Improving Base Station Coordination Based Packet Scheduling Schemes in Fixed Broadband Wireless Access Networks[1]

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Abstract— **In this paper, we present a novel transmission scheduling scheme for *fixed broadband wireless access* (FBWA) networks. In order to mitigate high co-channel interference resulting from dense reuse of frequency, scheduling schemes in FBWA systems often consider interference management issues as essential part of the scheduling. To that end, a series of literature has been published recently, where a group of base stations form an interference group, and 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 co-channel interference and hence the packet error rate can be reduced. However, prohibiting concurrent transmissions in these orthogonal schemes introduces higher end-to-end packet delay which might not be desirable for real-time traffic such as voice and video. Our proposed scheme aims to improve delay performance as well as to ensure better resource utilization in such orthogonal scheduling schemes in several ways, most notably by introducing opportunistic non-orthogonality in transmissions, incorporating channel state based scheduling decisions, and employing adaptive modulation & coding.**

I. INTRODUCTION

The FBWA [1, 2] is known to be a promising alternative technology to existing copper line *asymmetric digital subscriber loop* (ADSL) or *hybrid fiber-coaxial* (HFC) cable broadband services for its fast, simple, and less expensive deployment capability. 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 frequency reuse is a major design concern. Therefore, resource allocation strategies play 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 [3] have emerged as tailored versions of wireline scheduling to cope with the dynamic nature of wireless links. To account for co-channel interference, it is common to consider the issues of interference management as an integral part of scheduling techniques in FBWA networks [4-6]. Proposed by Ahmed et al. [6], 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 concept of this scheme is to group a number of BSs (termed as *interference group*) that are dominant interferer 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 *intra-sector and inter-sector scheduling* (ISISS).

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 traffic rate. Therefore, improving throughput and delay in an orthogonal scheduling scheme is essential. In this paper, we propose a novel scheduling scheme not only to improve packet delay but also to ensure better resource utilization in terms of area spectral efficiency. The performance of the proposed scheme is compared to that of a reference scheme, *intra-sector and orthogonal inter-sector scheduling with fixed modulation* (ISOISS-FM), adapted from basic ISISS [6].

The proposed scheme considers interference management issues, integrates adaptive modulation and coding (AMC), and takes channel state based scheduling decisions to enhance network performance. The in-group transmissions are not necessarily orthogonal and the scheme is named as *intra-sector and opportunistic non-orthogonal inter-sector scheduling with adaptive modulation and coding* (ISONOISS-AMC). Basically, if a number of co-channel BSs transmit simultaneously, each becomes interferer for others. The idea is that if the interference levels are predicted and are known to each BS transmitting concurrently, then every BS would potentially be able to transmit with its feasible AMC in the presence of others being interferers.

Two-fold improvements are obtained from AMC and opportunistic non-orthogonal transmissions in ISONOISS-AMC compared to ISOISS-FM. In order to quantify the performance improvements from AMC alone, an intermediate scheme called *intra-sector and orthogonal inter-sector scheduling with adaptive modulation and coding* (ISOISS-AMC) has also been investigated. This is an orthogonal scheme like ISOISS-FM with the exception that it employs AMC.

The rest of this paper is organized as follows. Section II describes the reference, proposed, and intermediate schemes. Section III discusses system model. Simulation results are presented in Section IV followed by conclusion in Section V.

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II. DESCRIPTION OF THE SCHEDULING SCHEMES

Let us consider a downlink *time division multiple access* (TDMA) system in a hexagonal six-sectored nine-cell network as shown in Fig. 1(a). We assume that a dense frequency reuse plan with a reuse factor of 1/6 is employed in the network. The shaded sectors[2] (for example, sector 1) in all cells use same frequency band. It should be noted here that a different sector to frequency assignment technique such as the rotational or *staggering* approach used in [4] or [5] is possible in order to reduce inter-sector interference, especially for lower network loading. The rationale behind the assignment used in this study where co-channel sectors are positioned in a line is to investigate the worst-case inter-sector interference scenario. However, the proposed scheduling scheme can be employed with any other frequency planning to enhance the performance on the top of 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 60^0 and 30^0 beamwidth, 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 & -10 dB side lobe) and 10 dB (5 dB main & -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. A detailed method for finding wraparound BS positions can be found in [7]. Fig. 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 *J* will 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*. And, wraparound BSs *J* and *K* are the most dominant interferes for SSs in BS *I*. Following these arguments, BSs *I*, *J*, and *K* form an *interference group*. Similarly, BSs {*I′*, *J′*, *K′*} and {*I″*, *J″*, *K″*} form another two interference groups in the network.

The scheduling scheme (reference or proposed) is employed in each interference group as shown in Fig. 2 for interference group {*I*, *J*, *K*}. The in-group BSs exchange information with each other as illustrated in the figure. The intra-sector scheduling discipline decides the service order of each SS inside the sector, while the inter-sector discipline determines the service order among different BSs in the group to ensure orthogonal or opportunistic non-orthogonal transmissions in the *interference group*. As the contributions of the schemes lie in the inter-sector scheduler, for simplicity *first come first serve* (FCFS) is considered as intra-sector discipline in the reference as well as in the proposed scheme.

[2] Only sector 1 is simulated in this study. Therefore, BS *I*, for instance, implies sector 1 of BS *I* throughout this paper.

A. Reference Scheme: ISOISS-FM

Transmissions use fixed 16-*quadrature amplitude modulation* (QAM) *bit-interleaved coded modulation* (BCIM) with a coding rate of 1/2 in this scheme. Base stations in the interference group exchange traffic related information such as the arrival times of the packets with their packet lengths arrived in previous 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 inter-sector 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; e.g. in group {*I*, *J*, *K*} at a particular instant,

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

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.

B. Proposed Scheme: ISONOISS-AMC

In order for the proposed scheme to be able to execute link state based scheduling decisions, employ AMC, and allow opportunistic non-orthogonal transmissions, SINR should be predicted at each BS. For the nine-cell network shown in Fig. 1(a), every transmission will have eight potential interferers. Let us consider the scenario shown in Fig. 1(b). The SINR of a received packet at SS *i* served by BS *I* can be expressed as,

$$\gamma^i = \frac{P_t G_I^i}{P_t \sum_{\psi \in IG, \psi \neq I} A_\psi G_\psi^i + P_t \sum_{\Theta \in OG} A_\Theta G_\Theta^i + P_N^i}, \qquad (2)$$

where P_t is the fixed transmit power. The first and the second terms in the denominator reflect the accumulation of interference from the in-group and out-of-group BSs, respectively. For the given scenario, $IG \approx \{I, J, K\}$ and $OG \approx \{I', J', K', I'', J'', K''\}$. G_I^i is the link gain between the serving BS *I* and SS *i*. G_ψ^i and G_Θ^i are the link gains to the desired SS *i* from 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 terminal as well as the propagation loss (including shadowing and fading) of the link. P_N^i is the average thermal noise computed at the receiver of SS *i*.

We note that all BSs do not transmit simultaneously because of either algorithm restrictions or empty queues. The parameters A_ψ and A_Θ in (2) denote *activity factor*s which take value of 1 if the interferer BS is transmitting and 0 if it is idle.

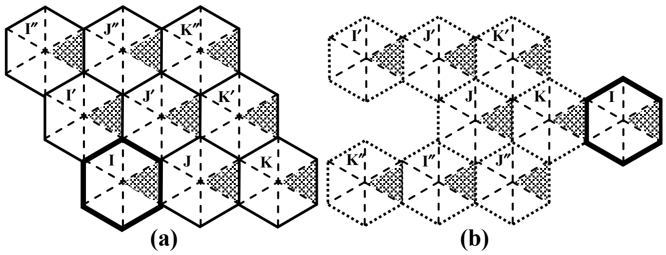

Fig. 1. (a) Nine-cell network, (b) wraparound interferer positions for SSs in BS I.

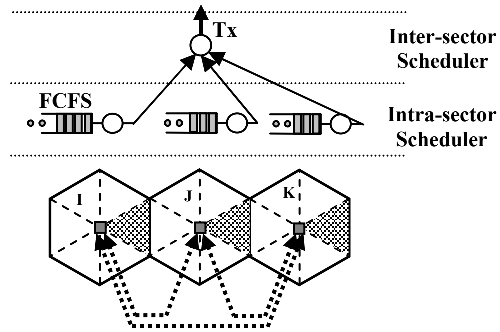

Fig. 2. Block diagram of the scheduling scheme in group $\{I, J, K\}$.

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 interference group of $\{I, J, K\}$ keeps track of G_I^i, G_J^i, and G_K^i, and reports to serving BS I time to time. BS I shares this information with in-group BSs J and K. It is important to note that 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 and it is completely feasible in such systems.

Since the inter-BS signaling is performed only among in-group BSs, out-of-group interference remains unpredicted and unaccounted for in the scheduling operations. The predicted SINR for the proposed opportunistic non-orthogonal scheme for SS i's packet is given as follows,

$$\gamma_{ONO}^{i} = \frac{P_t G_I^i}{P_t \sum_{\psi \in IG, \psi \neq I} A_\psi G_\psi^i + P_N^i}. \tag{3}$$

Using these predicted SINRs, the inter-sector scheduler finds a combination of concurrent transmissions that gives the highest aggregate throughput efficiency. If queues of all in-group BSs are non-empty, 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). For each combination, first, the SINRs are predicted 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 (3) the predicted SINR at SS i's packet given, I, J, and K are transmitting simultaneously, is

$$\gamma_{ONO}^{i|(I,J,K)} = \frac{P_t G_I^i}{P_t G_J^i + P_t G_K^i + P_N^i}. \tag{4}$$

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

$$\Gamma_{I,J,K} = \eta_I \times \frac{t_d^i}{t_r} + \eta_J \times \frac{t_d^j}{t_r} + \eta_K \times \frac{t_d^k}{t_r}, \tag{5}$$

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. t_r is the longest transmission time among all three transmission durations, i.e., $t_r = \max(t_d^i, t_d^j, t_d^k)$.

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

$$w = \arg \max_{combin(I,J,K)} \left(\Gamma_{I,J,K}, \Gamma_{I,J}, \Gamma_{J,K}, \Gamma_{K,I}, \Gamma_I, \Gamma_J, \Gamma_K \right), \tag{6}$$

where w is the combination of BSs transmit concurrently.

C. Intermediate Scheme: ISOISS-AMC

This scheme is essentially similar to ISONOISS-AMC except that it does not allow concurrent in-group transmissions. At any time, three HOL packets in the in-group BSs are compared to select the candidate BS that has the best link to the SS. Transmissions experience only the out-of group interference as a result of orthogonal in-group transmissions. In this scheme, the predicted SINR for a packet received by SS i from BS I is given by

$$\gamma_O^{i|I} = \frac{P_t G_I^i}{P_N^i}. \tag{7}$$

If SSs i, j, and k are the candidates for HOL packets in BSs I, J, and K in the interference group, and G_I^i, G_J^j, and G_K^k are the link gains from BSs to SSs, respectively, then,

$$w = \arg\max_{I,J,K}\left(G_I^i, G_J^j, G_K^k\right) \qquad (8)$$

where w is the BS that wins the scheduling opportunity.

The winner BS predicts the SINR according to (7) or similar expressions. Using this predicted SINR the feasible AMC mode is chosen from Table I and the packet is scheduled for the instant.

TABLE I
LOOKUP TABLE FOR AMC MODES[3]:
BICM WITH BIT ERROR RATE OF 1.0×10^{-4}

SINR Range (dB)	AMC Mode	Efficiency, η (Bits/Sec/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

III. SYSTEM MODEL

The cell radius is considered to be 2 kilometers. The operating frequency is 2.5 GHz and the channel bandwidth is 3 MHz. An exponential path-loss model with propagation exponent of 3.75 has been used. We have considered independent lognormal random variables with a standard deviation of 8 dB for shadowing. Time-correlated flat Rayleigh fading with Doppler frequency of 2 Hz has been considered in this study where the Doppler spectrum is rounded bell-shaped [8]. In particular, for a given link, the time-correlated fading power changes slightly from frame to frame as a result of low Doppler frequency, and the value is assumed to be fixed in a frame in our simulations. A fixed transmit power of 6.5 Watts has been used in this study to ensure 95% availability for a user at cell boundary receiving packets transmitted with 16-QAM with a coding rate of 1/2. With the given channel bandwidth and noise figure of 5 dB the average receiver noise power is -134.06 dBW.

We have considered real-time video traffic. Two *Interrupted Renewal Process* (2IRP) sources are superimposed to model user's video traffic in the downlink transmission as indicated in [9]. The average packet rate of one 2IRP generator is 126.3 packets per second determined from parameters given in Table II. The lengths of packets are uniformly distributed between 250 to 550 bytes giving the downlink data rate of 404.16 kbps per SS.

TABLE II
TRAFFIC MODEL PARAMETERS OF THE VIDEO STREAM [9]

IRP	Packet Arrival Rate (packets/sec)	Pareto Parameter for ON Distribution	Pareto Parameter for OFF Distribution
IRP1	112.38	1.14	1.22
IRP2	154.75	1.54	1.28

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 as expressed below:

$$t_d = \frac{L_p}{\log_2 M} \times \frac{1}{r_s} \times \frac{1}{r_c}. \qquad (9)$$

We assume asynchronous transmission such that interferers may arrive or leave anytime during the transmission time of a packet of interest. Therefore, the SINR varies and packet experiences different bit-error rates at different segments of the packet during the transmission time. 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:

$$N_e = \sum_{s=1}^{S} \Pr_{b(s)} \times N_{b(s)}\ , \qquad (10)$$

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

The total number of erroneous bits is used to decide if the packet is received correctly. In simulations, we 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 ms. Packets are scheduled in a frame by frame basis at the start of every frame. Any packet arrives at current frame time will have to wait at least until the start of next frame.

IV. SIMULATION RESULTS

Proposed scheduling scheme ISONOISS-AMC is evaluated by comparing with the reference scheme ISOISS-FM in terms of the essential network performance parameters such as

[3] Data for BICM modulation curves is provided by Dr. Sirikiat Lek Ariyavisitakul, Radia Communications, Norcross, GA, USA.

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

The network is executed in real-time using OPNET [10] modeler and wireless module, and the statistics are taken over long enough time duration until the observed parameters 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 location of SS nor the shadowing value is changed. For any particular SS, fading is correlated and 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.

Fig. 3 compares the PER performance of the proposed, reference, and intermediate schemes. The modulation and coding level used in the reference ISOISS-FM scheme is more robust than that of the channel state based chosen AMC modes in proposed ISONOISS-AMC scheme. Also, increased number of packets in the air results-in increased number of out-of-group interferers in ISONOISS-AMC. Consequently, the PER in proposed scheme is higher. PER levels of ISOISS-AMC fall in between the reference and proposed schemes as ISOISS-AMC suffers less interference than that in ISONOISS-AMC.

We present area spectral efficiency in Fig. 4. Although the PER is high, ISONOISS-AMC shows tremendous improvement in efficiency. This is due to the fact that the proposed scheme is capable of using much higher efficiency AMC modes than 16-QAM with a coding rate of 1/2 mode most of the times and therefore a larger number of packets per frame can be transmitted. While the area spectral efficiency in ISOISS-FM is limited by around 0.6 bps/Hz/sector, proposed ISONOISS-AMC shows 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. Improvement in ISONOISS-AMC compared to ISOISS-AMC is due to the higher overall transmission rate gained from opportunistic concurrent in-group transmissions.

Fig. 5 illustrates the mean ETE delay. We observe that the delay reaches the threshold 200 ms for loading as low as 6 SSs per sector in ISOISS-FM scheme. Because of less efficient AMC mode usage, a fewer number of packets gets transmitted per frame in ISOISS-FM scheme. As a result queue length grows at very low loading such as 5 or 6 SSs per sector causing high mean ETE delay beyond such loading values. In ISONOISS-AMC on the other hand, queues grow at much higher loading as a result of the proposed scheme being able to use efficient AMC modes and to transmit simultaneously. Therefore, we notice much better delay in the proposed scheme compared to the reference scheme. For a mean delay of 50 ms, ISSOISS-FM supports only 4 SSs, while ISONOISS-AMC is able to support 16 SSs in a sector. Again, delay in ISOISS-AMC falls in between ISOISS-FM and ISONOISS-AMC as expected. Observed improved delay performance in ISONOISS-AMC compared to ISOISS-AMC is due to the simultaneous in-group transmissions in ISONOISS-AMC scheme.

The comparison of PDR is shown in Fig. 6. ISONOISS-AMC shows much better performance than ISOISS-FM in terms of PDR for the same reasons as for the delay. PDR in the intermediate scheme ISOISS-AMC is lower than that obtained in ISOISS-FM and higher than that observed in ISONOISS-AMC.

V. CONCLUSIONS

The benefits of combining link state based scheduling decisions, AMC and opportunistic non-orthogonal transmissions in traditional orthogonal scheduling techniques in fixed broadband wireless access networks have been investigated in this paper. 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 always outperforms the reference scheme as expected. The proposed ISONOISS-AMC achieves up to 33% better ASE than the intermediate ISOISS-AMC scheme. This improvement is solely due to the opportunistic non-orthogonal transmissions in the proposed scheme.

While proposed scheme shows performance improvements in terms of area spectral efficiency, delay, and packet dropping rate, it experiences higher PER due to increased number of uncontrolled out-of-group interferers. Nevertheless, if even 10% PER is allowed by the upper layer, proposed ISONOISS-AMC can support as much as 16 SSs per sector with mean packet delay of around 50 ms and reasonable PDR, while ISOISS-FM supports only 4. For the similar PER and mean ETE delay the ISOISS-AMC scheme can accommodate 13 SSs per sector.

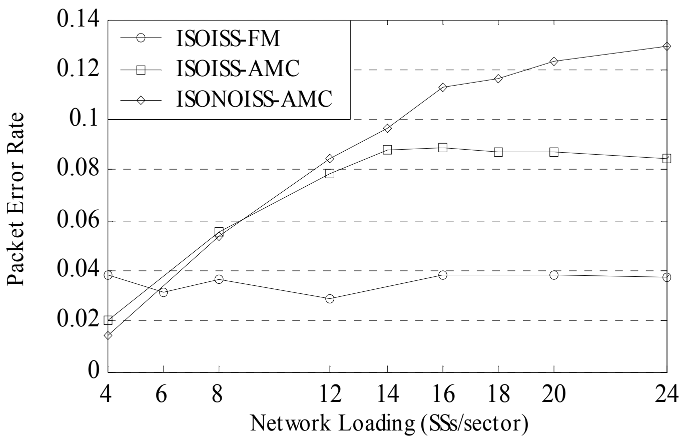

Fig. 3. Packet error rate.

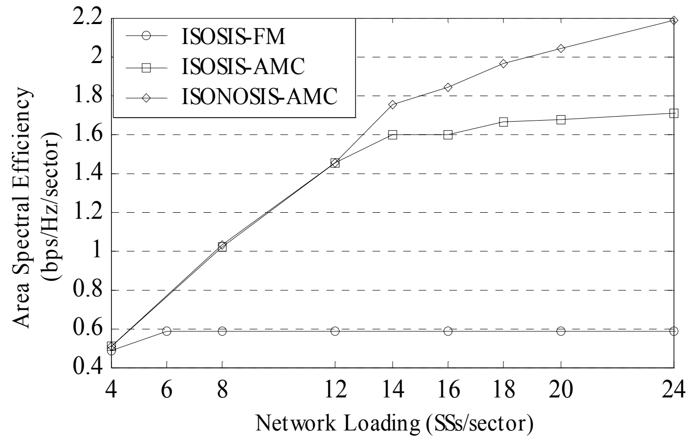

Fig. 4. Area spectral efficiency.

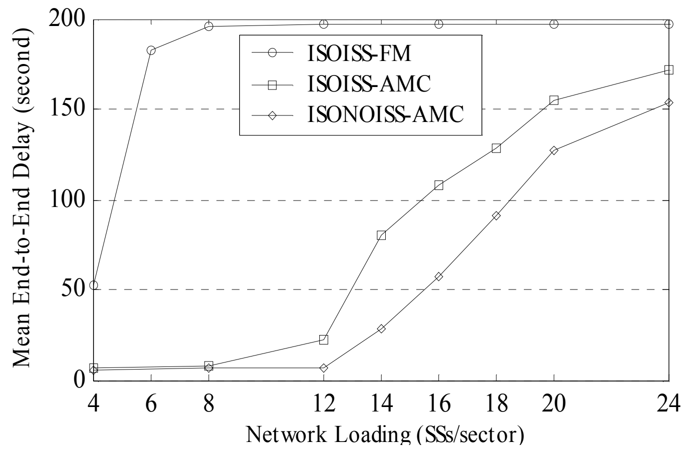

Fig. 5. Mean end-to-end packet delay.

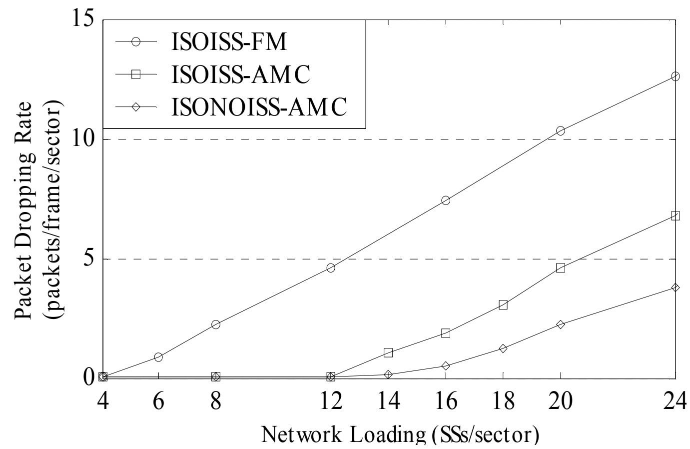

Fig. 6. Packet dropping rate.

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