On the Distributed Virtual Channel Based MAC for Spatial Reuse in Wireless LANs*

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Abstract

Existing MAC protocols for wireless LANs employ CSMA/CA that avoids collisions by preserving the wireless medium exclusively within 2-hop network. This medium reservation obstructs neighboring nodes at both sides from concurrent transmission. This problem reduces medium utilization and overall throughput in Wireless LANs. In this work, we offer parallel data transfers using concurrent virtual channels over same physical channel by distributed transmit/receive synchronization. Each virtual channel is used by a transmitter/receiver pair and all virtual channels within 2-hop network utilize the medium and avoid inter virtual channel interference. This virtual channel based protocol eliminates the exclusive medium reservation and improves the performance in terms of latency and overall network throughput.

1. Introduction

Wireless LANs use shared medium that requires an efficient channel access function for successful data transmissions. The RTS/CTS signal based distributed channel access functions (named as DCF) avoid collisions by reserving the medium for a connection pair (CP). Neighboring nodes of both sender and receiver cannot transfer data until previous one is completed (or timeout occurs). Although this scheme supported the wireless LANs for more than a decade, it requires enhancement for increasing demand for higher network throughput. Recent developments in the physical layer removed the barrier for using block acknowledgement for reliable transfer; and IEEE 802.11e MAC provides the Block Acknowledgement (BA) scheme to avail high data rate. In this work, we try to enhance the 802.11e MAC toward distributed spatial reuse of wireless medium using the BA scheme. Our proposed protocol forms a virtual channel (VC) for every sender-receiver pair. Multiple VCs can coexist within same physical channel in 2-hop networks; and, packets can be transferred over these VCs concurrently using BA scheme.

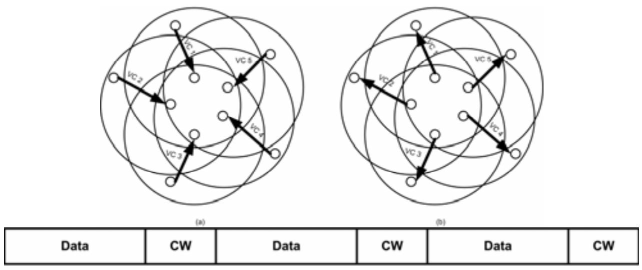
This rest of this paper is organized as follows: related works has been described in section 2; section 3 introduces the virtual channel concept, section 4 describes the mechanism for VC-MAC. The obtained simulation and numerical analysis results are presented in section 5. Finally, section 6 concludes the paper.

2. Related Works

Researchers are working on parallel transmission in single channel wireless medium over a long period. The conservative nature of IEEE 802.11 DCF for avoiding collisions creates challenge for parallel transmission. Parallel transmissions using transmission power control is proposed by Sigh et al. [2]. However, the power control from MAC requires enhancements in the physical layer. The MACA-P [3] and its extension [4] use a delay between the first RTS signal and data transmission in order to schedule non-interfering parallel transmission. The control delay creates and computation for scheduling adds large overheads. Some solutions are also available that uses directional antennas in order to avoid interference between concurrent transmissions [6][7], but the solutions causes huge increase in cost. In all solutions, enhancements in the basic DCF architecture or in the physical layer are required.

Our scheme is proposed as an enhancement of the IEEE 802.11e MAC layer protocol that can be implemented without power control or directional antennas; i.e., without any change in the physical layer. Moreover, it allows conventional channel reservation based schemes to support legacy devices. The complexity in synchronization between nodes is small compared to other proposed protocols.

3. The VC-MAC



(Fig. 1) Multiple Concurrent Virtual Channels sharing physical channel, (a) The Data Window, and, (b) Control Window (CW), (c) The construct of a virtual channel Concurrent Virtual Channel

A virtual channel is a series of alternating Data and Control windows (DW and CW) providing a half-duplex connection between sender and receiver in order to transfer blocks of data packets (referred as data frames) using block

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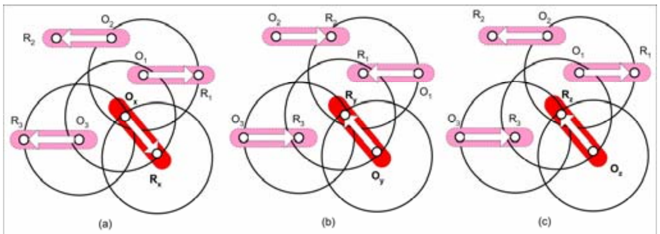
acknowledgement scheme. The originator transmits data frames one after one during the data window; whereas the recipient acknowledges received packets at control windows. Synchronized concurrent virtual channels in neighboring nodes allow non-interfering data transfers within 2-hop network. Fig. 1 shows how it can be used for parallel data transfer in 2-hop network.

For spatial reuse of wireless medium, concurrent VCs within two-hop network are allowed in several cases. We introduce a variable *vcState* at every node that determines whether a node can start new VC or not. The *vcState* indicates the existence and type of VCs in neighboring nodes. The *vcState* values and corresponding meaning are given in the following table:

<Table 1> Values of Virtual Channel Variable (vcState)

Value	Description
VCNO	No Virtual Channel exist within 1-hop neighborhood
VCTX	One or more synchronized (with common control window) Virtual Channel Originator exist within 1-hop neighborhood
VCRX	One or more synchronized (with common control window) Virtual Channel Recipient exist within 1-hop neighborhood
VCXX	More than one of different type (RX/TX) or non-synchronized Virtual Channels exist within 1-hop neighborhood

Since a new virtual channel formation depends on the existence of previous VC(s) within its neighborhood, we use this variable in the determination process.



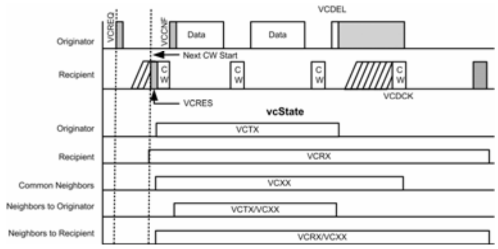
(Fig. 2) Concurrent Virtual Channel origination/acceptance cases: (a) when neighbor is an originator, (b) when neighbor is a recipient, and (c) when a neighbor is an originator and another neighbor is a recipient

A Node having either VCNO or VCTX in the *vcState* can initiate the VC formation process. However, the recipient can accept a VC formation request depending on its *vcState* value. Receivers having VCNO or VCRX can accept any virtual channel request. In Fig. 2(a) and 2(b) O_1 and O_3 could originate VCs because they didn't have any neighboring node that is participating in any other VC. O_2 finds a neighbor only one virtual channel (VCTX) in fig 2(a) so it can originate and aligned with that virtual channel whereas O_x in the same figure finds two virtual channels within its neighborhood and may be with different data and control window timing (non-synchronized to each other), so it can have either VCXX or VCTX (barely). In case of VCXX, O_x cannot originate a VC establishment. But if the order of origination is reverse (O_x creates VC earlier than O_3) then both of them would have VCTX in *vcState* and concurrent virtual channels could be established. Similarly, if the *vcState* value at R_y in figure 2(b) is VCRX then it can accept the VC establishment request from O_y. In the figure 2(c), the R_z node has two neighbors with virtual channels but they are in different types of participations. So, it is impossible to originate or accept request for new virtual channel establishment. The *vcState* value for such nodes becomes VCXX when heterogeneous participations on virtual channel are found within its neighborhood. This is also true for nodes having originator and recipient of same virtual channel as neighbors.

The formation of virtual channels is completely distributed; local situations in each 2-hop network would allow/deny the concurrent virtual channels. The order of virtual connections in the locality would take vital roles in virtual channel chaining.

4. The Mechanism and Operational Strategies

A virtual channel is a point to point half-duplex channel where the originator and recipient synchronize themselves by predefined time periods. The entire virtual channel data transfer is a 3-phase process: Virtual Channel Opening, Transfer, and Closing down. Five new control frames (VCREQ, VCRES, VCCNF, VCDEL, and VCDCK response) are offered to handle the virtual channel establishment and closing phases. Data transfer can be done using existing BAReq and BA frames in IEEE 802.11e MAC protocol.



(Fig.3) Virtual Channel Signals and vcState values

4.1 Virtual Channel Establishment: The originator initiates the virtual channel establishment phase by sending a *VCREQ Request* frame containing data stream size, proposed Data Window size and *vcState* of the originator. The recipient then checks whether it can accept the request or not. Depending on the *vcState* value at the receiver, it replies with VC response (VCRES) frame mentioning data window size, next control window start time and receive buffer size. Recipients having VCNO state, the control window starts immediately, and VCRES is supplied in the control window, yet, the VCRX recipients waits for next control window and then sends VCRES with changed data window size and next control window time to synchronize new VC with previous VC(s) at the recipient neighborhood. Neighbors of the recipient update their *vcState* value with VCRX upon receipt of the VCRES frame; and common neighbors of both originator and recipient turn into VCXX state.

The originator then waits for the next data window and then sends the VC confirm frame (VCCFM) followed by first block of the data stream. The VCCFM is used to inform neighbors of the originator about new virtual channel. Neighbors of the originator update the *vcState* value to VCTX or VCXX and can participate in data transfer by forming another synchronized virtual channel only.

4.2 Data Transfer: After virtual channel is established, the originator sends data stream in a series of blocks separated by control windows during the data windows. Each burst of data block contains several data frames interleaved by shortest inter frame space period (SIFS in IEEE 802.11).

Recent developments in physical layer inspired researchers to adapt block acknowledgement in MAC layer and recently IEEE Computer Society released the IEEE 802.11e MAC protocol supporting block acknowledgement [1]. In VC-MAC we follow the immediate policy of block acknowledgement scheme in the 802.11e standard.

Before sending the first data frame in the first data window of a virtual channel, the originator transmits the *VC confirmation* (VCCNF) frame first then starts the data burst. This VCCNF is sent to inform neighbors of the originator that are out of range from the recipient about VC establishment to update their *vcState*. This is required to synchronize future virtual channels.

4.3 Closing down: When there is no more data left to send at the originator and the final block acknowledgement has been received by the originator over any of the existing virtual channel; the virtual channel closing process is initiated by the originator by sending a *virtual channel delete* (VCDEL) frame to the recipient. In addition to this, if any of the stations moved beyond the range of the other, then the receiver initiates the closing operation. The VCDEL is acknowledged by VCDCK by the recipient during the next control window.

4.4 Joining EDCA: After closing a virtual channel down, the originator or recipient may contend to get access to the medium and start sending data packets in presence of other virtual channels resulting in error in received data at neighboring recipients with virtual channels. In order to eliminate such situations, contending the medium for data transmission after closing virtual channel is delayed for next data/control windows and the delaying continues until it receives VCDEL or VCDCK frame from other originator or receiver.

In such cases, each participant in virtual channels or the neighbors of such participants takes different actions. The originator listens the medium just after issuing the VCDEL and if it finds any transmission, its virtual channel is closed but it continues the VCTX state. However, if it does not receive any signal it turns into the VCNO state. This is same for other neighbors in the originator side only. In the recipient side, as soon as the recipient gets the control window, it closes the virtual channel but continues the VCRX state for next control windows until it receives the VCDCK frame from the last recipient. If it gets any corrupt data during next control windows; it is inferred that there exists other virtual channels within its neighborhood and it continues with VCRX state. Neighbors of both originator and recipient turns into VCNO state after it receives the VCDSK from last recipient (if any).

5. Simulation

The VC-MAC protocol has been simulated on *x*, *y* grid topology; from 2×2 to 5×6 grids and compared with recent 802.11e block acknowledgement (BA) scheme. Our simulation considers parameters as follows. The data rate at physical layer is 54Mbps (IEEE802.11g) and in the MAC layer IEE802.11e EDCA and Block Acknowledgement (BA) scheme in IEEE802.11e is used without prioritization. Data-frame size was fixed to 5K bytes. The entire DW-CW cycle in a virtual channel is 3000μs, where 2965μs allocated to data window and the rest 35μs for control window. The control window duration is sufficient to transmit VCRES, BA and VCDCK signals. Data stream sizes varied from 5K bytes to 250 K bytes and their arrivals at nodes follow Poisson distribution. In addition to this, the environment is assumed to be completely error free so there is no retransmission in the network.

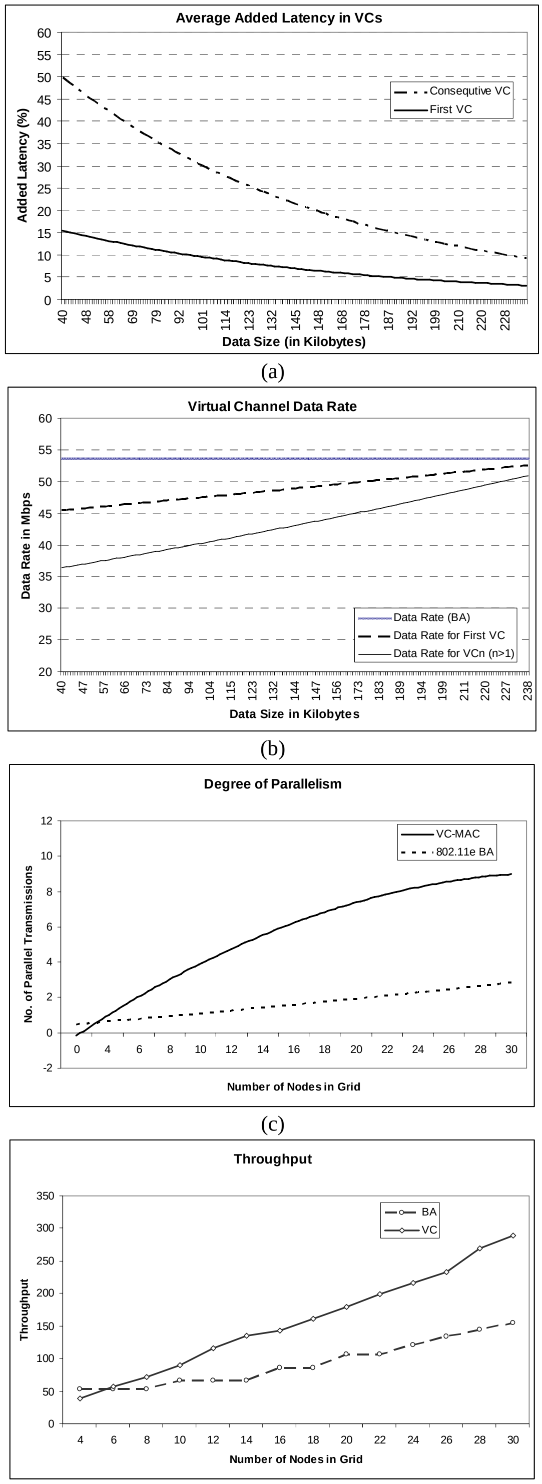


Fig.4. Simulation Results: (a) Added latency in VCs, (b) Data rate in VCs, (c) Observed degree of parallelism in Grids, and, (d) Network throughput

The rate of added latency for each virtual channel due to delay in initial response and the control window intervals compared to block acknowledgement BA scheme in 802.11e is depicted in Fig. 4(a). Simulation result shows that the added latency (mean delay) in each virtual channel decreases as the data stream size increases for fixed data window duration. Latency in VCs reduces with increased data stream size because of smaller influence of $t_{remainDW}$ over total turnaround time. For data stream of 100K bytes, the added latency is approximately 10% and less than 30% for the first and consecutive VCs in each 2-hop network respectively. Corresponding reduction in data rate at each virtual channel is presented in the Fig 4(b). Virtual channel capacity increases with increased data stream size, and approaches to the physical channel capacity.

The curve in Fig. 4(c) shows the average degree of parallelism obtained for the grid networks. The number of parallel VCs increases at higher rate than that of IEEE 802.11e BA scheme with increased number of nodes in the grid. Fig. 4(d) shows the influence in throughput for the degree of parallelism obtained. Control window durations in VCs reduces the network throughput due to reduction in channel capacity, however, overall throughput of the network increases when the network can create concurrent virtual channels within 2-hops. The proposed VC-MAC offers better throughput because it allows hidden and exposed terminals to participate in parallel transmissions, whereas conventional RTS/CTS bases MAC protocols cannot.

6. Conclusion

This work investigates the bottleneck in improving medium utilization in 2-hop wireless networks. It is identified that conventional RTS/CTS based CSMA/CA MAC denies hidden or exposed nodes to initiate or participate in parallel transmissions because of transmit/receive switching of participating nodes during data transmissions. Our investigation identifies cases where parallel transmissions are possible within 2-hop network; and proposes the virtual-channel based MAC (VC-MAC) to achieve this. The virtual channel is a schedule of transmit/receive switching of participant nodes during data transmissions and hidden or exposed nodes can initiate parallel transmissions and avoid collisions at receiving nodes by adapting this schedule.

Proposed VC-MAC scheme is analyzed and simulated on grid topology, and then results are compared with the Block Acknowledgement scheme of IEEE 802.11e standard for large data streams. Analysis and simulation shows that VC-MAC can successfully avoid interference at the receivers and can allow hidden and exposed terminals to create parallel virtual channels. This scheme improves the overall network throughput although it reduces the data rate of each connection pair (virtual channel).

Our work considered cases for large data streams and did not consider impact of retransmissions on network capacity or throughput. Finding the optimum data window size and incorporating service differentiation for QoS are also open issues for future work.

Reference:

[1] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications (Part 11), Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements, Std. 802.11e, Nov. 2005.

[2] K. P. Sigh, C. M. Chou, M. Y. Lu, and, S. M. Chen. A Distributed Spatial Reuse (DSR) MAC Protocol for IEEE 802.11 Ad-Hoc Wireless LANs. In the proceedings of the 10th IEEE symposium on Computers and Communications, ISCC 2005, pages 658-663, 2005.

[3] A. Acharya, A. Misra, and S. Bansal. MACA-P: A MAC for concurrent transmissions in multi-hop wireless network. In proceedings of the IEEE International Conference on Pervasive Computing and Communications, pages 505-508, 2003.

[4] A. Acharya, A. Misra, and S. Bansal. Design and Analysis of a Cooperative Medium Access Scheme for Wireless Mesh Networks. In proceedings of the First International Conference on Broadband Networks (BROADNETS'04), pages 321-631, 2004.

[5] R. Rozovsky, and P. R. Kumar. SEEDEX: A MAC protocol for ad hoc networks. In proceedings of ACM Mobihoc, 2001.

[6] R. R. Chowdhury, X. Yang, N. H. Vaidya, and, R. Ramanathan. Using directional antennas for medium access control in ad hoc networks. In Proceedings of the ACM international Conference on Mobile Computing and Networking, pages 59-70, 2002.

[7] Y. Wang, and J. J. Garcia-Luna-Aceves. Spatial reuse and collision avoidance in ad hoc networks with directional antennas. In proceedings of the IEEE Global Telecommunications Conference, volume 1, pages 112-116, 2002.

[8] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang. MACAW: A media access protocol for wireless LANs. In Proceedings of the ACM SIGCOMM’94, pages 212–215, London, UK, Aug. 1994.