. Wang and B. Bensaou, "Achieving Fairness in IEEE802.11 DFWMAC with Variable Packet Lengths," *IEEE GLOBECOM '01*, vol. 6, 2001, pp. 3588–93.

[10] A. Veres *et al.*, "Supporting Service Differentiation in Wireless Packet Networks Using Distributed Control," *IEEE JSAC*, vol. 19, no. 10, Oct. 2001.

[11] A. Imad and C. Castelluccia, "Differentiation Mechanisms for IEEE 802.11," *Proc. INFOCOM*, Anchorage, AK, Apr. 2001.

[12] N. H. Vaidya, P. Bahl, and S. Gupta, "Distributed Fair Scheduling in Wireless LAN," *Proc. ACM MOBICOM*, Boston, MA, Aug. 2000.

[13] V. Kanodia *et al.*, "Distributed Multi-Hop with Delay and Throughput Constrains," *Proc. ACM MOBICOM*, Rome, Italy, July 2001.

[14] A. Banchs, M. Radimirsch, and X. Perez, "Assured and Expedited Forwarding Extensions for IEEE802.11 Wireless LAN," *10th IEEE Int'l. Wksp. QoS*, 2002.

[15] J. L. Sobrinho and A. S. Krishnakumar, "Real-Time Traffic over the IEEE 802.11 Medium Access Control Layer," *Bell Labs Tech. J.*, Autumn 1996.

[16] Y. Xiao and J. Rosdahl, "Throughput and Delay Limits of IEEE802.11," *IEEE Commun. Lett.*, vol. 6, no. 8, Aug. 2002.

[17] S. T. Sheu *et al.*, "An Improved Data Flushing MAC Protocol for IEEE802.11 Wireless Ad Hoc Network," *VTC2002*, Vancouver, BC, Canada, 2002.

[18] D. Kim, C. K. Toh, and Y. Choi, ROADMAP: A Robust ACK-driven Media Access Protocol for Mobile Ad Hoc Networks," *MILCOM 2001*, vol. 2, 2001, pp. 983–87.

BIOGRAPHIES

SUMIT ROY (roy@ee.washington.edu) received a B. Tech. degree from the Indian Institute of Technology, Kanpur, in 1983, and M. S. and Ph.D. degrees from the University of California at Santa Barbara, all in electrical engineering in 1985 and 1988, respectively, as well as an MA in statistics and applied probability in 1988. His previous academic appointments were at the Moore School of Electrical Engineering, University of Pennsylvania, and at the University of Texas, San Antonio. He is presently a professor of electrical engineering, University of Washington, where his research interests center around analysis/design of physical and data link layer of communication systems, with a topical emphasis on next-generation mobile/wireless networks. He is currently on academic leave at Intel Wireless Technology Laboratory working on high-speed UWB radios and next-generation wireless LANs. His activities for the IEEE Communications Society includes membership of several technical committees and technical program committees for conferences, and he serves as an Editor for *IEEE Transactions on Wireless Communications* and *Wiley Journal on Wireless Communications and Mobile Computing*.

JING ZHU [StM] (zhuj@ee.washington.edu) received his B.S. and M.Sc. degrees, both in electronic engineering from Tsinghua University, Beijing, PR China, in 2000 and 2001, respectively. Since August 2001 he has been working toward a Ph.D. degree at the Electrical Engineering Department of the University of Washington, Seattle. His main research interests are performance issues in mobile networks (MONET), including land mobile satellite (LMS) systems, next-generation cellular systems, WLAN, ad hoc networks, and others and their applications (e.g., Internet-on-Move, Home-Networking, and Intelligent Transport System), focusing on protocol design issues at different layers, that is, transport layer (e.g., TCP), link layer (e.g., ARQ), and MAC layer (e.g., IEEE802.11). His current work is on MAC design for multihop ad hoc networks.

Due to shortened connection time, burst download speeds in DSRC systems should aim for higher rates than current WLANs. However, it has been shown that simply increasing the data rate without reducing overhead leads to bounded throughput.