INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. 2009; **22**:1045–1061
Published online 27 May 2009 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/dac.1025

Enhanced high-performance distributed coordination function for IEEE 802.11 multi-rate LANs

Chih-Heng Ke[1], Bin Li[2], Yueh-Min Huang[3,*,†] and J. Morris Chang[4]

[1]*Department of Computer Science and Information Engineering, National Kinmen Institute of Technology, Kinmen, Taiwan*
[2]*Department of Computer Science and Engineering, Texas University, Arlington, U.S.A.*
[3]*Department of Engineering Science, National Cheng Kung University, Taiwan*
[4]*Department of Electrical and Computer Engineering, Iowa State University, U.S.A.*

SUMMARY

To compensate for the effects of fading in wireless channels, IEEE 802.11 systems utilize a rate-adaptation mechanism to accomplish a multi-rate capability. However, the IEEE 802.11 distributed coordination function results in a fundamental performance anomaly in multi-rate networks; namely, when stations with different transmission rates collide, the throughput performance of the high-rate station is significantly degraded by the relatively longer channel occupancy time of the low-rate station. This study resolves this problem through the use of an enhanced high-performance distributed coordination function (EHDCF) protocol. While most existing solutions to the multi-rate performance anomaly problem have the form of simple contention-based protocols, EHDCF has two modes, namely a contending mode and an active mode. In the proposed protocol, new stations joining the network are assigned a contending mode, but switch to an active node (and are therefore permitted to transmit data packets) as soon as they have gained access to the channel. Having transmitted a data packet, the active node then selects the next transmission station in accordance with a probability-based rule designed such that the high-rate stations within the network receive a greater number of transmission opportunities than the low-rate stations. The simulation results show that the EHDCF protocol not only yields a significant improvement in the network throughput but also guarantees the temporal fairness of all the stations. Copyright © 2009 John Wiley & Sons, Ltd.

Received 14 November 2008; Revised 2 March 2009; Accepted 27 March 2009

KEY WORDS: performance anomaly; IEEE 802.11; multi-rate; EHDCF

1. INTRODUCTION

As the IEEE 802.11 [1–3] continues to evolve, an increasing number of wireless products are being developed and deployed. To counter the inevitable effects of fading in wireless channels, various rate-adaptation mechanisms [4, 5] have been developed to facilitate the co-existence of

*Correspondence to: Yueh-Min Huang, Department of Engineering Science, National Cheng Kung University, Taiwan.
†E-mail: huang@mail.ncku.edu.tw

multiple transmission rates within the same channel. In general, IEEE 802.11 provides a high level of support for multi-rate transmission environments. For example, IEEE 802.11b supports rates of 1, 2, 5.5 and 11 Mbps, respectively, while IEEE 802.11a supports eight different rates ranging from 6 to 54 Mbps. However, the IEEE 802.11 standard faces a fundamental performance anomaly [6] in multi-rate environments. In that when a high-rate station collides with a low-rate station, it must wait for the low-rate station to complete its transmission, and hence its throughput is significantly reduced. As a consequence, developing the means to reduce the occurrence of collisions between the stations with different rates [7] is an essential concern in multi-rate networks.

In [8–10], it was shown experimentally that IEEE 802.11 systems with RTS/CTS access generally achieve a better performance in multi-rate networks than those with basic access mechanisms, but perform less well than systems with basic access capabilities in single-rate networks under low-traffic load conditions. Thus, it was inferred that the RTS/CTS mechanism achieves an effective reduction in the number of channel collisions, and therefore prompts a significant improvement in the performance of multi-rate networks. In [11], the authors proposed an adaptive contention window (CW) mechanism in which the number of active nodes in the network was estimated using the Kalman Filter Estimation scheme [12] and the Particle Filters method [13], and the size of the CW was then adjusted appropriately in accordance with the level of network congestion. The experimental results demonstrated that the proposed approach yielded a further improvement in the performance of IEEE.802.11 networks relative to that achieved using the RTS/CTS access method.

Although the methods described above achieve an effective improvement in the network throughput as a result of the avoidance of collisions, they assign the same degree of channel access priority to both the high-rate stations and the low-rate stations. As a result, all stations have the same throughput, and thus the performance of the network is artificially constrained. At present, three basic methods exist for enhancing the performance of IEEE 802.11 medium access control (MAC) by assigning different channel priorities to stations with different rates, namely packet size differentiation (PSD) [14], CW differentiation [15, 16] and interframe gap (IFG) differentiation [17]. In the PSD approach, the size of the packets transmitted by the different stations is varied in accordance with their respective data rates, i.e. high-rate stations transmit longer packets, while low-rate stations transmit shorter packets. Although the PSD method yields a notable improvement in the network performance, it requires the packets to be fragmented at the sender and then reassembled at the receiver, which not only increases the computational burden at the MAC layer, but also consumes a greater amount of power. In the CW differentiation method, the high-rate stations are simply assigned a smaller CW such that they can access the channel more easily. Finally, in the IFG differentiation approach, stations with a shorter IFG (i.e. a higher transmission rate) are granted preferential access to the channel relative to those with a longer IFG. However, while the IFG method improves the network performance, it inevitably induces a temporal unfairness among the various channel users.

All three methods described above are basically based on contention-based operation, and therefore cannot guarantee to maximize both the throughput and the fairness of the network. Accordingly, this study proposes a new MAC protocol based on the high-performance distributed coordination function (HDCF) scheme presented in [18] for achieving a higher and more stable throughput in single-rate networks, while simultaneously ensuring a fair access to all the network users. The principal difference between the scheme presented in this paper and that proposed in [18] is the use of a selection rule based upon a data-rate ratio metric.

The remainder of this paper is organized as follows. Section 2 simply reviews the HDCF protocol proposed in [18] and discusses the performance anomaly problem in multi-rate wireless systems.

DOI: 10.1002/dac

Section 3 introduces the enhanced high-performance distributed coordination function (EHDCF) protocol developed in this study and formulates an analytical expression for the maximum attainable network throughput. Section 4 describes the results of a series of simulations designed to evaluate the throughput and to confirm the ability of the EHDCF protocol to resolve the performance anomaly problem. Finally, Section 5 presents some brief concluding remarks and indicates the intended direction of future research.

2. BACKGROUND

2.1. HDCF protocol

The HDCF protocol has two working modes, namely an active mode and a contending mode. In the active mode, once the current transmission station has transmitted a packet and received an ACK message, it selects the next transmission station in accordance with a uniform distribution, i.e. each station in the active list has the same probability of being selected as the next transmission station. As shown in Figure 1(a), the selected station waits for an interval of one PIFS following the previous transmission and then sends out a packet of its own. Thus, in the active mode, all the stations are guaranteed to be contention free. In the contending mode, the HDCP protocol is identical with the original IEEE 802.11 distributed coordination function (DCF) protocol, i.e. the stations start transmitting as soon as the back-off and DIFS expire. However, fewer collisions occur in the HDCF protocol contending mode than in the original DCF protocol since only new transmission stations need to contend for the wireless channel.

When the selected next transmission station detects a signal before the PIFS has elapsed, it stops its transmission to allow the new stations to contend for the channel access and then enter into the active mode. As shown in Figure 1(b), the new station issues a jamming signal after the finish of the current active transmission plus one SIFS interval. Then if the idle time for the channel lasts for the duration of DIFS–SIFS plus back-off time, the new station can transmit its data frame.

2.2. Performance anomaly problem

If all the stations in a wireless network select a data rate in accordance with the auto rate feedback (ARF) mechanism or the receiver-based auto rate (RBAR) scheme, the network will

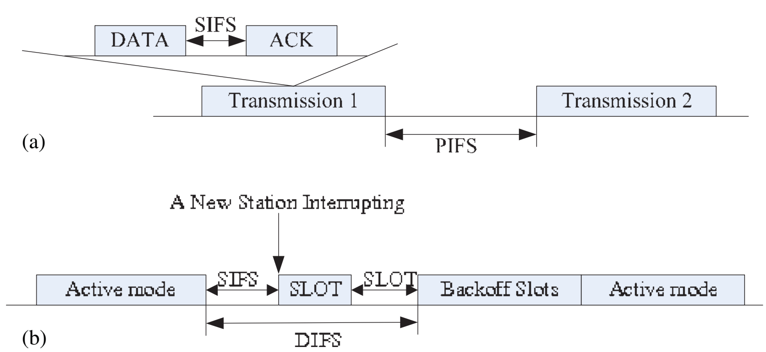

Figure 1. HDCF protocol (redrawn from [18]): (a) no new station interruption and (b) new station interruption.

DOI: 10.1002/dac

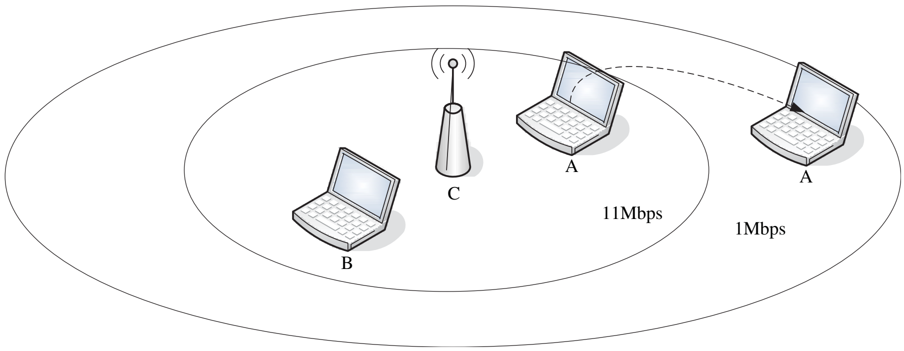

Figure 2. Simulation scenario.

inevitably contain multiple transmission rates, and thus the performance anomaly problem may arise. For example, consider the IEEE 802.11b system shown in Figure 2 in which stations A and B both wish to transmit data to the server C, and station A moves progressively away from the server. Assume that in accordance with the rate-adaptation MAC protocol, the data rate of station A reduces from 11 to 1 Mbps as the distance between it and the server increases. In addition, assume that the size of the data packets transmitted by the two stations is the same and remains constant. As a result, the channel occupancy time of each station varies inversely with the respective data rate. Consequently, as station A moves away from the server, its channel occupancy time increases since the IEEE 802.11 DCF is designed to guarantee the fairness of each node in accessing the channel. However, since station B does not move, the time for which it occupies the channel remains constant. Thus, in the same time interval, the total number of packets transmitted by stations A and B reduces as the data rate of station A decreases.

To clarify the performance anomaly problem, a simulation was performed in which stations A and B in Figure 2 both transmitted CBR traffic with a packet generating rate of 2 Mbps to station C with a packet size of 1000 bytes. The simulation was run for a total of 60 s. From 0 to 20 s, the data rates of stations A and B were both specified as 11 Mbps. However, from 20 to 40 s, the data rate of station A was reduced to 1 Mbps, while that of station B remained constant at 11 Mbps. Finally, from 40 to 60 s, station A was removed from the network, while station B continued to transmit data at the same rate of 11 Mbps. Figure 3 illustrates the variation over time of the throughputs at station C received from stations A and B, respectively. Over the period 0–20 s, both stations transmit their data at a rate of 11 Mbps, and thus station C receives 2 Mbps of data from each station. As a result, the overall throughput of the system is 4 Mbps. However, from 20–40 s, the data rate of station A reduces to 1 Mbps. As shown in Figure 3, the throughput of station A therefore reduces from 2 Mbps to 750 kbps. Although the data rate of station B remains unchanged at 11 Mbps, the simulation results show that the greater channel occupancy of station A arising as a result of its lower data rate causes the throughput of station B to reduce to a similar level to that of station A. Consequently, the total throughput reduces from 4 to 1.5 Mbps. After 40 s, station A leaves the network, and thus the throughput of station B (and that of the total network) increases to 2 Mbps.

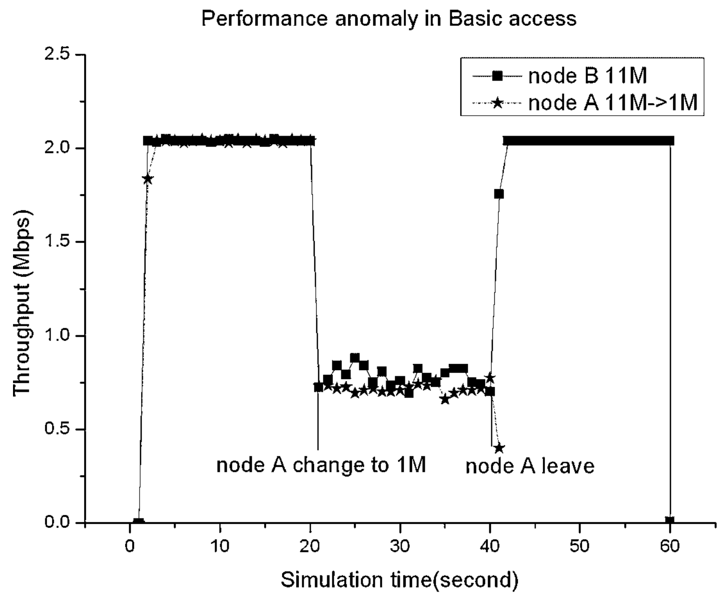

Figure 3. Performance anomaly problem in multi-rate IEEE 802.11b system.

3. EHDCF PROTOCOL

This section describes the EHDCF protocol proposed in this study. As in the original HDCF protocol, EHDCF has two working modes, namely an active mode and a contending mode. Each active node maintains an active station list containing all the active stations that still have data frames to transmit and their corresponding transmission rates.

3.1. Selection rule

The main difference between EHDCF and HDCF is the selection rule. In the HDCF protocol, each station has equal opportunity to be selected as the next transmission station while in the EHDCF protocol, the selection rule applied by the current transmission station in selecting the next transmission station is based on a data-rate ratio metric. Assume that the network contains a total of K different rates and the number of stations with a rate R_i is denoted as N_i. According to the proposed selection rule, the probability of any station in the active station list being chosen as the next transmission station is specified as

$$P_{\text{select}} = \frac{N_i \times R_i}{\sum_{i=1}^{K} N_i \times R_i} \tag{1}$$

For example, consider the case of two active stations with data rates of 1 and 2 Mbps, respectively. According to Equation (1), the station with a rate of 1 Mbps transmits just once, while that with a rate of 2 Mbps transmits twice in every interval of three time slots on average.

DOI: 10.1002/dac

3.2. Information broadcasting in EHDCF protocol

In the EHDCF protocol, the header frame of each packet transmitted by an active station includes the following three key items of information: (1) whether the station has more data to transmit, (2) the transmission rate of the station and (3) the identity of the station chosen as the next transmission station. In indicating whether or not it has more data to transmit, the station simply uses the 'More Data' control field in the conventional IEEE 802.11 MAC frame (see Figure 4). Meanwhile, the data transmission rate is indicated in an appropriate field in the physical layer frame, e.g. the 'Signal' field in the IEEE 802.11b standard (see Figure 5) or the 'Rate' field in the IEEE 802.11a standard (see Figure 6). Finally, the address of the next transmission station is indicated in an additional field appended to the MAC header. Although the additional field incurs a 6 byte overhead, this overhead is very small compared with the average data packet size and therefore has a negligible effect upon the system throughput.

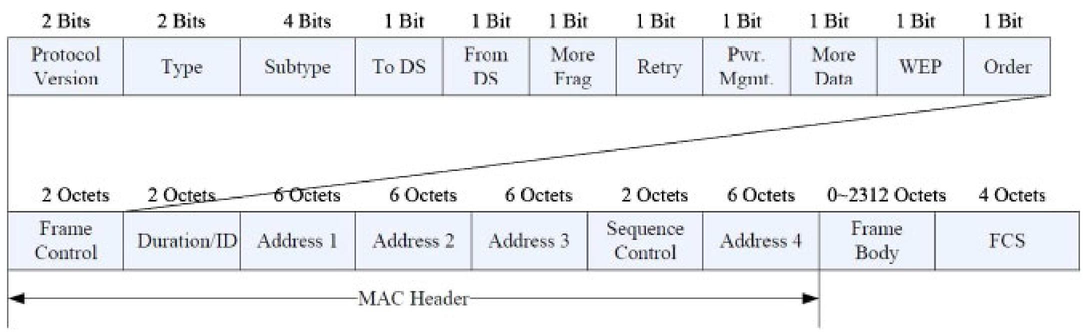

Figure 4. IEEE 802.11 MAC frame.

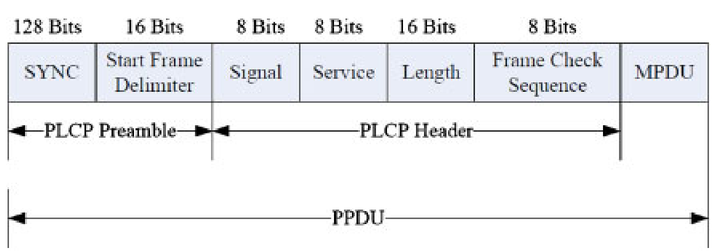

Figure 5. IEEE 802.11b header.

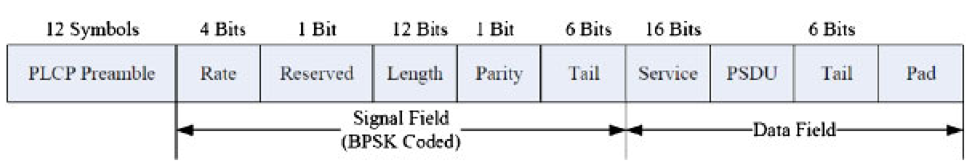

Figure 6. IEEE 802.11a header.

DOI: 10.1002/dac

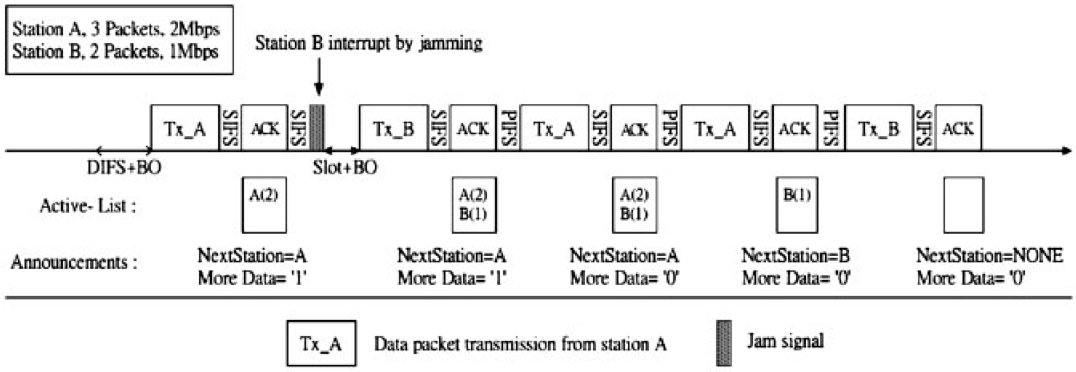

Figure 7. Illustrative EHDCF example.

3.3. EHDCF illustrative example

As a further illustration of the EHDCF protocol, consider the example shown in Figure 7, in which station A with a 2 Mbps data rate has three packets to transmit, while station B with a 1 Mbps data rate has two packets. Initially, both stations use DCF to contend for channel access. Assuming that A wins the contention, it transmits one packet, and adds itself with a data rate of 2 Mbps to its active station list. The packet sent by A informs all the other stations in the network that A still has packets to transmit. Furthermore, the packet header indicates that the next transmission station is once again station A since no other stations currently exist in the active list. However, station B subsequently interrupts station A by jamming for one slot SIFS after the ACK packet. After jamming, station B waits for one slot and a random number of back-off (BO) slots, and then starts to transmit its first data frame and adds itself to its active list with a data rate of 1 Mbps. Moreover, station B calculates the next transmission station probability in accordance with Equation (1) and obtains a result of $\frac{2}{3}$ for station A and $\frac{1}{3}$ for station B. In other words, station A has a higher probability of being selected as the next transmission station. Assume that A is indeed selected and starts to transmit after the PIFS has elapsed. Having transmitted its packet, station A calculates the next transmission station probability using Equation (1), and once again receives a higher probability. Thus, station A is retained as the next transmission station. Once station A has transmitted its third and final packet, it removes itself from the active list. Consequently, in the next turn, station B is automatically selected as the next transmission station and therefore sends out its final packet. Having received an ACK message, station B removes itself from the active list such that the active list becomes empty.

3.4. Maximum achievable throughput in EHDCF protocol

The maximum attainable throughput under the EHDCF protocol can be formulated as

$$S_{\mathrm{EHDCF}} = \frac{E[L]}{\mathrm{PIFS} + \mathrm{SIFS} + E[T_{\mathrm{data}}] + T_{\mathrm{ack}} + 2\delta} \tag{2}$$

where δ is the propagation delay, $E[L]$ is the average packet size, $E[T_{\mathrm{data}}]$ is the average time needed to send one data packet and T_{ack} is the time needed to send an ACK.

DOI: 10.1002/dac

For example, in a multi-rate IEEE 802.11b system in which an equal number of nodes have transmission rates of 1, 2, 5.5 and 11 Mbps, respectively, the probability of any station with a rate i being selected as the next transmission station is obtained from Equation (1) as

$$P_i = \frac{R_i}{\sum_{K=1}^{n} R_i} \tag{3}$$

The time required to transmit a single data frame at a rate of 1 Mbps is given by

$$T_{\text{data},1} = \text{PhyHeader} + \frac{\text{MacHeader} + \text{PacketSize}}{1} \tag{4}$$

Similarly, the times required to transmit a single data frame at a rate of 2, 5.5 and 11 Mbps can be expressed, respectively, as follows:

$$T_{\text{data},2} = \text{PhyHeader} + \frac{\text{MacHeader} + \text{PacketSize}}{2} \tag{5}$$

$$T_{\text{data},5.5} = \text{PhyHeader} + \frac{\text{MacHeader} + \text{PacketSize}}{5.5} \tag{6}$$

$$T_{\text{data},11} = \text{PhyHeader} + \frac{\text{MacHeader} + \text{PacketSize}}{11} \tag{7}$$

Thus, $E[T_{\text{data}}]$ in Equation (2) can be expressed as

$$E[T_{\text{data}}] = \frac{T_{\text{data},1} \times 1 + T_{\text{data},2} \times 2 + T_{\text{data},5.5} \times 5.5 + T_{\text{data},11} \times 11}{1 + 2 + 5.5 + 11} \tag{8}$$

The current solutions for resolving the performance anomaly problem in multi-rate channels, e.g. PSD [14], CW differentiation [15, 16] and IFG differentiation [17], all utilize the DCF mechanism, i.e. the stations must all contend to access the channel. The maximum DCF throughput is formulated as [19]

$$S_{\text{DCF}} = \frac{E[L]}{\frac{\text{CW}_{\min}\sigma}{2} + \text{DIFS} + \text{SIFS} + E[T_{\text{data}}] + T_{\text{ack}} + 2\delta} \tag{9}$$

Comparing Equation (9) with the EHDCF throughput given in Equation (2), it is clear that EHDCF does not require a back-off interval and therefore obtains a higher throughput.

4. PERFORMANCE EVALUATION

This section commences by comparing the model for the maximum achievable throughput of the proposed EHDCF protocol with the simulation results, and then compares the fairness index of EHDCF with that of existing solutions for the performance anomaly problem. The simulations consider an IEEE 802.11b system with four different data rates, i.e. 1, 2, 5.5 and 11 Mbps, respectively. The transmission rates of the RTS, CTS and ACK frames are specified as 1 Mbps in every case. The remaining simulation parameters are summarized in Table I. In performing the simulations, three different multi-rate scenarios are considered, i.e. 1:1:1:1, 1:2:3:4 and 4:3:2:1,

DOI: 10.1002/dac

Table I. Simulation parameters.

SIFS (μs)	10	Phy header (bits)	192
σ (μs)	20	MAC header (bits)	272
DIFS (μs)	50	ACK (bits)	112
CW_{min}	32	δ (μs)	1
CW_{max}	1024	Packet size (bytes)	1000
PIFS (μs)	30	Long retry limit	7

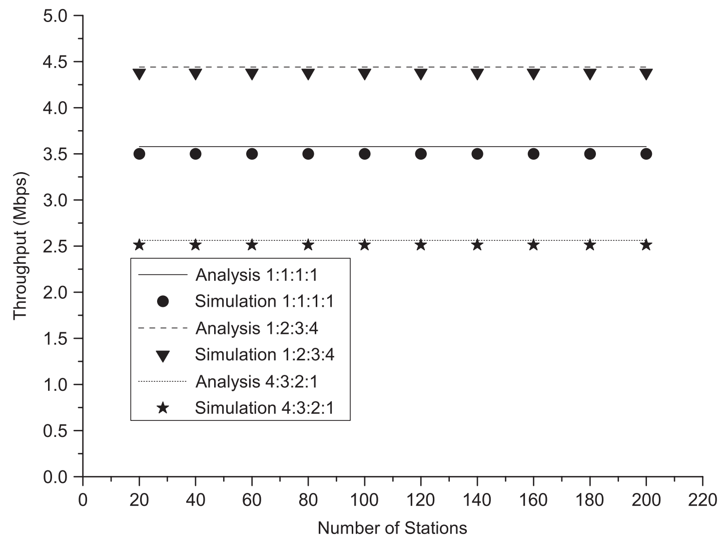

Figure 8. EHDCF throughput: analytical model vs simulation.

where 1:2:3:4 (for example) indicates that for a network with a total of n stations, the number of stations with transmission rates of 1, 2, 5.5 and 11 Mbps, respectively, is distributed in the ratio 1:2:3:4. In other words, in a network containing 20 stations, 2 stations have a data rate of 1 Mbps, 4 stations have a data rate of 2 Mbps, 6 stations have a data rate of 5.5 Mbps and 8 stations have a data rate of 11 Mbps. In addition, it is assumed that all the stations always have data packets to send and remain within transmission range of one another at all times.

4.1. Analytical model vs simulation

Figure 8 presents the analytical and simulation results for the total system throughput under each of the three simulation scenarios for networks of varying size. It is observed that the simulation results are very close to the analytical results, even though the stations first need to contend and then switch to the active mode.

4.2. Throughput

Figures 9–11 illustrate the variation of the saturation throughput with the number of stations for the proposed EHDCF protocol and various other protocols in each of the three simulation

DOI: 10.1002/dac

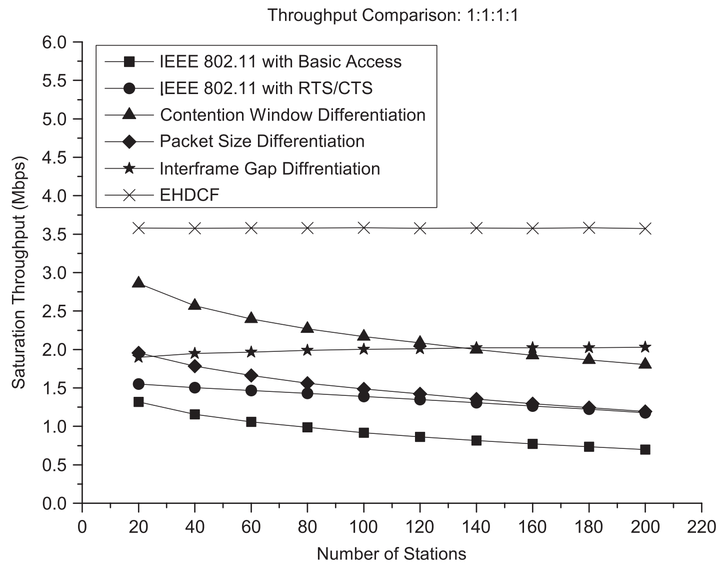

Figure 9. Throughput comparison in 1:1:1:1 network.

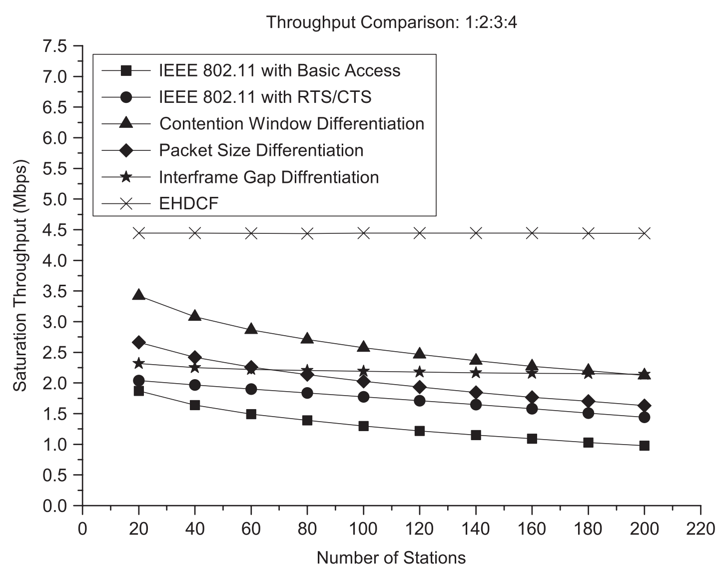

Figure 10. Throughput comparison in 1:2:3:4 network.

environments. It is observed that the EHDCF protocol consistently achieves the highest throughput of all the protocols due to its ability to effectively reduce the number of collisions (or to avoid collisions entirely when all the nodes are in an active mode).

DOI: 10.1002/dac

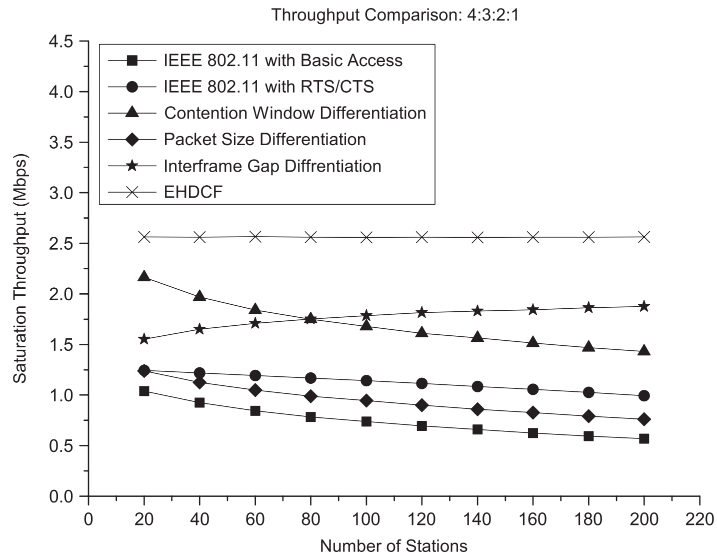

Figure 11. Throughput comparison in 4:3:2:1 network.

4.3. Fairness

The previous section has demonstrated that the EHDCF protocol achieves an effective improvement in the throughput of multi-rate networks. This section compares the fairness of the EHDCF protocol with that of the same set of protocols considered above. In performing the analysis, the throughput fairness and temporal fairness are evaluated using the Jain index [20], defined as

$$\mathrm{FI}=\frac{(\sum_{i=1}^{n} S_i)^2}{n\sum_{i=1}^{n} S_i^2} \tag{10}$$

where n denotes the total number of stations and S_i represents the amount of resource that station i acquires, i.e. the throughput of station i when evaluating the throughput fairness and the time for which station i occupies the channel when evaluating the temporal fairness. Note that the fairness index has a value between 0 and 1, with a higher value indicating a greater degree of fairness.

4.3.1. Throughput fairness. Figures 12–14 compare the throughput fairness of the EHDCF protocol with that of the other protocols for the 1:1:1:1, 1:2:3:4 and 4:3:2:1 simulation environments, respectively. It can be seen that of the various schemes, the IEEE 802.11 DCF protocol (with or without RTS/CTS) achieves the highest throughput fairness in every environment. In contrast to this protocol, EHDCF and the other traditional performance anomaly solutions assign different transmission priorities, i.e. different packet sizes or different channel access opportunities, to stations with different transmission data rates. As a result, high-rate stations receive more transmission opportunities than low-rate stations, and therefore achieve a higher throughput. However, this higher throughput is obtained at the expense of the lower-rate stations, and thus the throughput fairness

DOI: 10.1002/dac

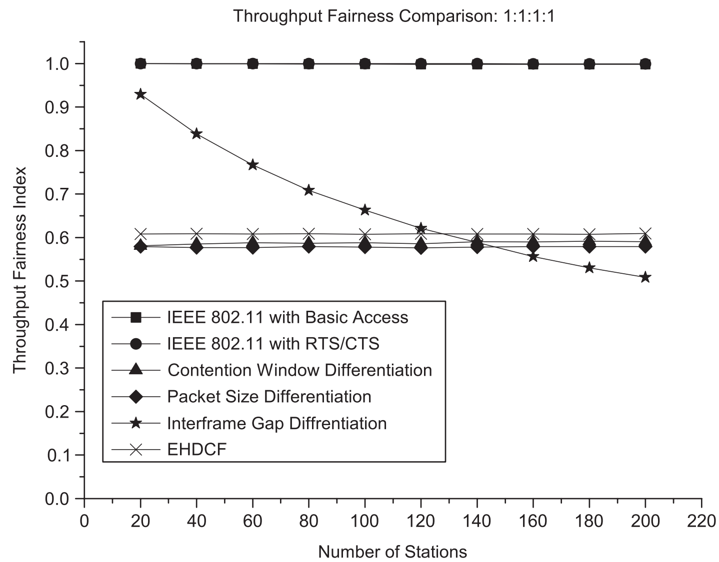

Figure 12. Throughput fairness in 1:1:1:1 network.

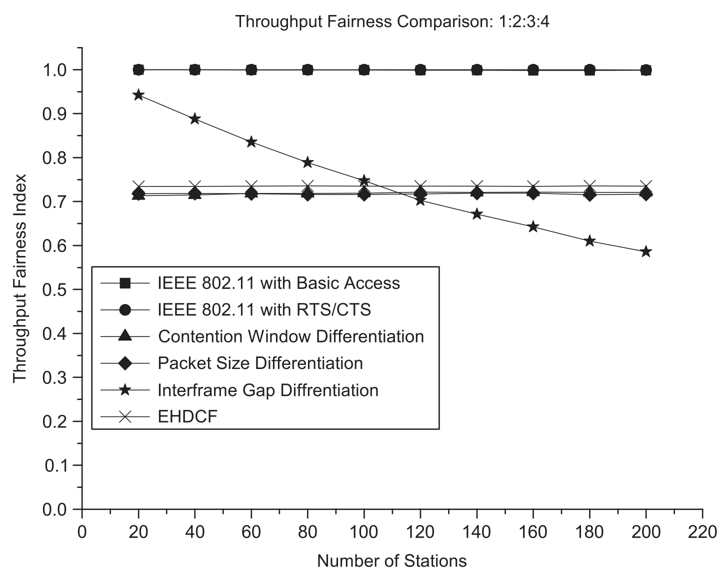

Figure 13. Throughput fairness in 1:2:3:4 network.

is less than that achieved using the IEEE 802.11 DCF protocol. Of the performance anomaly solutions, the IFG differentiation scheme achieves the highest throughput fairness under light-loaded network, while the EHDCF protocol achieves the second highest. However, it is noted that as

DOI: 10.1002/dac

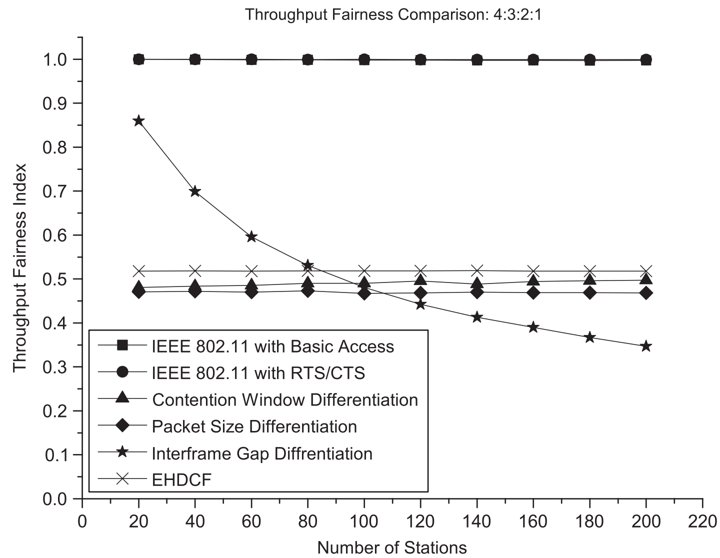

Figure 14. Throughput fairness in 4:3:2:1 network.

the number of stations increases, the throughput fairness index of the IFG differentiation scheme decreases, while that of the EHDCF protocol remains relatively unchanged. The degradation in the throughput fairness of the IFG differentiation scheme reflects the fact that the transmission channel is dominated by the high-rate stations, which increase in number and therefore occupy the channel for a greater proportion of time as the network size increases. By contrast, the EHDCF protocol always assigns transmission opportunities in accordance with Equation (1) irrespective of the number of nodes in the network, and thus the value of the throughput fairness index remains approximately constant as the size of the network is increased.

4.3.2. Temporal fairness. Figures 15–17 compare the temporal fairness of the EHDCF protocol with that of the IEEE 802.11 protocols and the traditional performance anomaly solutions in the three simulation environments, respectively. The results show that the various protocols can be ranked in terms of reducing temporal fairness as follows: PSD > EHDCF > CW differentiation > IEEE 802.11 (with or without RTS/CTS) > IFG differentiation. Although the PSD method yields the highest temporal fairness of the various schemes, its implementation requires the fragmentation and reassembly of the original data packets at the MAC layer of the source and receiver nodes, respectively, which increases both the computational complexity and the overall power consumption. By contrast, the EHDCF protocol transmits the data packets of the various stations in their original form, and thus no fragmentation or reassembly processes are required. Furthermore, although the EHDCF protocol assigns more transmission chances to the high-rate stations in the network than to the low-rate stations, the channel occupancy time is virtually the same for the two types of station provided that the packet size is fixed and of the same size. As a result, the EHDCF method achieves a good temporal fairness in all the considered networks.

DOI: 10.1002/dac

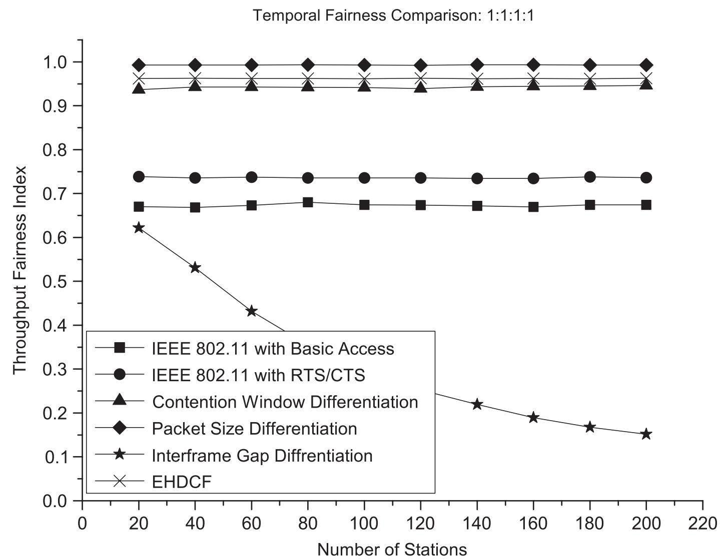

Figure 15. Temporal fairness in 1:1:1:1 network.

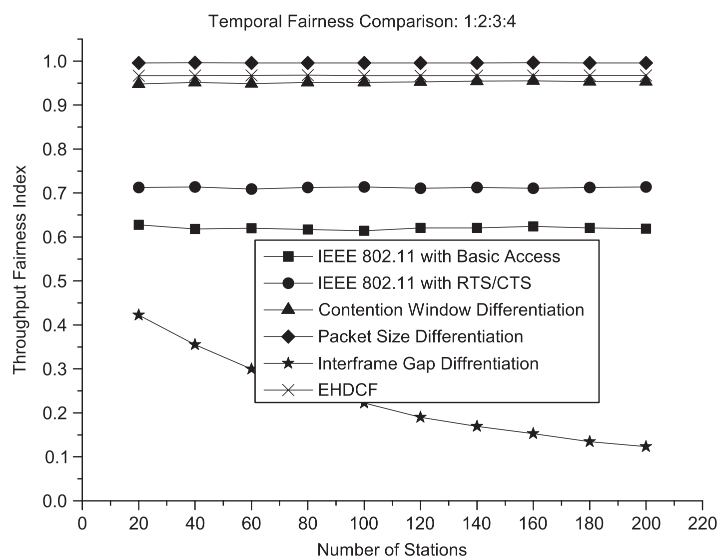

Figure 16. Temporal fairness in 1:2:3:4 network.

5. CONCLUSION

This paper has proposed an EHDCF protocol for alleviating the performance anomaly problem in multi-rate wireless networks. The efficacy of the proposed protocol has been confirmed by

DOI: 10.1002/dac

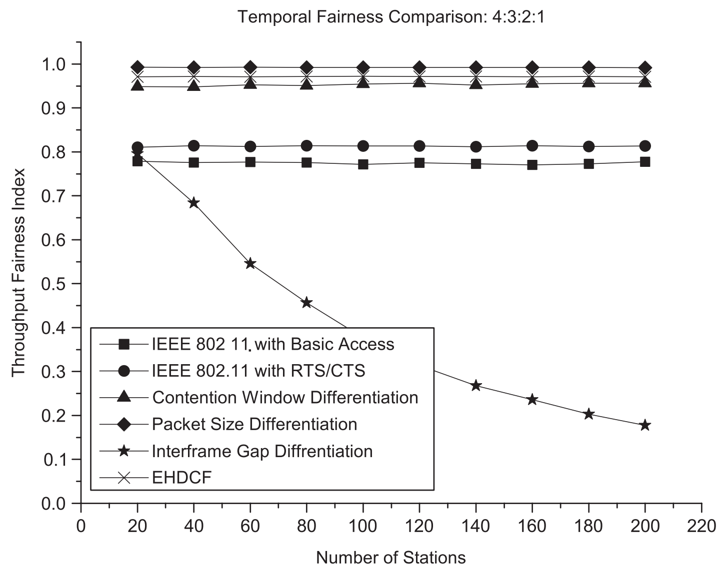

Figure 17. Temporal fairness in 4:3:2:1 network.

comparing its throughput and fairness characteristics with those of existing performance anomaly solutions, including the PSD method, the CW differentiation scheme and the IFG differentiation method. The simulation results have shown that EHDCF not only yields an effective improvement in the throughput of multi-rate wireless networks, but also guarantees the temporal fairness of all the stations within the network, irrespective of their transmission rates. In a future study, the EHDCF protocol will be extended to the resolution of the performance anomaly problem in multi-hop wireless network environments.

REFERENCES

1. IEEE Std 802.11b-1999. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: higher-speed physical layer extension in the 2.4 GHz band, 1999.
2. IEEE Std 802.11g-2003. Part 11: wireless LAN medium access (MAC) and physical layer (PHY) specifications. Amendment 4: further higher data rate extension in the 2.4 GHz band, 2003.
3. IEEE Std 802.11e-2005. Part 11: wireless LAN medium access (MAC) and physical layer (PHY) specifications. Amendment 8: medium access control (MAC) quality of service enhancement, 2005.
4. Kamerman A, Monteban L. WaveLAN-II: a high-performance wireless LAN for the unlicensed band. *Bell Labs Technical Journal* 1997; **2**(3):118–133.
5. Holland G, Vaidya N, Bahl P. A rate-adaptive MAC protocol for multi-hop wireless networks. *Proceedings of the Seventh Annual International Conference on Mobile Computing and Network*, Rome, Italy, 2001.
6. Heusse M, Rousseu F, Berger-Sabbatel G, Duda A. Performance anomaly of 802.11b. *Proceedings of the 22nd, Summer Annual Joint Conference of the IEEE Computer and Communication Societies*, San Francisco, U.S.A., 2003.
7. Heusse M, Rousseau F, Guillier R, Duda A. Idle sense: An optimal access method for high throughput and fairness in rate diverse wireless LANs. *Proceedings of SIGCOMM'05*, Philadelphia, U.S.A., August 2005.
8. Deng DJ, Li B, Huang L, Ke CH, Huang YM. Saturation throughput analysis of multi-rate IEEE 802.11 wireless networks. *Wireless Communication and Mobile Computing* 2008. DOI: 10.1002/wcm.668.

9. Deng DJ, Ke CH, Huang YM, Chen HH. Contention window optimization for IEEE 802.11 DCF access control. *IEEE Transactions on Wireless Communications* 2008; **7**(12):5129–5135.
10. Chatzimisios P, Boucouvalas AC, Vitsas V. Performance analysis of the IEEE 802.11 MAC protocol for Wireless LANs. *International Journal of Communication Systems* 2005; **18**(6):545–569.
11. Xiao Y, Pan Y. Differentiation, QoS guarantee, and optimization for real-time traffic over one-hop ad hoc networks. *IEEE Transactions on Parallel and Distributed Systems* 2005; **16**(6):538–549.
12. Bianchi G, Tinnirello I. Kalman filter estimation of the number of competing terminals in an IEEE 802.11 network. *Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications Societies*, San Francisco, U.S.A., 2003.
13. Arulampalam MS, Maskell S, Gordon N, Clapp T. A tutorial on particle filters for online nonlinear/non-Gaussian Bayesian tracking. *IEEE Transactions on Signal Processing* 2002; **50**(2):174–188.
14. Abu-Sharkh O, Tewfik AH. Throughput evaluation and enhancement in 802.11 WLANs with access point. *Proceedings of the IEEE 61st Vehicular Technology Conference*, Stockholm, Sweden, 2005.
15. Kim H, Yun S, Kang I, Bahk S. Resolving 802.11 performance anomalies through QoS differentiation. *IEEE Communication Letters* 2005; **9**(7):655–657.
16. Chetoui Y, Bouabdallah N. Adjustment mechanism for the IEEE 802.11 contention window: an efficient bandwidth sharing scheme. *Computer Communications Journal* 2007; **30**(13):2686–2695.
17. Chen DR, Zhang YJ. Distributed MAC strategy for exploiting multi-user diversity in multi-rate IEEE 802.11 wireless LANs. *Proceedings of IEEE International Conference on Mobile Adhoc and Sensor System*, Pisa, Italy, October 2007.
18. Al-Mefleh H, Chang JM. High performance distributed coordination function for wireless LANs. *Proceedings of IFIP Networking*, Singapore, May 2008.
19. Xiao Y, Rosdahl R. Throughput and delay limits of IEEE 802.11. *IEEE Communications Letters* 2002; **6**(8): 355–357.
20. Jain R, Chiu D, Hawe W. A quantitative measure of fairness and discrimination for resource allocation in shared computer systems. *DEC Research Report TR-301*, September 1984.

AUTHORS' BIOGRAPHIES

Chih-Heng Ke received his BS and PhD degrees in Electrical Engineering from National Cheng-Kung University, in 1999 and 2007. His is an assistant professor of Computer Science and Information Engineering, National Kinmen Institute of Technology, Kinmen, Taiwan. His current research interests include multimedia communications, wireless network and QoS network.

Bin Li is a PhD candidate in the Department of Computer Science and Engineering at the University of Texas at Arlington, U.S. He received his MS degree in Communication Engineering and BS degree in Electronic Engineering from Xiamen University, China, in 2008 and 2005, respectively. His research interests include wireless network and wireless communication.

DOI: 10.1002/dac

Yueh-Min Huang is a distinguished professor and chairman of the Department of Engineering Science, National Cheng-Kung University, Taiwan. His research interests include multimedia communications, wireless networks, artificial intelligence and e-Learning. He received his MS and PhD degrees in Electrical Engineering from the University of Arizona in 1988 and 1991, respectively. He has co-authored two books and has published about 200 refereed professional research papers. Dr Huang has received many research awards, such as the Best Paper Award of 2007 IEA/AIE Conference, Best Paper Award of the Computer Society of the Republic of China in 2003, the Awards of Acer Long-term Prize in 1996, 1998 and 1999, Excellent Research Awards of National Microcomputer and Communication Contests in 2006. Dr Huang has been invited to give talks or served frequently in the program committee at national and international conferences. Dr Huang is in the editorial board of the Journal of Wireless Communications and Mobile Computing, Journal of Security and Communication Networks and International Journal of Communication Systems. Huang is a member of the IEEE as well as IEEE Communication, Computer, and Circuits and Systems Societies.

J. Morris Chang joined Iowa State University in August 2001. His industrial experience includes positions at Texas Instruments, Taiwan (1983–1984), Microelectronics Center of North Carolina, Research Triangle Park, North Carolina (1986–1988) and AT&T Bell Laboratories, Allentown, Pennsylvania (1988–1990). He was on the faculty of the Department of Electrical Engineering at the Rochester Institute of Technology, Rochester, NY (1993–1995) and the Department of Computer Science at Illinois Institute of Technology, Chicago, IL (1995–2001). He received the IIT University Excellence in Teaching Award in 1999.

DOI: 10.1002/dac