Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2006, Article ID 80493, Pages 1–11
DOI 10.1155/WCN/2006/80493

Opportunistic Nonorthogonal Packet Scheduling in Fixed Broadband Wireless Access Networks

Mahmudur Rahman,[1] Halim Yanikomeroglu,[1] Mohamed H. Ahmed,[2] and Samy Mahmoud[1]

[1] *Broadband Communications and Wireless Systems (BCWS) Centre, Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada K1S 5B6*
[2] *Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL, Canada A1B 3X5*

Received 14 October 2005; Revised 11 March 2006; Accepted 13 March 2006

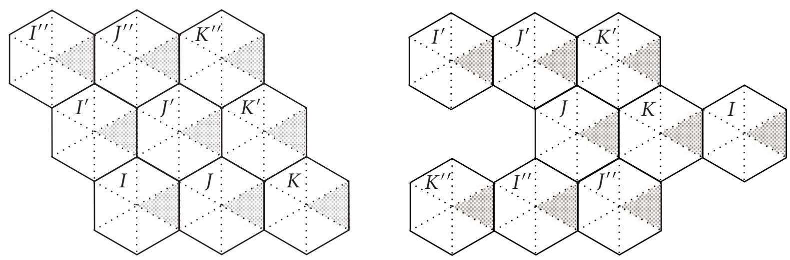
In order to mitigate high cochannel interference resulting from dense channel reuse, the interference management issues are often considered as essential part of scheduling schemes in *fixed broadband wireless access* (FBWA) networks. To that end, a series of literature has been published recently, in which a group of base stations forms an *interferer group* (downlink transmissions from each base station become dominant interference for the users in other in-group base stations), and the scheduling scheme deployed in the group allows only one base station to transmit at a time. As a result of time orthogonality in transmissions, the dominant cochannel interferers are prevented, and hence the packet error rate can be improved. However, prohibiting concurrent transmissions in these orthogonal schemes introduces throughput penalty as well as higher end-to-end packet delay which might not be desirable for real-time services. In this paper, we utilize *opportunistic nonorthogonality* among the in-group transmissions whenever possible and propose a novel transmission scheduling scheme for FBWA networks. The proposed scheme, in contrast to the proactive *interference avoidance* techniques, strives for the improvements in delay and throughput efficiency. To facilitate opportunistic nonorthogonal transmissions in the interferer group, estimation of *signal-to-interference-plus-noise ratio* (SINR) is required at the scheduler. We have observed from simulations that the proposed scheme outperforms the reference orthogonal scheme in terms of spectral efficiency, mean packet delay, and packet dropping rate.

1. INTRODUCTION

Fixed broadband wireless access (FBWA) [1, 2] is recognized to be a promising alternative technology to existing copper line *asymmetric digital subscriber loop* (ADSL) [3, 4] and *hybrid fiber-coaxial* (HFC) [5] cable broadband services for its fast, simple, and less expensive deployment. However, efficient system planning and resource allocation policies are warranted for such systems, because in addition to the challenges posed by the dynamic nature of wireless links, interference resulting from aggressive channel reuse is a major design concern. Therefore, resource allocation strategies play a major role for the successful evolution of FBWA. In this paper, we focus on one of the most important aspects of resource allocation, *packet scheduling*.

Wireless scheduling techniques [6–10] have emerged as tailored versions of wireline scheduling to cope with the dynamic nature of wireless links. To account for cochannel interference, it is common to consider the issues of interference management as an integral part of scheduling techniques in FBWA networks [11–16]. In our previous works [12, 13], we have shown that a very effective means of managing interference is to employ coordinated orthogonal transmissions among dominant interferers achieved by inter-base station (BS) signaling. The main idea of this scheme is to group a number of BSs (termed as *interferer group*) that are dominant interferers to each other and to schedule transmission orthogonally so that only one BS in the group transmits at a particular time. This scheme is composed of two independent scheduling disciplines and hence named as *intrasector and intersector scheduling* (ISISS) [13].

High end-to-end packet delay is the main drawback of the ISISS scheme. Packet delay is an important *quality-of-service* (QoS) parameter for a variety of delay-sensitive applications, which is directly related to the throughput for a given data rate. Therefore, improving throughput and delay in an orthogonal scheduling scheme is essential. In this paper, we propose a novel scheduling scheme that improves both packet delay and resource utilization in terms of area spectral efficiency. The performance of the proposed scheme



(a) (b)

Figure 1: (a) Nine-cell network, (b) wraparound interferer positions for SSs in BS I.

is compared to that of a reference scheme adapted from basic ISISS [13]. This reference scheme is named as *intrasector and orthogonal intersector scheduling with fixed modulation* (ISOISS-FM).

Proposed scheme in this paper considers interference management issues, integrates adaptive modulation and coding (AMC), and makes channel-state-based scheduling decisions to enhance network performance. We investigate the performance of the proposed scheme in two steps. First, we introduce AMC instead of fixed modulation and evaluate the performance of the scheme. The resulting scheme is still orthogonal, while it makes channel-state-based scheduling decisions. This intermediate scheme is named as *intrasector and orthogonal intersector scheduling with adaptive modulation and coding* (ISOISS-AMC). Investigation of this intermediate scheme quantifies the performance gain achieved from the use of AMC in an orthogonal scheme. We then employ opportunistic nonorthogonality in transmissions, where multiple cochannel BSs are allowed to transmit simultaneously. This final scheme is named as *intrasector and opportunistic nonorthogonal intersector scheduling with adaptive modulation and coding* (ISONOISS-AMC). Basically, if a number of cochannel BSs transmit simultaneously, each becomes interferer for the users in other BSs. The idea is that if the interference levels (hence the SINRs) are predicted and are transparent to each BS in the group, then every BS in the interferer group would potentially be able to transmit simultaneously with its feasible AMC mode in the presence of others being interferers.

Opportunistic scheduling, in general, implies a scheduling mechanism that exploits channel variations and schedules a user having the best channel condition at the time of interest [17]. However, according to the context of our study in this paper, *opportunistic nonorthogonal scheduling* means exploitation of channel variations among a group of mutually interfering BSs and scheduling concurrent in-group transmissions opportunistically based on the mutual interference situation.

The proposed scheme in contrast to the widely studied proactive interference avoidance techniques predicts the interference and achievable SINR on the fly. It then decides whether or not concurrent transmissions in the interferer group should be allowed at a particular instant. This reactive interference-aware scheduling scheme allows controlled in-group interference, which functions adaptively in an optimistic manner yielding the capability of improving throughput and the delay. The details of the proposed scheme are illustrated in Section 3.

Similar notion of concurrent cochannel transmissions based on terminal classifications has been previously considered in the *enhanced staggered resource allocation* (ESRA) scheme [14]. However, the time slot allocation in that scheme is static, which might result in low resource utilization especially for bursty traffic such as in FBWA. The proposed scheme in this paper, on the contrary, is dynamic in nature, adaptive according to the channel state, and optimistic.

The intermediate and proposed schemes are more prone to packet errors compared to the reference ISOISS-FM, primarily because the predicted SINRs in these schemes do not account for the out-of-group interference. We define parameter *interference compensation guard* to offset overestimation in the predicted SINR. This guard acts as a method of protecting the in-group transmissions to a certain degree from out-of-group interference. The effect of *interference compensation guard* on the performance of proposed ISONOISS-AMC scheme has also been investigated.

The rest of this paper is organized as follows. Section 2 describes the reference ISOISS-FM scheme. The intermediate ISOISS-AMC and proposed ISONOISS-AMC schemes are illustrated in Section 3. Section 4 describes system model. Simulation results are presented in Section 5 followed by conclusions in Section 6.

2. REFERENCE SCHEME: ISOISS-FM

A downlink *time-division multiple-access* (TDMA) system in a hexagonal six-sectored nine-cell network as shown in Figure 1(a) is considered in the reference as well as in the intermediate and proposed schemes. It is assumed that a frequency reuse plan with a reuse factor of 1/6 is employed in the network. The shaded sectors[1] (e.g., sector 1 in Figure 1) in all cells use the same frequency band. It should be noted here that an alternative assignment technique for sectors,

[1] Only the shaded cochannel sectors (one sector per cell site) are simulated in this study. Therefore, BS I, for instance, implies shaded sector of BS I throughout this paper. Note that the reuse factor is 1/6, and therefore there is no intersector interference among the sectors of a particular cell.

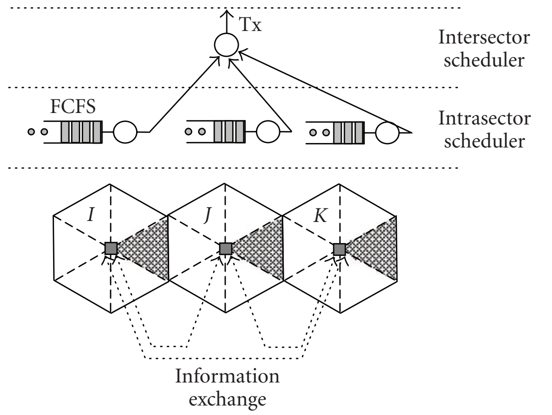


Figure 2: Block diagram of the scheduling scheme in group $\{I, J, K\}$.

such as the rotational or *staggering* approach used in [11] or [14], is also possible in order to reduce intersector interference, especially for lower network loading. The rationale behind the assignment used in this study, where cochannel sectors are positioned in a line, is to investigate the worst-case intersector interference scenario. However, the proposed scheduling scheme can be employed with any other frequency planning to enhance the performance in addition to what can be obtained by the static frequency assignment alone. We assume that base stations and subscriber station (SS) terminals are equipped with directional antennas with 60° and 30° beamwidths, respectively. The SS antennas are pointing towards the serving BSs. The effective gains of BS transmit and SS receive antennas are considered to be 20 dB (10 dB main and −10 dB side lobe) and 10 dB (5 dB main and −5 dB side lobe), respectively.

We have considered wraparound interference model such that an interferer BS position is taken to be at a place from where it contributes the maximum interference for the SSs in the BS of interest (see [18] for details). Figure 1(b) shows the positions of the interferer BSs for the SSs in BS I. Base station sets $\{J, K\}$ and $\{I', J', K', I'', J'', K''\}$ are potential in-group and out-of-group interferers for the SSs in BS I, respectively. A similar approach can be followed to find out the positions of interferers for SSs in other BSs. It can easily be conceived that as a result of combined effects of the antenna directivities, gains, and relative positions of the cells, the downlink transmissions from BSs I and Jwill be the two most dominant interferers for the SSs in BS K. Similarly, BS I and wraparound BS K (considered to be at the left of BS I) would be the most dominant interferers for the SSs in BS J. Moreover, wraparound BSs J and K are the most dominant interferers for SSs in BS I. Following these arguments, BSs I, J, and K form an *interferer group*. Similarly, BSs $\{I', J', K'\}$ and $\{I'', J'', K''\}$ form two other interferer groups in the network.

The scheduling scheme (reference, intermediate, or proposed) is employed in each interferer group as shown in Figure 2 for interferer group $\{I, J, K\}$. The in-group BSs exchange information with each other as illustrated in the figure. The intrasector scheduling discipline decides the service order of each SS inside the sector, while the intersector discipline determines the service order among different BSs in the group to ensure orthogonal or opportunistic nonorthogonal transmissions in the *interferer group*. As the contributions of the schemes lie in the intersector scheduler, for simplicity the *first-come-first-serve* (FCFS) principle is considered as the intrasector discipline in the reference system as well as in the intermediate and proposed schemes.

Transmissions use fixed 16-*quadrature amplitude modulation* (16-QAM) *bit-interleaved coded modulation* (BICM) with a coding rate of 1/2 in the reference ISOISS-FM scheme. Base stations in the interferer group exchange traffic-related information, such as the arrival times of the packets (with the packet lengths) arrived in previous data frame duration. Therefore, each BS in the group is aware of the arrival times of the packets of its own queue as well as the packets of the queues of the other BSs in the group. The intersector scheduler checks the arrival times of the *head-of-line* (HOL) packets in all three queues in the group and selects the candidate packet to be transmitted that has the earliest arrival time; for example, in group $\{I, J, K\}$at a particular instant,

$$w = \arg\min_{I,J,K} \left(t_a^i, t_a^j, t_a^k \right), \tag{1}$$

where w is the BS that wins the service opportunity at that instant, and t_a^i, t_a^j, and $t_a^k$are the arrival times of the HOL packets at BSs I, J, and K destined to SSs i, j, and k, respectively.

3. DESCRIPTIONS OF THE INTERMEDIATE AND PROPOSED SCHEMES

Schematically, the reference, intermediate, and proposed schemes are alike in the sense that they all are composed of two independent schedulers (intrasector and intersector). The main difference is in the function of the intersector schedulers and modulation (fixed or adaptive). The intermediate and proposed schemes make channel-state-based scheduling decisions and employ AMC based on the predicted SINR for transmissions towards particular SSs. In this section, we provide an overview of the SINR estimation first, and then we describe how the intersector schedulers work in ISOISS-AMC and ISONONISS-AMC schemes.

3.1. SINR estimation and BS information exchange

In order for the intermediate and proposed schemes to be able to execute link-state-based scheduling decisions and employ AMC, SINR would have to be estimated at each BS. For the nine-cell network shown in Figure 1(a), every transmission will have eight potential interferers. Let us consider the scenario shown in Figure 1(b). The SINR of a received packet at SS i served by BS I can be expressed as

$$\gamma^i = \frac{P_t G_I^i}{P_t \sum_{x \in IG,\, x \neq I} A_x G_x^i + P_t \sum_{y \in OG} A_y G_y^i + P_N^i}, \tag{2}$$

where P_t is the fixed transmit power. The first term in the denominator is the summation of interference from in-group BSs (IG) and the second term expresses the total interference from out-of-group BSs (OG). For the given scenario, $IG \approx \{I, J, K\}$and $OG \approx \{I', J', K', I'', J'', K''\}$. Parameter G_I^i is the link gain between the serving BS I and SS i. Parameters G_x^i and G_y^i are the link gains to the desired SS i from the interfering in-group and out-of-group BSs, respectively. These link gain parameters include the effect of antenna gains at the BS and the SS terminals, as well as the propagation loss (including shadowing and fading) of the link. In (2), P_N^i is the average thermal noise computed at the receiver of SS i.

We note that all BSs do not necessarily transmit simultaneously because of either algorithm dictation or empty queues. The parameters A_x and A_y in (2) denote *activity factor*s which take value of 1 if the interferer BS is transmitting and 0 if it is idle. An expression similar to (2) is applicable for the SINR at any SS in other BSs.

The link gain parameters are monitored at the SS terminal and reported back to the serving BS from where they are exchanged among in-group BSs by inter-BS signaling. For example, SS i in the interferer group of $\{I, J, K\}$ keeps track of G_I^i, G_J^i, and G_K^i, and reports this information to the serving BS I as often as necessary. BS I shares this information with in-group BSs J and K. It is important to note that the channel changes slowly because of the fixed SS locations; this yields low Doppler shifts in FBWA networks. Therefore, link state reporting does not have to be very frequent, which makes it completely feasible in such systems.

Since the inter-BS signaling is performed only among in-group interferers, BSs do not have knowledge about the out-of-group interference, and hence the estimated SINRs do not include the second denominator term in (2). The estimated SINRs for orthogonal ISOISS-AMC scheme, γ_O^i, and for opportunistic nonorthogonal ISONOISS-AMC scheme, γ_{ONO}^i, for SS i are given as follows:

$$\gamma_O^i = \frac{P_t G_I^i}{P_N^i}, \tag{3}$$

$$\gamma_{ONO}^i = \frac{P_t G_I^i}{P_t \sum_{x \in IG, x \neq I} A_x G_x^i + P_N^i}. \tag{4}$$

From (3), we see that only the link gains from the serving BSs to desired SSs, for example, $\{G_I^i, G_J^j, G_K^k\}$ for BS group $\{I, J, K\}$, are required in order to estimate SINRs in ISOISS-AMC, while additional link gain information $\{G_I^j, G_I^k, G_J^i, G_J^k, G_K^i, G_K^j\}$ are to be exchanged in ISONOISS-AMC as in (4). The number of in-group interference contributing terms in the denominator of (4) equals the number of in-group BSs transmitting simultaneously, minus one.

3.2. Intersector scheduler in the intermediate ISOISS-AMC scheme

Similar to ISOISS-FM scheme, this scheme is orthogonal as well; however, it employs AMC instead of fixed modulation and makes channel-state-based scheduling decisions as opposed to the arrival-time-based decisions in ISOISS-FM. At any time, three HOL packets in the in-group BSs are compared by the intersector scheduler to select the candidate BS that has the best link to the SS. If SSs i, j, and k are the candidates for HOL packets in BSs I, J, and K in the interferer group, and G_I^i, G_J^j, and G_K^k are the link gains from BSs to SSs, respectively, then

$$w = \arg\max_{I,J,K} \left(G_I^i, G_J^j, G_K^k\right), \tag{5}$$

where w is the BS that wins the scheduling opportunity.

The selected BS predicts the SINR according to (3) or a similar expression. Using this estimated SINR, the feasible AMC mode is chosen from Table 1 and the packet is scheduled for the instant. It should be noted that the modulation schemes listed in Table 1 are the mandatory schemes for downlink transmissions recommended by the 802.16 a standard [1].

Table 1: Lookup table for AMC modes. Data for BICM modulation curves are provided by Dr. Sirikiat Lek Ariyavisitakul.

SINR range (dB)	AMC mode	Efficiency, (bits/s/Hz)
$3.39 \le \gamma < 5.12$	QPSK rate 1/2	1.0
$5.12 \le \gamma < 6.02$	QPSK rate 2/3	1.33
$6.02 \le \gamma < 7.78$	QPSK rate 3/4	1.5
$7.78 \le \gamma < 9.23$	QPSK rate 7/8	1.75
$9.23 \le \gamma < 11.36$	16-QAM rate 1/2	2.0
$11.36 \le \gamma < 12.50$	16-QAM rate 2/3	2.67
$12.5 \le \gamma < 14.21$	16-QAM rate 3/4	3.0
$14.21 \le \gamma < 16.78$	16-QAM rate 7/8	3.5
$16.78 \le \gamma < 18.16$	64-QAM rate 2/3	4.0
$18.16 \le \gamma < 20.13$	64-QAM rate 3/4	4.5
$20.13 \le \gamma < 24.30$	64-QAM rate 7/8	5.25
$\gamma \ge 24.30$	64-QAM rate 1	6.0

3.3. Intersector scheduler in the proposed ISONOISS-AMC scheme

Using estimated SINRs from (4), the intersector scheduler finds a combination of concurrent transmissions that gives the highest aggregate throughput efficiency. If queues of all in-group BSs are nonempty, there are seven possible combinations of transmissions at a particular instant. For example, all three BSs transmit (1 choice) or two BSs transmit (3 choices), or only one BS transmits (3 choices). We note that the last 3 choices are only available transmission options in ISOISS-AMC. For each combination, first, the SINRs are estimated from exchanged information as discussed. Then, the spectral efficiency for each transmission is calculated. Finally, the aggregate spectral efficiency for the combination of simultaneous transmissions is predicted.

Let us illustrate the steps for the first combination when all three BSs I, J, and K have potential to transmit concurrently to respective SSs i, j, and k. Each reception will have two in-group interferers. Therefore, according to (4) the estimated SINR at SS i's packet, given I, J, and K are transmitting simultaneously, is

$$\gamma_{ONO}^{i|(I,J,K)} = \frac{P_t G_I^i}{P_t G_J^i + P_t G_K^i + P_N^i}. \quad (6)$$

Similarly, for BSs J and K, $\gamma_{ONO}^{j|(I,J,K)}$ and $\gamma_{ONO}^{k|(I,J,K)}$ can be found in a straightforward manner.

From these estimated SINRs, the achievable AMC modes, and corresponding spectral efficiencies η_I, η_J, and η_K can be obtained from Table 1. Then, the aggregate spectral efficiency $\Gamma_{I,J,K}$ for the combination is calculated from the following relation:

$$\Gamma_{I,J,K} = \left(\eta_I \times \frac{t_d^i}{t_r}\right) + \left(\eta_J \times \frac{t_d^j}{t_r}\right) + \left(\eta_K \times \frac{t_d^k}{t_r}\right), \quad (7)$$

where t_d^i, t_d^j, and $t_d^k$are the transmission durations for BSs I, J, and K's packet determined by the packet length and AMC modes as discussed later. The longest transmission time among all three transmission durations is denoted as t_r, that is, $t_r = \max(t_d^i, t_d^j, t_d^k)$.

Similarly, aggregate spectral efficiencies for other combinations, namely $\Gamma_{I,J}$, $\Gamma_{J,K}$, $\Gamma_{K,I}$, Γ_I, Γ_J, and Γ_K, can be calculated. Service opportunity is granted to the combination of BSs that gives highest aggregate spectral efficiency according to the following:

$$w = \arg\max(\Gamma_{I,J,K}, \Gamma_{I,J}, \Gamma_{J,K}, \Gamma_{K,I}, \Gamma_I, \Gamma_J, \Gamma_K), \quad (8)$$

where w is the set of BSs transmiting concurrently.

We note here that packets in different BSs take different lengths of frame time due to the variability of packet size, modulation level, and coding rate. In order to avoid excessive interference, a new scheduling event cannot be made until the largest transmission time t_r of the previous event elapses.

3.4. *Out-of-group interference guard*

An effort has been made in order to avoid out-of-group interference as much as possible in all simulated scheduling schemes by using groupwise time partitioning in the frame. The frame is partitioned into three subframes (SFs), indexed as SF1, SF2, and SF3 from start to the end of the frame. BSs in the interferer group $\{I, J, K\}$ schedule their traffic with the subframe sequence of {SF1, SF2, SF3}, while, group $\{I', J', K'\}$ and $\{I'', J'', K''\}$ use the sub-frames in the sequences of {SF2, SF3, SF1} and {SF3, SF1, SF2}, respectively. Clearly, this technique is effective as long as the arriving traffic in each group is such that it can be accommodated into 1/3 of the frame. However, the system must be designed for loaded network where out-of-group interference is inevitable.

SINR estimations discussed in Section 3.1 do not take the out-of-group interference into account. As a result, the estimations are optimistic, which might result in higher packet error rate. To investigate the effects of out-of-group interference on network performance, we consider an out-of-group interference guard while making SINR estimations. Let us denote that 50th percentile value of the error between the actual and estimated SINR is $\phi(l)$ (dB), which is a function of the network loading l users/sector. There could be numerous ways to find this error in a real network. For example, the network can be equipped with a mechanism to track out-of-group interference from history. However, in this study, we find this error from simulations as follows. First, a set of SINRs for different loading values is noted in the presence of out-of-group interferers. Then, a second set is generated where the out-of-group interferers are neglected. Now, the difference of the 50th percentile SINR (dB) of these two sets gives $\phi(l)$. Table 2 shows different $\phi(l)$ values for different network loading levels obtained in the ISONOISS-AMC scheme. We investigate the effect of this guard only for the proposed scheme.

Table 2: Out-of-group interference compensation values for ISONOISS-AMC.

Network loading (SSs/sector)	Compensation guard (dB)
4	0.17
8	0.84
12	1.29
14	2.20
16	2.08
18	2.33
20	2.40
24	2.44

The amount of error $\phi(l)$ (dB) is subtracted from (4) (dB) to obtain the expected SINR in ISONOISS-AMC. The estimated SINR with guard at SS i's packet, given I, J, and K are transmitting simultaneously, is

$$\gamma_{ONO,\text{guard}}^{i|(i,J,K)} = 10\log_{10}\left(\frac{P_t G_I^i}{P_t G_J^i + P_t G_K^i + P_N^i}\right) - \phi(l). \quad (9)$$

However, while employing this guard is expected to improve the packet error rate performance of the proposed scheme, it will lower the throughput, as the scheduler chooses the AMC modes more conservatively. Therefore, this interference guard can be regarded as a system design parameter to be adjusted according to desired tradeoff between the packet error rate and throughput efficiency.

3.5. *A note on implementations*

It should be mentioned that in a practical deployment scenario, a single BS would qualify as a member of three independent interferer groups for the above-described setting. Therefore, there is an issue of resolving the conflicts that might arise from the commands of three different groups. Our focus in this paper is to present the basic concept of opportunistic nonorthogonal scheduling; nevertheless, we state a number of solutions to this issue. First, the interferer groups can be determined in such a way that each BS can only be a member of only one interferer group. This deployment

Table 3: System parameters.

Parameters	Values
Hexagonal six-sectored cell radius (km)	2.0
Propagation exponent, n	3.75
Fixed transmit power (Watts)	6.5
BS antenna (60^0 beam width) gain (dB)	20 (front 10, back −10)
SS antenna (30^0 beam width) gain (dB)	10 (front 5, back −5)
Transmission direction	Downlink
Uplink-downlink duplexing	FDD
Multiple access	TDMA
Frequency reuse factor	1/6
Carrier frequency, f (GHz)	2.5
Channel bandwidth, B (MHz)	3.0
Time-correlated Rayleigh fading: max. Doppler freq., f_m (Hz)	2.0
Independent lognormal shadowing: standard deviation (dB)	8.0
Noise power, P_N (dBW)	−134.06
Frame length (ms)	5.0
Average data rate per user (kbps)	404.16
Simulation tool used	OPNET Modeler 9.1 [19]

solution would result in some degradation in performance in terms of overall network interference; however, this solution would still control in-group interference for a subset BSs in the group. Secondly, even when a BS is a member of different interferer groups and receives different commands, a second tier of the control scheme (e.g., the majority rule algorithm) can be employed to resolve the conflicts. For instance, when a BS is a member of three groups, it can only transmit when the decisions from two or more groups go in favor of transmissions.

4. SYSTEM MODEL

Table 3 summarizes system parameters used in this study. The path-loss model has been taken from [20, 21]. For a transmitter-receiver (T-R) separation of d meters the large-scale path-loss (in linear scale) PL including shadowing is given by the following relation:

$$PL = \begin{cases} \left(\frac{4\pi d_0}{\lambda}\right)^2 \left(\frac{d}{d_0}\right)^n \left(\frac{f}{2000}\right)^{0.6} \left(\frac{h_r}{2}\right)^{-2} 10^{X_\sigma/10}, & d \geq d_0, \\ \left(\frac{4\pi d}{\lambda}\right)^2 10^{X_\sigma/10}, & d < d_0, \end{cases} \tag{10}$$

where n is the propagation exponent (we have taken $n = 3.75$ for 50-meter antenna height in terrain type C; see [20, 21] for details). Parameter d_0 is the close-in reference distance considered to be 50 m, f is the operating frequency in MHz, λ is the operating wavelength related to speed of light c and operating frequency f, and h_r is the receiver antenna height in meters which is considered to be 3 meters. Parameter X_σ is a Gaussian distributed random variable with a mean of 0 and a standard deviation of σ used for shadowing. We have considered independent lognormal random variables with a standard deviation of 8 dB for shadowing.

Table 4: Traffic model parameters of the video stream [22].

IRP	Packet arrival rate (packets/s)	Pareto parameter for ON distribution	Pareto parameter for OFF distribution
IRP#1	112.38	1.14	1.22
IRP#2	154.75	1.54	1.28

Time-correlated flat Rayleigh fading with Doppler frequency of 2.0 Hz has been considered in this study, where the Doppler spectrum $S(f)$ is given by the following equation [20, 21]:

$$S(f) = \begin{cases} 1 - 7.2 f_0^2 + 0.785 f_0^4, & |f_0| \leq 1, \\ 0, & |f_0| > 1. \end{cases} \tag{11}$$

In the above, $f_0 = f/f_m$, where f_m is the maximum Doppler frequency.

With a channel bandwidth of 3.0 MHz and noise figure (NF) of 5 dB, the average noise power is −134.06 dBW.

To evaluate the proposed scheme, real-time video traffic is used in this study. *Two interrupted renewal process* (2IRP) sources are superimposed to model the user's video traffic in the downlink transmission as indicated in [22]. The average packet rate of one 2IRP generator is 126.3 packets per second determined from parameters given in Table 4. The length of packets is assumed to be variable and is uniformly distributed between 250 to 550 bytes. Therefore, the average downlink data rate for each SS is 404.16 kbps.

End-to-end packet delay is the summation of queuing delay and packet transmission delay. Packet transmission delay depends on the packet size L_p, symbol rate of the transmission channel r_s, modulation level M, and coding rate r_c, and is expressed as

$$t_d = \frac{L_p}{r_s r_c \log_2 M}. \tag{12}$$

We assume asynchronous transmission such that interferers may arrive or leave anytime during the transmission time of a packet of interest. Therefore, SINR varies, and the packet experiences different bit error rates at different segments of the packet. The number of erroneous bits in a segment s is given by the product of the probability of the bit error in the segment $\Pr_{b(s)}$ and the number of bits corresponding to the segment length $N_{b(s)}$. The total number of bits in error in the packet N_e can be written by the following relation:

$$N_e = \sum_{s=1}^{S} pr_{b(s)} N_{b(s)}, \tag{13}$$

where S is the total number of segments in that packet experiencing different SINR.

The total number of erroneous bits is used to decide whether the packet is received correctly. In simulations, we

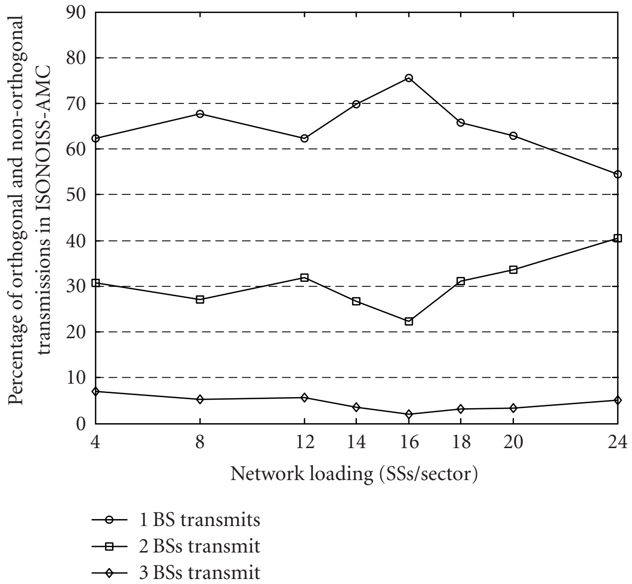


Figure 3: Percentage of single and multiple transmissions in ISONOISS-AMC.

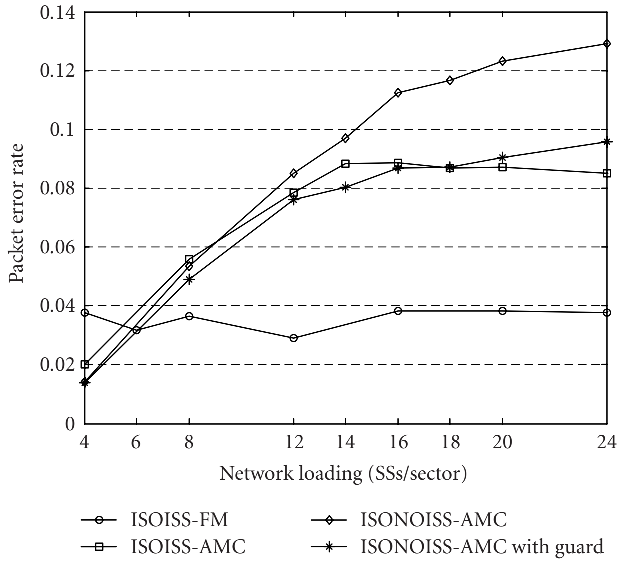


Figure 4: Packet error rate in different schemes.

assume that a packet is considered to be in error if more than 1% of the total bits present in the packet are erroneous. Retransmissions of erroneous packets by *automatic repeat request* (ARQ) are not considered in this study.

The frame length is considered to be 5 milliseconds. Packets are scheduled in a frame-by-frame basis at the start of every frame. Any packet arriving at current frame time will have to wait at least until the start of the next frame.

5. SIMULATION RESULTS

The performance of the proposed scheduling scheme ISONOISS-AMC is evaluated by comparing it with that of the reference scheme ISOISS-FM in terms of the essential network performance parameters such as *packet error rate*, *area spectral efficiency*, *packet dropping rate*, and the *mean end-to-end packet delay*. Also, the performance of ISOISS-AMC is shown in order to quantify the benefits of employing AMC alone. These performance metrics are functions of network loading and are observed against the number of SSs per sector (varied from 4 to 24).

The packet error rate is the ratio of the number of erroneous packets to the total packets received during the simulation period. The area spectral efficiency is expressed as the correctly received information bits per second per Hz per sector. Packet is dropped from the BS queue when the queuing delay exceeds 195 milliseconds. The delay constraint is assumed to be 200 milliseconds (For interactive video, such as videoconferencing) with a 5- milliseconds safety margin provided to ensure that every packet received by the SS meets the delay requirement. We express packet dropping rate in packets per frame per sector. The mean end-to-end delay measure does not include the delays of the dropped packets in the queue at transmitter side.

The network simulation is executed in real time, using OPNET [19] Modeler and wireless module, and the statistics are taken over a long enough time for the observed parameters to converge. It should be noted that *shadowing* for a particular SS does not change over simulation time as the SS location is fixed. At any loading, a set of shadowing values is assigned for all SSs (randomly placed) in the network. During the course of simulation time, neither the locations of SSs nor the shadowing values are changed. For any particular SS, fading is correlated and it changes over time. Therefore, performed simulation is Monte Carlo in the time axis, but not for SS locations and shadowing. However, statistics are collected in sectors of all nine cells in the network, and hence there is a certain degree of averaging with respect to the SS locations.

Figure 3 shows the percentage of the scheduling decisions that yields into 1, 2, and 3 (all) in-group BSs transmissions in ISONOISS-AMC scheme. We observe that around 35% of the time, the scheme is capable of using opportunistic nonorthogonality in transmissions (all three BSs transmit 5% of the time and any 2 BSs transmit 30% of the time) giving higher aggregate spectral efficiency than single transmission.

Figure 4 compares the packet error rate performance of the proposed, reference, and intermediate schemes. The modulation and coding level used in the reference ISOISS-FM scheme is more robust than the channel-state-based chosen AMC modes in the proposed ISONOISS-AMC scheme. Also, increased number of packets in the air results in increased number of out-of-group interferers in ISONOISS-AMC scheme. Consequently, the packet error rate in proposed scheme is higher. The packet error rate of ISOISS-AMC fall in between the reference and proposed schemes as ISOISS-AMC suffers less from interference in comparison to

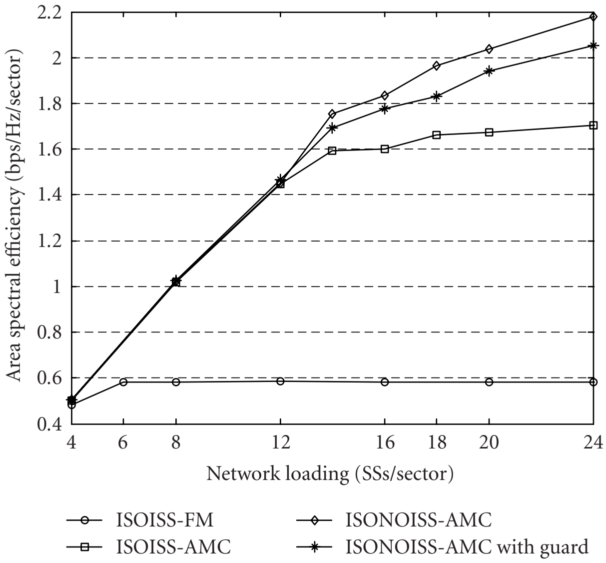


Figure 5: Area spectral efficiency in different schemes.

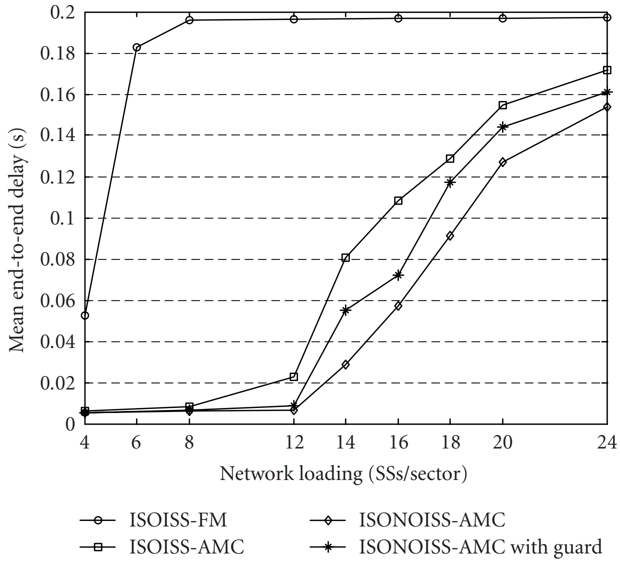


Figure 7: Mean end-to-end packet delay in different schemes.

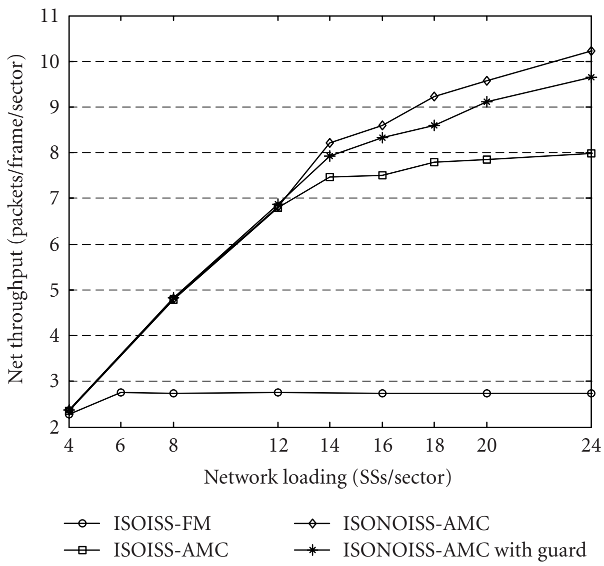


Figure 6: Net throughput in different schemes.

ISONOISS-AMC. However, when out-of-group interference guard is considered in ISONOISS-AMC, packet error rate is reduced drastically and the resulting error rate is comparable to that of ISOISS-AMC.

We present area spectral efficiency and net throughput in Figures 5 and 6, respectively. Although packet error rate is high, ISOISS-AMC and ISONOISS-AMC show tremendous improvements in terms of area spectral efficiency and net throughput. This is because the intermediate and proposed schemes are capable of using much higher AMC modes whenever possible in comparison to 16-QAM with a coding rate of 1/2 mode used in ISOISS-FM; therefore, a larger number of packets per frame can be transmitted in these schemes. While the area spectral efficiency in ISOISS-FM is limited by around 0.6 bps/Hz/sector, the proposed ISONOISS-AMC shows an area spectral efficiency of around 2.2 bps/Hz/sector at the network loading of 24 SSs per sector. ISOISS-AMC delivers spectral efficiency of around 1.65 bps/Hz/sector at the same loading. At this loading value, around 3 times higher area spectral efficiency and throughput are achieved in the ISONOISS-AMC compared to those obtained in the ISOISS-FM. Improvements in ISONOISS-AMC compared to ISOISS-AMC are solely due to the benefits of in-group opportunistic multiple transmissions. As employing out-of-group interference guard in the proposed scheme led the schedulers to choose AMC modes conservatively, the area spectral efficiency and net throughput are reduced slightly. However, while packet error rates are similar in ISONOISS-AMC with guard and in ISOISS-AMC, the former achieves much higher area spectral efficiency and net throughput.

Figure 7 illustrates the mean end-to-end delay. We observe that the delay reaches the threshold 200 milliseconds for a loading level as low as 6 SSs per sector in the ISOISS-FM scheme. Because of less efficient AMC mode usage, fewer packets get transmitted per frame in the ISOISS-FM scheme. As a result, the queue length grows even at very low loading levels such as 5 or 6 SSs per sector, causing high mean end-to-end delay. In ISONOISS-AMC, on the other hand, the queues grow at much higher loading levels, as the proposed scheme is able to use efficient AMC modes, and it allows concurrent transmissions among in-group BSs. Therefore, we notice a much better delay performance in the proposed scheme compared to the reference scheme. For instance, for a mean delay of 50 milliseconds, ISOISS-FM supports only 4 SSs, while ISONOISS-AMC is able to support 16 SSs in a sector. Once again, the mean end-to-end delay in ISOISS-AMC falls between those in ISOISS-FM and

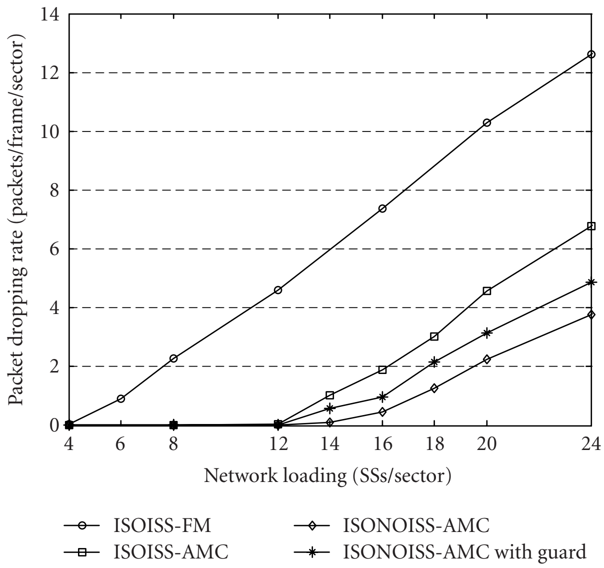


Figure 8: Packet dropping rate in different schemes.

in ISONOISS-AMC as expected. Observed improved delay performance in ISONOISS-AMC compared to ISOISS-AMC is due to the simultaneous in-group transmissions in the ISONOISS-AMC scheme. When out-of-group interference guard is used in ISONOISS-AMC, the mean end-to-end delay increases slightly, however, it is always less than that in ISOISS-AMC.

The comparison of packet dropping rate is shown in Figure 8. ISONOISS-AMC shows much better performance than ISOISS-FM in terms of packet dropping rate for the same reasons as for the delay. The packet dropping rate in the intermediate scheme ISOISS-AMC is lower than that obtained in ISOISS-FM and higher than that observed in ISONOISS-AMC.

It is observed that the performances of ISOISS-AMC and ISONOISS-AMC are comparable until the loading level of 12 users/sector. This is due to the fact that at this point of loading, ISOISS-AMC becomes fully loaded and packets start to drop, while ISONOISS-AMC still has some capacity left in the frame. The difference in performance increases as the loading values grow further beyond this point. Simulations are prevented from going beyond 24 users/sector due to the long simulation time needed. However, the trends of the performance curves show that the benefits in ISONOISS-AMC are even higher at higher loading than presented here.

6. CONCLUSIONS

The benefits of combining link-state-based scheduling decisions, AMC, and opportunistic nonorthogonal transmissions in fixed broadband wireless access networks have been investigated in this paper. A reference orthogonal scheduling scheme that makes arrival-time-based scheduling decisions and uses fixed modulation, namely ISOISS-FM, has been adapted from [13]. The intermediate scheme, ISOISS-AMC, is still orthogonal, while it makes link-state-based scheduling decisions and uses AMC. Finally, the proposed interference-aware scheme, ISONOISS-AMC, makes link-state-based scheduling decisions, employs AMC, and allows controlled in-group interference in order to improve throughput and packet delay.

It has been observed that the area spectral efficiency in ISONOISS-AMC is around three times higher than that in ISOISS-FM. Moreover, higher throughput results in significant improvements in end-to-end packet delay and packet dropping rate in ISONOISS-AMC. To quantify the benefits of AMC alone, we also have studied ISOISS-AMC, which outperforms the reference scheme in terms of area spectral efficiency, net throughput, mean end-to-end delay, and packet dropping rate. The proposed ISONOISS-AMC achieves up to 33% better area spectral efficiency than the intermediate ISOISS-AMC scheme. This improvement is solely due to the opportunistic nonorthogonal transmissions in the proposed scheme.

While the proposed scheme shows performance improvements in terms of area spectral efficiency, delay, and packet dropping rate, it experiences higher packet error rate due to increased number of uncontrolled out-of-group interferers. However, when out-of-group interference guard is used in ISONOISS-AMC, the packet error rate becomes comparable to that observed in ISOISS-AMC. Nevertheless, if even 10% packet error rate is allowed by the upper layer, the proposed ISONOISS-AMC can support as many as 16 SSs per sector with mean packet delay of around 50 milliseconds and the reasonable packet dropping rate, while ISOISS-FM supports only 4 SSs. For the similar packet error rate and mean end-to-end delay, the ISOISS-AMC scheme can accommodate 13 SSs per sector.

ACKNOWLEDGMENTS

The authors would like to thank OPNET Technologies, Inc. for providing software license to carry out the simulations of this research. The authors are grateful to Dr. Keivan Navaie for his review and comments. This research has been funded in part by National Capital Institute of Telecommunications (NCIT), Ottawa, Canada. Part of this paper has been presented at the Proceedings of IEEE International Conference on Communications (ICC), 16–20 May 2005, Seoul, Korea.

REFERENCES

[1] *IEEE Std. 802.16a for Local and Metropolitan Area Networks*, Air interface for fixed broadband wireless access systems, IEEE, April 2003.

[2] H. Bölcskei, A. J. Paulraj, K. V. S. Hari, R. U. Nabar, and W. W. Lu, "Fixed broadband wireless access: state of the art, challenges, and future directions," *IEEE Communications Magazine*, vol. 39, no. 1, pp. 100–108, 2001.

[3] D. L. Waring, "The asymmetrical digital subscriber line (ADSL): a new transport technology for delivering wideband capabilities to the residence," in *Proceedings of IEEE Global Telecommunications Conference and Exhibition (GLOBECOM '91)*, vol. 3, pp. 1979–1986, Phoenix, Ariz, USA, December 1991.

[4] K. Maxwell, "Asymmetric digital subscriber line (ADSL): interim technology for the next forty years," *IEEE Communications Magazine*, vol. 34, no. 10, pp. 100–106, 1996.
[5] C. Bisdikian, K. Maruyama, D. I. Seidman, and D. N. Serpanos, "Cable access beyond the hype: on residential broadband data services over HFC networks," *IEEE Communications Magazine*, vol. 34, no. 11, pp. 128–135, 1996.
[6] P. Bhagwat, P. Bhattacharya, A. Krishna, and S. K. Tripathi, "Enhancing throughput over wireless LANs using channel state dependent packet scheduling," in *Proceedings IEEE of 15th Annual Joint Conference of the IEEE Computer Societies (INFOCOM '96)*, vol. 3, pp. 1133–1140, San Francisco, Calif, USA, March 1996.
[7] T. S. E. Ng, I. Stoica, and H. Zhang, "Packet fair queueing algorithms for wireless networks with location-dependent errors," in *Proceedings of IEEE 17th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '98)*, vol. 3, pp. 1103–1111, San Francisco, Calif, USA, March-April 1998.
[8] S. Desilva and S. M. Das, "Experimental evaluation of channel state dependent scheduling in an in-building wireless LAN," in *Proceedings of 7th International Conference on Computer Communications and Networks (ICCCN '98)*, pp. 414–421, Lafayette, La, USA, October 1998.
[9] C. Fragouli, V. Sivaraman, and M. B. Srivastava, "Controlled multimedia wireless link sharing via enhanced class-based queuing with channel-state-dependent packet scheduling," in *Proceedings of IEEE 17th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '98)*, vol. 2, pp. 572–580, San Francisco, Calif, USA, March-April 1998.
[10] S. Lu, V. Bharghavan, and R. Srikant, "Fair scheduling in wireless packet networks," *IEEE/ACM Transactions on Networking*, vol. 7, no. 4, pp. 473–489, 1999.
[11] T. K. Fong, P. S. Henry, K. K. Leung, X. Qiu, and N. K. Shankaranarayanan, "Radio resource allocation in fixed broadband wireless networks," *IEEE Transactions on Communications*, vol. 46, no. 6, pp. 806–818, 1998.
[12] M. H. Ahmed, H. Yanikomeroglu, and S. Mahmoud, "Interference management using packet sheduling in broadband wireless access networks," *Willey Journal on Wireless Communications and Mobile Computing*, vol. 6, no. 1, pp. 95–103, 2006.
[13] M. H. Ahmed, H. Yanikomeroglu, S. Mahmoud, and D. D. Falconer, "Scheduling of multimedia traffic in interference-limited broadband wireless access networks," in *Proceedings of 5th International Symposium on Wireless Personal Multimedia Communications (WPMC '02)*, Honolulu, Hawaii, USA, October 2002.
[14] K. K. Leung and A. Srivastava, "Dynamic allocation of downlink and uplink resource for broadband services in fixed wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 5, pp. 990–1006, 1999.
[15] F. Borgonovo, M. Zorzi, L. Fratta, V. Trecordi, and G. Bianchi, "Capture-division packet access for wireless personal communications," *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 4, pp. 609–622, 1996.
[16] K. Chawla and X. Qiu, "Quasi-static resource allocation with interference avoidance for fixed wireless systems," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 3, pp. 493–504, 1999.
[17] X. Liu, E. K. P. Chong, and N. B. Shroff, "Opportunistic transmission scheduling with resource-sharing constraints in wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, pp. 2053–2064, October 2001.
[18] M. Rahman, "Adaptive modulation & coding-based packet scheduling with inter-base station coordination in cellular fixed broadband wireless networks," M.S. thesis, Carleton University, Ottawa, Ontario, Canada, 2004, http://www.sce.carleton.ca/faculty/yanikomeroglu/cv/publications.shtml.
[19] OPNET University Program: http://www.opnet.com/services/university.
[20] V. Erceg, L. J. Greenstein, S. Y. Tjandra, et al., "An empirically based path loss model for wireless channels in suburban environments," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 7, pp. 1205–1211, 1999.
[21] V. Erceg, et al., *Channel models for fixed wireless applications*, IEEE 802.16 work in progress document # 802.16.3c-01/29r4, July 2001.
[22] C. R. Baugh and J. Huang, *Traffic model for 802.16 TG3 MAC/PHY simulations*, IEEE 802.16 work in progress document # 802.16.3c-01/30r1, March 2001.

Mahmudur Rahman received the B.S. degree in electrical and electronic engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, in 1991. He obtained an M.Eng. degree in telecommunications from Asian Institute of Technology (AIT), Bangkok, Thailand, and an M.A.S. degree in electrical engineering from Carleton University, Ottawa, Canada, in 1994 and 2004, respectively. He received Finnish International Development Agency (FINNIDA) Scholarship for his studies at AIT. He worked as an Electronics Engineer in Bangladesh Atomic Energy Commission, Dhaka, Bangladesh, from 1991 to 1993. From 1995 to 1996, he was a Process Engineer in Johnson Electric Industrial Manufactory, Ltd., (Thailand). Initially appointed to the position of Senior R&D Engineer in 1996, he served ACE Electronics Industries Co., Ltd., Bangkok, Thailand, as an R&D Division Manager from 1997 to 1999. He is currently working towards a Ph.D. degree in electrical engineering at Carleton University. He is involved in the Wireless World Initiative New Radio (WINNER) Project. His current research interests include radio resource management, multihop wireless networks, and intercell coordination.

Halim Yanikomeroglu received a B.S. degree in electrical and electronics engineering from the Middle East Technical University, Ankara, Turkey, in 1990, and an M.A.S. degree in electrical engineering (now ECE), and a Ph.D. degree in electrical and computer engineering from the University of Toronto, Canada, in 1992 and 1998, respectively. He was with the Research and Development Group of Marconi Kominikasyon A.S., Ankara, Turkey, from January 1993 to July 1994. Since 1998, he has been with the Department of Systems and Computer Engineering at Carleton University, Ottawa, where he is now an Associate Professor and Associate Chair for Graduate Studies. His research interests include almost all aspects of wireless communications with a special emphasis on infrastructure-based multihop/mesh/relay networks. He has been involved in the steering committees and technical program committees of numerous international conferences in communications; he has also given several tutorials in such conferences. He was the Technical Program Cochair of the IEEE Wireless Communications

and Networking Conference 2004 (WCNC'04). He was an Editor for IEEE Transactions on Wireless Communications during 2002–2005, and a Guest Editor for Wiley Journal on Wireless Communications & Mobile Computing; he was an Editor for IEEE Communications Surveys & Tutorials for 2002–2003. Currently he is serving as the Chair of the IEEE Communications Society's Technical Committee on Personal Communications (TCPC), he is also a Member of IEEE ComSoc's Technical Activities Counsel (TAC).

Mohamed H. Ahmed received his B.S. and M.S. degrees in electronics and communications engineering from Ain Shams University, Cairo, Egypt, in 1990 and 1994, respectively. He obtained his Ph.D. degree in electrical engineering in 2001 from Carleton University, Ottawa. From 2001 to 2003, he worked as a Senior Research Associate at the Department of Systems and Computer Engineering, Carleton University. In April 2003, he joined the Faculty of Engineering and Applied Science, Memorial University of Newfoundland as an Assistant Professor of electrical and computer engineering. He served as a Technical Program Committee Member of various conferences and a Guest Editor for Wiley Journal on Wireless Communications & Mobile Computing. He won the Ontario Graduate Scholarship for Science and Technology in 1997, the Ontario Graduate Scholarship in 1998, 1999, and 2000, and Communication and Information Technology Ontario (CITO) Graduate Award in 2000. His research interests include wireless access techniques, resource management in wireless networks, multihop wireless networks, MIMO antenna systems, cooperative diversity, and broadband wireless networks.

Samy Mahmoud is the Dean of the Faculty of Engineering and Design, Carleton University. He was the Chair of the Department of Systems and Computer Engineering, Carleton University from 1987 to 1997. His main research work is in the areas of wireless communication systems and the transmission of voice and video signals over high-speed networks. He has published over 200 papers in these fields in recent years and supervised 32 doctoral and 85 M.Eng. theses to completion. He graduated with the M.Eng. and Ph.D. degrees in electrical engineering from Carleton University in 1971 and 1975, respectively. He coauthored a major book on *"Communication Systems Analysis and Design,"* published in 2004 by Pearson Prentice Hall. His recent research work in the field of radio-over-fiber has resulted in several archival publications and 8 patent applications. His research work received several international and national awards, including two Best Paper Awards for publications in the IEEE Transactions on Vehicular Technology and two TRIO Feedback Awards for best technology transfer to industry. He recently led a major initiative to establish the National Capital Institute of Telecommunications (NCIT), a joint research organization involving several large international companies in the telecommunications and computer industries, leading university researchers, scientists, and engineers from two major Canadian Government Research Laboratories (CRC and NRC).