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A coordinated multiple channel assignment scheme and AP deployment for channel reuse in metropolitan scale wireless networks

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ABSTRACT

In a wireless network, when a single channel is employed, hidden terminal and radio interference problems may occur. The two problems are the main factors that cause low network throughput. In fact, the hidden node problem results from radio interference. Up to the present, many researchers have used multi-channel schemes to solve the interference problem. However, a multi-channel system causes other problems, e.g., the multi-channel hidden terminal problem, and the channel assignment problem. Actually, a well-defined channel assignment can effectively solve the former problem. Therefore, in this paper, we propose a multi-channel assignment system, called a corona-oriented multi-channel assignment system (COMAS for short), which as a metropolitan scale system coordinates channel usage for wireless networks to mitigate radio interference among APs and nodes so as to improve network throughput and efficiency, particularly when many nodes are connected to APs. In the COMAS, APs are deployed as concentric circles, named coronas, and channels are grouped and then allocated to coronas. We also cluster APs into groups, and schedule available channels to avoid radio interference and multi-channel hidden terminal problems among adjacent AP groups and among APs in a group. Simulation results show that the COMAS can effectively improve wireless-network throughput, drop rate, packet delivery delay and jitter.

1. Introduction

Recently, wireless networks have become increasingly pervasive. More and more wireless devices, such as notebooks, smart phones, and sensor networks, support wireless protocols, and the convenience and rather low cost of wireless-device deployment have made wireless networks more attractive than before. But in wireless networks, some problems, e.g., the hidden node problem (Leu and Huang, 2008), radio collision (Le et al., 2007), and multi-channel hidden terminal problem (Wang et al., 2008), need to be solved before we can efficiently enjoy wireless network convenience.

Baiocchi et al. (2004) compared wireless network transmission throughputs for a single channel and multiple channels given a hidden-node scenario and a non-hidden-node scenario. The best throughput is on a single channel without hidden nodes because packets can be successfully transmitted without radio interference. With the hidden-node scenario, multi-channel throughput is higher than that of a single channel since packets are simultaneously delivered to their destinations through multiple channels.

Niranjan et al. (2006) and Kyasanur and Vaidya (2004) defined different channel assignment algorithms for wireless networks to improve their network throughputs, and avoid signal interference and hidden node problems. Nevertheless, when many nodes are connected to an AP, or two or more APs are located near or even at the same location, the two schemes cannot avoid radio interference between/among nodes which are now under the APs. To solve the signal interference problem, several problems and challenges must be conquered, including how to coordinate transmission between/among neighbor nodes (Ju and Li, 1999; Alnifie and Simon, 2007; Ju and Li, 1998; Huang et al., 2008), which channel should be switched to when a collision occurs (Xu et al., 2007), and how to interleave the transmission if at least two nodes have to share a channel (Zhou et al., 2007). But the solutions of these problems and challenges will further lead to two problems: (1) a coordinating system often has poor scalability (Zhou et al., 2007); (2) if a multi-channel system is employed, interference still exists, particularly when nodes change communication channels (Alnifie and Simon, 2007; Xu et al., 2007). Incel et al. (2006) proposed that channel spacing can be adjusted according to spatial distances so that multiple concurrent transmissions can be performed without interference. Incel and Jansen (2008) and Ahmed et al. (2009) claimed that multi-channel schemes without radio/signal interference can effectively improve wireless system performance.

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In this paper, we propose a multi-channel assignment system, called a corona-oriented multi-channel assignment system (COMAS), which can be deployed by a metropolitan scale wireless environment, such as WiMAX and LTE, and in which APs are organized as concentric circles, named coronas. In a corona, several adjacent APs and their subordinate nodes are grouped together as an AP and nodes group (AP-Nod group for short). Each AP-Nod group is assigned several interference-free channels to avoid radio interference. The details will be defined and described later. In an AP-Nod group, if the number of interference-free channels is insufficient to support the case in which all APs are allocated to different channels, then several APs and nodes should share a channel. Another case is, even if an AP is assigned at least one channel, if the number of mobile nodes under the AP is larger than the number of assigned channels, then nodes need to share the assigned channels. In both cases, to further avoid interference, we need to schedule the use of the channels. In this study, we adopt a time-sharing method. Experimental results indicate that network throughput, packet drop rate, jitter and packet delivery delay of our approach outperform other current state-of-the-art systems.

Contributions of this study are as follows:

(1) We organize APs into concentric coronas, and group APs using different methods to avoid signal interference among APs and their subordinate nodes.
(2) Due to the limited number of available channels, an AP's subordinate nodes are scheduled to share a single channel or several channels so the subordinate nodes can equally transmit their packets. Such a scheme can also avoid signal interference among nodes, and improve channel utilization and throughput.
(3) When a mobile node would like to hand off from one AP to another, its connection need not be disconnected if the COMAS is used as the wireless environment.

The rest of the paper is organized as follows. Section 2 describes the background and related work of this paper. In Section 3, we introduce the COMAS and the channel assignment algorithm. Experimental results are presented and discussed in Section 4. Section 5 draws the conclusions and describes future research.

2. Related work

2.1. The cellular system

Recently, the cellular phone systems and many wireless networks have organized their base stations/APs as hexagonal cellular systems (Andrews et al., 2007). In such a system, seven cells are grouped as a cluster. In each cluster, cells/APs are assigned different channels. The channel assignment scheme for all clusters is the same. So, any two neighbor cells/APs in the system use different channels. However, the radio/signal interference problem still exists in the system since two co-channel mobile nodes under different cells/APs belonging to two neighbor clusters may not be far enough apart. We will demonstrate this case in the first experiment of this study. Moreover, for handoff requirements, the co-area of two adjacent APs' communication ranges should be expanded (Bien et al., 2010). To solve this problem, we may shrink a cell's area without reducing its AP's emission power. But this method will increase the number of APs if a fixed area is given. Another solution is that each AP simply enhances its emission power (Kim et al., 2008; Jung and Vaidya, 2002). But this solution would worsen the signal/radio interference between the two nearby co-channel mobile nodes. Our conclusion is that if we would like to solve this problem, the distance between two co-channel cells/APs should be longer than it currently is.

2.2. Multi-channel systems

Kyasanur and Vaidya (2004) proposed a multi-channel assignment approach using multiple interfaces for wireless networks, called the interface algorithm. With the algorithm, a node is allocated several channels in which one is a "fixed" channel used to receive packets, and the remaining channels are employed to transmit packets. When two nodes simultaneously transmit packets to the same node, of course, through the same channel, then interference occurs.

Past studies (Zhou et al., 2007; Park and Jung, 2008) used multi-channel systems to improve their original systems. Park and Jung (2008) introduced a Placement-Based Allocation algorithm to classify independent data items, and scheduled these items to channel time slots. The algorithm is used in practice to process stock-price data, traffic data, etc. Zhou et al. (2007) proposed a multi-channel medium access control protocol for wireless mesh networks by using busy tones to prevent data packets from collisions. If a node is neither transmitting nor receiving packets, it randomly monitors a free data channel. When a node, e.g., A, would like to transmit packets to another node, e.g., B, A sends RTS packet to B, then B chooses an available channel, and tells A which channel is chosen. Then, A transmits packets to B through the channel. This can truly avoid packet collision. However, two nearby wireless environments which have no coordination may result in collision.

A multi-channel system can indeed effectively boost wireless network throughput and efficiency. However, such a system also brings forth some problems, e.g., how to coordinate channel usage, and how to effectively reuse data channels.

2.3. Other related research

Niranjan et al. (2006) designed and evaluated a multi-channel multi-rate protocol on a wireless network, and tested four schemes: single channel single rate, single channel multi-rate, multi-channel single rate, and multi-channel multi-rate. The multi-channel single rate has the best throughput because in a multi-rate environment a low-rate link segment will slow down other high-rate link segments if a routing path consists of several link segments. The authors propose a Data Rate Adaptive Channel Assignment algorithm to improve a wireless network. The main idea is assigning heavy traffic to high data-rate links. Past studies (Baiocchi et al., 2004; Wang and Yow, 2006) also concluded that a multi-channel system improves the wireless network throughput. Xu et al. (2007) used multiple channels to avoid channel interference. The authors propose a coordinated channel switching scheme with which when packets are jammed or interference occurs, a node switches its channel and announces the switch to its neighbors. The authors also propose a synchronous spectral multiplexing algorithm and a round-robin asynchronous spectral multiplexing algorithm. The main idea of the asynchronous one is that all nodes periodically switch channels to communicate with their own child nodes. The idea of the synchronous one is that a node switches its channel and announces the switch to its parent. Then, the parent periodically switches channels to communicate with the node. Its advantage is employing non-overlapping channels to avoid channel interference, hidden node problems, and traffic jams so as to improve system performance. But, the corresponding scheduling algorithm is hard to design since nodes switch channels frequently, particularly when traffic is busy.

Wang et al. (2008) introduced several multi-channel MAC protocols, and reserved a dedicated control channel to perform time synchronization among nodes. The disadvantage is that it requires a dedicated control channel, which decreases network efficiency since the control channel is often a communication bottleneck. In a time division scheme, channel communication is divided into an alternating sequence of control phase and data exchange phase. In the former phase, all nodes transmit RTS and CTS packets to negotiate with others for channels. In the latter phase, all nodes transmit data through corresponding channels. The advantage is that all nodes share the only control channel so only one control channel is required, but nodes take time to synchronize with each other. Wang et al. (2008) proposed a multiple transceivers approach with which each node has several transceivers. Each transceiver is allocated an individual channel, so a node can transmit packets through different channels simultaneously. Of course, the cost is high.

3. System architecture

Fig. 1 shows deployment of APs in the COMAS's wireless environment/network. Coronas from the innermost to the outermost are numbered as coronas 0, coronas 1, coronas 2, …, coronas $n-1$, where n is the number of coronas that the environment has, $n \in N^{+}$. Also, an AP, except those in the outermost coronas, is surrounded by six APs.

In this study, from the innermost to the outermost, every four adjacent coronas form an adjacent corona group (Adj-Co group for short), i.e., coronas $0 \sim 3$ belong to Adj-Co-group 0, coronas $4 \sim 7$ together are Adj-Co-group 1, … coronas $4m \sim 4m+3$ belong to Adj-Co-group m, …, and the remaining coronas form group $\lceil \frac{n+1}{4} \rceil -1$, where corona j, $0 \le j \le n-1$, is assigned to Adj-Co-group k, if $k = \lceil \frac{j+1}{4} \rceil -1$. In addition, we divide all coronas into four corona groups, in which coronas 0, 4, 8, 12, 16, … $4m$ … belong to Corona-group 0, coronas 1, 5, 9, … $4m+1$ … form Corona-group 1, and so on.

3.1. AP deployment scheme

The communication range of an AP, also of a node, is the range inside a circle x meters in radius, e.g., $x=3200$ m in 802.16e (Andrews et al., 2007) and $x=250$ m in 802.11 (Baiocchi et al., 2004). Let L be the line segment connecting two adjacent APs (see Fig. 2), and let Q be the line segment of L in the overlapped communication range of the two APs. According to Leu and Huang (2008), Baiocchi et al. (2004),

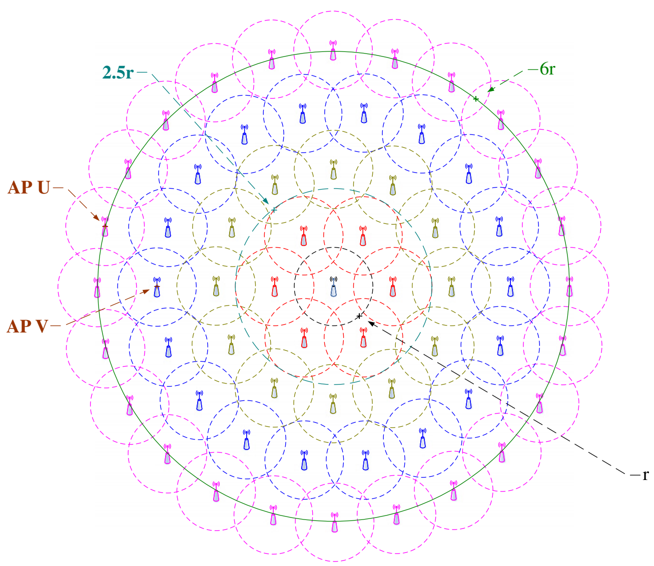

Fig. 1. AP deployment in the COMAS wireless network.

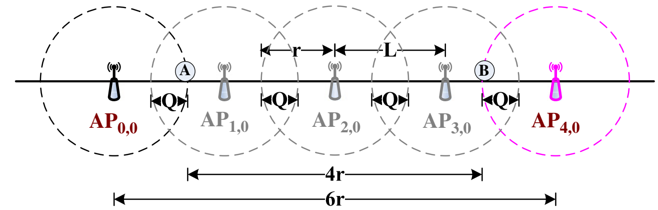

Fig. 2. L is the line segment connecting two adjacent (inner and outer) APs, and Q is the line segment of L in the overlapped communication range of the two APs, where $L=3r/2$.

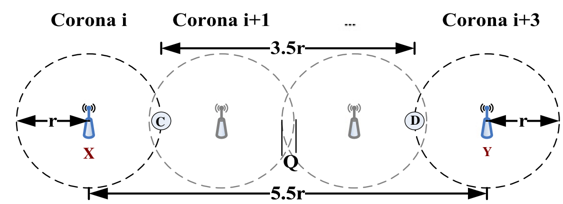

Fig. 3. The distance between APs X and Y is 5.5r, and the distance between nodes C and D is 3.5r.

McGarry et al. (2006), and Wormsbecker and Williamson (2006), the interference range of an AP or a node is about $2r \sim 2.5r$. In this study, we adopt the largest value, i.e., 2.5r, to mitigate possible interference. To further avoid the hidden node problem, two APs, e.g., AP R and AP S, should be separated by at least 3.5r (i.e., increased by r), and the distance between the two APs' subordinate nodes, e.g., node A under AP R and node B under AP S, should be also longer than or equal to 3.5r. Otherwise, hidden node problem may occur.

In fact, if nodes C and D shown in Fig. 3 can send packets without interfering with each other and the occurrence of hidden node problem, the distance between APs X and Y should be at least 5.5r ($=3.5r+2r$). Between the two APs, if $|Q|=0$, then $2 (= \lceil \frac{3.5r}{2r} \rceil)$ APs can be inserted. That means at least two coronas are required to connect the two APs' coronas if we would like to have a mobile node moved from AP X to AP Y or vice versa without its connection being disconnected. According to (Leu and Ko, 2009), if a car's driving speed is 100 km/h and its passenger's mobile device can seamlessly hand off between two WiFi APs, it should be that $|Q| \ge 39$ m ($\doteq 40$ m).

$$2 \times 2r - 3 \times \frac{40\,\mathrm{m}}{250\,\mathrm{m}} = 4r - 3 \times 0.16r \cong 3.52r > 3.5r \tag{1}$$

where $2 \times 2r$ and $3 \times 0.16r$, respectively, represent that there are two APs and three Qs (i.e., three overlapped regions) located between APs X and Y. For WiMAX, Eq. (1) is $2 \times 2r - 3 \times (40\,\mathrm{m}/3200\,\mathrm{m}) \cong 3.9625r$ which is also longer than 3.5r. Both show that nodes under APs X and Y are far away enough to avoid receiving interference from each other.

3.2. Cross-corona signal interference

For handoff considerations, two APs (or coronas) are enough to connect APs X and Y (or corona i and corona j). However, such a case will result in the radio coverage of the whole area shown in Fig. 1 being less than 100%, where the current $|Q|=r/2$. In WiFi, if $|Q|=0.16r$, the distance between two adjacent APs, e.g., APs U and V, will be longer than it is now, and the area between the two APs will not be completely covered by radio signal. In WiMAX, the situation is worse since $|Q|=0.0125r$. In fact, $|Q|=39$ m is proposed under the assumption that there is only one mobile node and no channel contention during handoff. If k mobile nodes, $k>1$, would like to hand off from an AP to another at the same time, or vehicle speed is high, e.g., up to 300 km/h (TGV in France and the high speed rail in Taiwan are two examples), Q should be very much longer than 39 m. Hence, for handoff and communication coverage considerations, in this study, three APs are deployed to connect APs X and Y, and $|Q| = r/2$. Under this circumstance, the distance between nodes A and B shown in Fig. 2 is $4r$ and that between $AP_{0,0}$ and $AP_{4,0}$ is $6r$, implying that nodes A and B can simultaneously communicate with other nodes without interfering with each other. In other words, $AP_{0,0}$'s subordinate nodes when communicating with other nodes or with $AP_{0,0}$ will not interfere with $AP_{4,0}$ and $AP_{4,0}$'s subordinate nodes. This can explain why from corona 0 to corona $n-1$ every four coronas are grouped as an Adj-Co group since interference will not go across four coronas. Now, we can conclude that channels can be reused for every Adj-Co group.

As illustrated in Fig. 1, there are six corona-1 APs that surround $AP_{0,0}$, and the angle between two adjacent APs, e.g., $AP_{1,i}$ and $AP_{1,i+1}$, to $AP_{0,0}$ as shown in Fig. 4a is $60^\circ (=360^\circ \div 6)$. There are twelve APs in corona 2, the angle between $\overline{AP_{2,j}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{2,j+1}}$ is $30^\circ (=360^\circ \div 12)$. There are eighteen and twenty-four APs in coronas 3 and 4, respectively. So, the angle between $\overline{AP_{3,k+1}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{3,k+2}}$ is $20^\circ (=360^\circ \div 18)$, and that between $\overline{AP_{4,l+2}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{4,l+3}}$ is $15^\circ (=360^\circ \div 24)$. The number of APs in corona j can be derived as

$$|AP_j| = \begin{cases} 1 & \text{if } j=0 \\ 6j & \text{if } n-1 \ge j \ge 1 \end{cases} \tag{2}$$

where n is the number of coronas in the environment under consideration. In corona j, the angle between two adjacent APs, e.g., $AP_{j,i}$ and $AP_{j,i+1}$, to $AP_{0,0}$, i.e., $\overline{AP_{j,i}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{j,i+1}}$, is $360^\circ/6j$, where $n-1 \ge j \ge 1$.

Further, from the corona chain between $AP_{0,0}$ and $AP_{4,l+1}$ shown in Fig. 4a, we can derive that $|\overline{AP_{0,0}AP_{1,i+2}}| = 3(r/2)$, $|\overline{AP_{0,0}AP_{2,j+1}}| = 6(r/2)$, $|\overline{AP_{0,0}AP_{3,k+1}}| = 9(r/2)$, …, and the distance between two adjacent APs in corona q, e.g., $AP_{q,p}$, and $AP_{q,p+1}$, as shown in Fig. 4b, is

$$|\overline{AP_{q,p}AP_{q,p+1}}| = 2\left(3q\frac{r}{2}\sin\left(\frac{360}{12q}\right)\right) = 3qr\sin\left(\frac{30}{q}\right), \quad 1 \le q \le n-1 \tag{3}$$

Table 1 lists several examples of distance between two adjacent APs in the same corona.

3.3. Signal interference in a corona

As shown in Fig. 5, the interference range (i.e., $3.5r$) of node A under $AP_{2,i}$ (e.g., $AP_{2,0}$ in corona 2) covers the communication ranges of $AP_{2,1} \sim AP_{2,4}$ and $AP_{2,11} \sim AP_{2,8}$. These APs' communication ranges also receive interference from nodes C and E. From this, we can see that the interference range of an AP in corona 1 (instead of corona 2) covers all corona-1 APs since the longest distance between two corona-1 APs is only $3r(=2(3(r/2)))$. In Fig. 6, $AP_{3,1} \sim AP_{3,3}$ in corona 3, excluding $AP_{3,4}$, are all in node A's and node C's interference ranges. Similarly, $AP_{3,17}$, $AP_{3,16}$ and $AP_{3,15}$ are covered by $AP_{3,0}$'s and its subordinate nodes' interference ranges. In

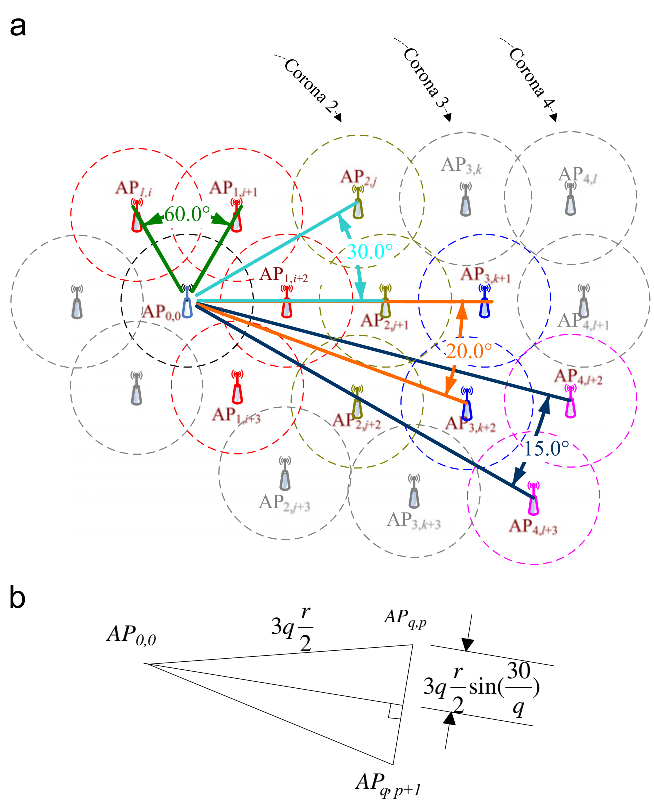

Fig. 4. The angles among APs in coronas 0~3 and between $AP_{q,p}$ and $AP_{q,p+1}$ in corona q. (The angle between $\overline{AP_{1,i}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{1,i+1}}$ is 60° $(=360^\circ \div 6)$, the angle between $\overline{AP_{2,j}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{2,j+1}}$ is $30^\circ (=360^\circ \div 12)$, that between $\overline{AP_{3,k+1}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{3,k+2}}$ is $20^\circ (=360^\circ \div 18)$, and that between $\overline{AP_{4,l+2}AP_{0,0}}$ and $\overline{AP_{0,0}AP_{4,l+3}}$ is $15^\circ (=360^\circ \div 24)$, and so on.) (a) The angles among APs in coronas 0~3. (b) The angle between $AP_{q,p}$ and $AP_{q,p+1}$ in corona q.

Table 1
Examples of distance between two adjacent APs in the same corona.

Corona #	The distance between two adjacent APs
1	$3r\sin(30^o) = 1.5r$
2	$6r\sin(15^o) = 1.553r$
3	$9r\sin(10^o) = 1.563r$
4	$12r\sin(7.5^o) = 1.566r$
…	…

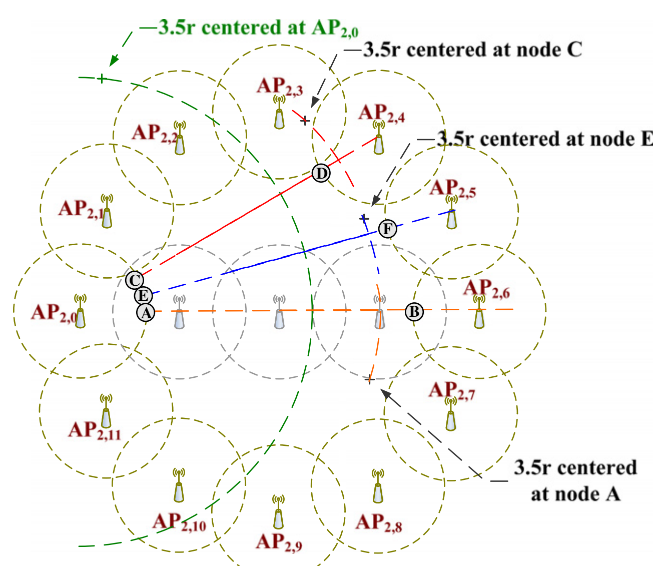

Fig. 5. The interference range of $AP_{2,i}$, e.g., $AP_{2,0}$. ($AP_{2,1}$, $AP_{2,2}$, and $AP_{2,3}$ are in $AP_{2,0}$'s interference range, so are $AP_{2,11}$, $AP_{2,10}$, and $AP_{2,9}$. Node D is in node C's interference range. But nodes B and F are, respectively, out of node A's and E's interference ranges.).

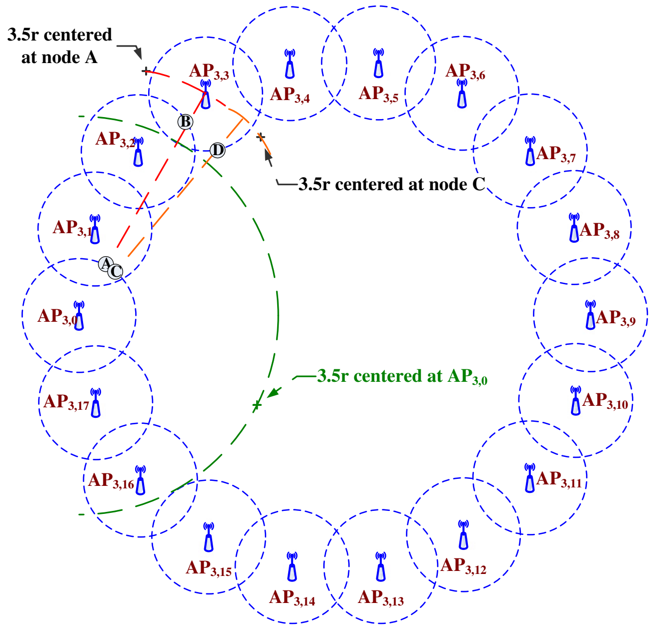

Fig. 6. The interference range of $AP_{3,i}$, e.g., $AP_{3,0}$. ($AP_{3,1}$, $AP_{3,2}$, and $AP_{3,3}$ are in $AP_{3,0}$'s interference range, so are $AP_{3,17}$, $AP_{3,16}$, and $AP_{3,15}$. Node B (node D) is in node A's (node C's) interference range.).

an outer corona, e.g., corona k, $k \geq 4$, the distance between $AP_{k,0}$ and $AP_{k,4}$ is longer than that between $AP_{3,0}$ and $AP_{3,4}$ since in a relatively outer corona, e.g., corona k, the relationship between $AP_{k,0}$ and $AP_{k,4}$ approaches a straight line. Please compare the relationship between $AP_{2,0}\sim AP_{2,4}$ in Fig. 5 and $AP_{3,0}\sim AP_{3,4}$ in Fig. 6. Now, from what has been shown in the two figures, we can conclude that $AP_{2,4}$ is out of $AP_{2,0}$'s interference range, but not completely out of $AP_{2,0}$'s subordinate nodes', and $AP_{k,4}$ is out of $AP_{k,0}$'s and $AP_{k,0}$'s subordinate nodes' interference ranges, where $n-1 \geq k \geq 3$.

3.3.1. Channel assignment to coronas

The COMAS evenly divides available channels of the employed wireless protocol into four channel groups, Channel-group 0 to Channel-group 3. Channel-group i is assigned to all elements of Corona-group i, $i=0, 1, 2, 3$, e.g., members of Corona-group 2, including coronas 2, 6, 10, 14 … $4m+2$, …, are all given Channel-group 2.

From an Adj-Co group viewpoint, Channel-group q ($q=0,1,2,3$) as shown in Fig. 7 is assigned to corona j where $q=j$ mod 4. For example, in Adj-Co-group 0, Channel-groups 0, 1, 2 and 3 are, respectively, assigned to coronas 0, 1, 2 and 3. The purpose is to avoid interference among coronas in an Adj-Co group and in two adjacent Adj-Co groups. Table 2 shows the relationship among Channel groups, Adj-Co groups and Corona groups. In the following, we would like to consider how to assign channels to APs so as to avoid interference among APs in a corona.

Here, we formally define an AP-Nod group. Six adjacent APs in a corona, e.g., corona j, $j \geq 2$, are clustered into a subgroup, named an AP subgroup, i.e., $AP_{j,0}\sim AP_{j,5}$ form AP-subgroup 0, $AP_{j,6}\sim AP_{j,11}$ form AP-subgroup 1, …, $AP_{j,6(k-1)}\sim AP_{j,6(k-1)+5}$ belong to AP-subgroup $k-1$, …, $AP_{j,6(j-1)}\sim AP_{j,6(j-1)+5}$ are grouped as AP-subgroup $j-1$, where $2<k<j$, even though in each subgroup, e.g., $AP_{j,0}\sim AP_{j,5}$, as stated above, the last two APs, i.e., $AP_{j,4}$ and $AP_{j,5}$, receive no interference from the first AP, i.e., $AP_{j,0}$ (except that $AP_{2,4}$ may receive interference from $AP_{2,0}$'s subordinate nodes, see Fig. 5), and other AP subgroups have the same phenomena, $2 \leq j \leq n-1$. In fact, corona j has j AP subgroups, e.g., corona 3 has 3 ($=18/6$) AP subgroups. Corona 0 itself is an AP subgroup which has only one AP.

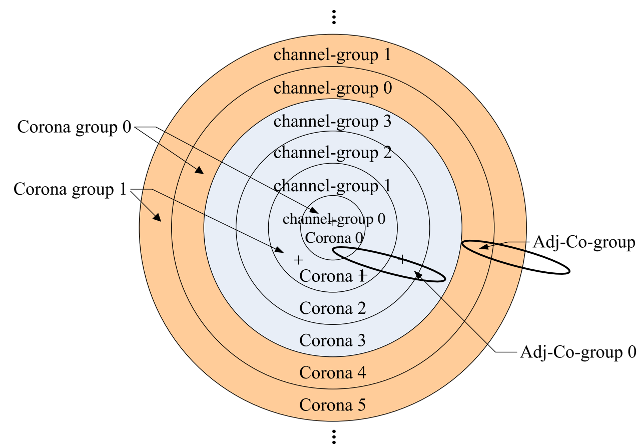

Fig. 7. The assignment of channel groups to coronas in the COMAS.

Table 2
Channel assignment among Adj-Co groups and Corona groups, $0\sim 4(\lceil \frac{n+1}{4} \rceil -1)+3$ are coronas.

	Adj-Co group							
	0	1	2	…	m	…	$\lceil \frac{n+1}{4} \rceil -1$	
Channel-group 0	0	4	8	…	$4m$	…	$4(\lceil \frac{n+1}{4} \rceil -1)$	Corona-group 0
Channel-group 1	1	5	9	…	$4m+1$	…	$4(\lceil \frac{n+1}{4} \rceil -1)+1$	Corona-group 1
Channel-group 2	2	6	10	…	$4m+2$	…	$4(\lceil \frac{n+1}{4} \rceil -1)+2$	Corona-group 2
Channel-group 3	3	7	11	…	$4m+3$	…	$4(\lceil \frac{n+1}{4} \rceil -1)+3$	Corona-group 3

In corona j, an AP subgroup, e.g., AP-subgroup i, and all its subordinate nodes together are called AP-Nod-group i, $0 \leq i \leq j-1$.

3.3.2. Channel assignment to AP-Nod groups

Now, we will discuss how to allocate channels of a channel group, e.g., Channel-group q, to AP-Nod groups of corona j so interference inside an AP-Nod group and between adjacent AP-Nod groups can be avoided where $q=j$ mod 4. The discussion is based on the number of available channels (NoACs) of the employed wireless protocol.

(1) **NoACs ≧ 24:** In this case, each channel group has at least 6 ($=24$ channels/4 coronas) channels since an Adj-Co group consists of 4 adjacent coronas. We then evenly divide the channels of a channel group assigned to corona j into six subgroups, Channel-subgroups 0∼5. Channel-subgroup i is assigned to the ith APs of all AP-Nod groups in corona j, $0 \leq i \leq 5$. For example, Channel-subgroup 0 is assigned to $AP_{j,0}$, $AP_{j,6}$, $AP_{j,12}$, … which are the first APs of AP-Nod-groups 0, 1, 2, … , respectively, and Channel-subgroup 5 is assigned to $AP_{j,5}$, $AP_{j,11}$, $AP_{j,17}$, … which are the sixth APs of AP-Nod-groups 0, 1, 2, …, respectively. It is evident that each AP-Nod group is assigned at least six channels, and then each AP has at least one channel, e.g., h channels, h≧1. When the number of active subordinate nodes that an AP currently has is larger than h, the Time Division Multiple Access (TDMA) scheme is invoked by the AP and its active subordinate nodes, where active subordinate nodes are subordinate nodes that are communicating with their correspondent nodes. In fact, it is better that each AP has the same number of channels. So, the number of channels actually allocated to APs is $24h$. Since the number of active subordinate nodes is dynamically changed, the working process is involved periodically. One may point out that corona 0 only needs one channel, instead of 6 channels. Hence, 19

channels are sufficient. This is true, but, when the number of coronas is higher than 4, we need 24 channels.

(2) **15≦NoACs < 24:** Please note that in this case each channel group generally consists of 3 channels, and corona j is allocated 3 channels, $2 \le j$. Coronas 0 and 1, respectively, require 1 channel and 6 channels, and the corona-0 channel and 3 corona-1 channels can be, respectively, reused by coronas 4 and 5, indicating that 3 extra channels are required by corona 1. Therefore, the actual number of channels required is 15 (=4 coronas × 3 channels+3 corona-1 channels). But, from corona 2 to corona $n-1$, 12 channels, e.g., channels 0∼11, are sufficient. Generally, channel-group 0 consists of channels 0∼2, and channel-group 1 comprises channels 3∼5,…. As stated above, channel-group (j mod 4), $2 \le j$, is assigned to corona j's j AP-Nod groups, e.g., channel-group 3 is allocated to corona 3's three AP-Nod groups. In an AP-Nod group, the ith two APs share the ith channel of the given channel group, i=0, 1 and 2. Every AP-Nod group does the same assignment. For example, in corona 3, $AP_{3,0}$ and $AP_{3,1}$ in AP-Nod-group 0, $AP_{3,6}$ and $AP_{3,7}$ in AP-Nod-group 1, $AP_{3,12}$ and $AP_{3,13}$ in AP-Nod-group 2 are given channel-group 3's first channel, i.e., channel 9. We call the two adjacent co-channel APs, which are in the same AP-Nod group, an AP pair.

To further avoid interference between/among the two APs of an AP pair and their active subordinate nodes, the AP pair follows the TDMA scheme to assign the only channel that they share to these subordinate nodes. As shown in Fig. 8, $AP_{j,0}$ and $AP_{j,1}$ share the first channel of channel-group (j mod 4). If (j mod 4) is 0, 1, 2, or 3, then the channel will be, respectively, channel 0, 3, 6, or 9. The channel is further divided into $N_{j,0}+N_{j,1}$ time slots, where $N_{j,0}$ and $N_{j,1}$ are the numbers of $AP_{j,0}$'s and $AP_{j,1}$'s current active subordinate nodes, respectively. The working process is as follows. There is an AP pair, e.g., $AP_{j,i}$ and $AP_{j,i+1}$, in which $AP_{j,i}$ ($AP_{j,i+1}$) establishes a scheduling table to assign $N_{j,i}$ ($N_{j,i+1}$) time slots to its $N_{j,i}$ ($N_{j,i+1}$) nodes. It also sends the table to $AP_{j,i+1}$ ($AP_{j,i}$). $AP_{j,i+1}$ ($AP_{j,i}$) on receiving the table merges the table with its own one. After that, both the two APs have the same schedule, and they follow the schedule to periodically allocate time slots to their nodes.

(3) **11≦NoACs < 15:** In this case, only 11 channels (4 coronas × 2 channels+3 extra corona-1 channels) are required. The first three adjacent APs in an AP-Nod group (e.g., $AP_{j,0}$∼$AP_{j,2}$, $2 \le j$) share a channel, and the last three (e.g., $AP_{j,3}$∼$AP_{j,5}$) share the other one. However, our approach still works since the shortest distance between two co-channel APs, e.g., $AP_{j,2}$ and $AP_{j,6}$, which belong to two adjacent AP-Nod groups, is about four APs away, i.e., separated by three APs. According to Fig. 2, like that between $AP_{0,0}$ and $AP_{4,0}$, interference between $AP_{j,2}$ and $AP_{j,6}$ will not occur. The working process is the same as the one described above, but this time three APs (called an AP triple) are involved.

When NoACs < 11, our approach is infeasible since corona j, $2 \le j$, is assigned only one channel. Although TDMA works, all APs and their active subordinate nodes share the channel. Each node's waiting time will be long. Now, we can further conclude that an AP-Nod group in a corona, e.g., AP-Nod-group k in corona j, will not receive interference from any AP-Nod-groups in all coronas, including other AP-Nod groups in corona j since the channel that $AP_{j,i}$ uses is reused by those coronas at least four coronas/APs away, i.e., coronas $j-4$, $j+4$, $j-8$, $j+8$, …, and by those AP-Nod groups (in corona j) far away enough (when NoACs≧24, it is six APs away; when 15≦NoACs < 24, it is at least five APs away), and coronas $j+1$∼$j+3$ and $j-1$∼$j-3$ use the other three channel groups.

One may figure out that in corona 2 when 15≦NoACs < 24, like the case shown in Fig. 5, node C will interfere with node D since the distance between the two nodes is less than 3.5r, i.e., the hidden node problem may occur. Please note that the distance between C and D is longer than 2.5r, and the nodes located between C and D are all in corona 1, which uses different channels from those used by nodes C and D. Therefore, there is no hidden node problem. In other words, when the employed wireless protocol's NoACs≧11, the proposed scheme can be completely interference-free.

3.3.3. Radio coverage

Given an area A which is a circle k meters in radius where $|A| = k^2\pi$, the number of coronas required to cover A (see Fig. 2) is $n = \lceil (k-r)/(2r-r/2) \rceil + 1 = \lceil (k-r)/(3r/2) \rceil + 1$ since two adjacent AP's communication ranges overlap (r/2) (i.e., Q) where 1 represents corona 0, and also from Fig. 2, we can see that the effective length of n coronas, denoted by L, is $L = (n-1)(3r/2)+r$ $(=(n-1)2r+r-(n-1)r/2) \ge k$.

Hence, the total number of APs required by the n coronas is $1+\sum_{i=1}^{n-1} 6i$. Their cumulative radio area is $(1+\sum_{i=1}^{n-1} 6i)r^2\pi$. The radio area ratio R, defined as the ratio of all APs' cumulative radio area over the effective geographic communication area (instead of A) is $R = \frac{(1+\sum_{i=1}^{n-1} 6i)r^2\pi}{L^2\pi} = \frac{1+\sum_{i=1}^{n-1} 6i}{(3(n-1)/2+1)^2}$. Let R' be the ratio of all APs' cumulative radio area over the real geographical area A, then $R' = \frac{(1+\sum_{i=1}^{n-1} 6i)r^2\pi}{k^2\pi} = \frac{(1+\sum_{i=1}^{n-1} 6i)r^2}{k^2}$. When seamless handoff can be successfully performed, we hope R and R' can be as small as possible.

For example, given a metropolitan-scale city with radius k of 21,000 m, theoretically, $5\,(=\lceil (21{,}000-3200)/4800 \rceil + 1)$ coronas and 61 (=1+6+12+18+24) APs are required. Its L=22,400 m, R=1.24 and R'=1.42. However, if a traditional cellular system is deployed, $5\,(=2 \times \lceil (21{,}000-3200)/(3 \times 3200) \rceil + 1)$ layers of concentric hexagons (Andrews et al., 2007) and then 61 cells/APs are required where 3 × 3200 is the distance generated by two adjacent coronas from $AP_{0,0}$'s communication boundary to the system boundary. Its L=22,400∼24,940 m $(=7r \sim 9(\sqrt{3}/2)r)$ of which the average value is 23,670 m, $R = \frac{61r^2\pi}{6((1/2)\times 7r \times 9(\sqrt{3}/2)r)} = \frac{244\pi}{378\sqrt{3}} = 1.17$ and R'=1.42 where 7r and 9 $(\sqrt{3}/2)r$ are, respectively, the shortest and longest distances between $AP_{0,0}$ and the system boundary.

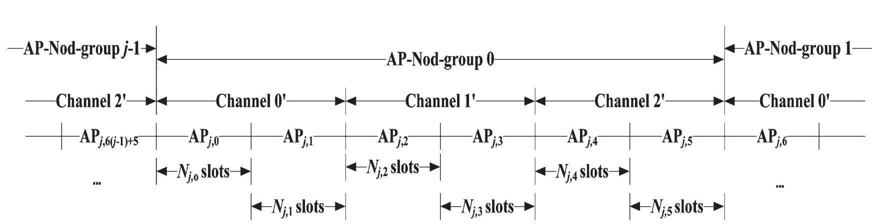

Fig. 8. A channel distribution scheme when 15≦NoACs < 24. From corona 2 to corona $n-1$, an AP pair is assigned a channel. Channels 0', 1' and 2', respectively, represent the first, second and third channels of channel-group (j mod 4). Let p= (j mod 4). If (p=0), channels 0', 1' and 2' will be, respectively, channel 0, 1, and 2. If (p=1), channels 0', 1' and 2' will be, respectively, channels 3, 4, and 5. If (p=2),….

4. Experimental results

In this study, we used *ns*-2 (NS2 Notebook, 2009) as our simulation tool, and enhanced the tool by integrating it with a modified version of the multi-channel model introduced by USC/ISI (2009) to give the tool multi-channel capability. The default values of the parameters used in the following experiments are listed in Table 3. But the values in different experiments will be changed when necessary.

The compared schemes include the interface assignment algorithm (the interface algorithm for short) (Kyasanur and Vaidya, 2004), the cellular system (the cell scheme for short) (Andrews et al., 2007) and the random channel assignment algorithm (the random algorithm for short) with which an AP or a node randomly selects a channel from the available channels (see Table 3) before transmitting packets to a node or an AP.

Five experiments were performed in this study. The first studied the interference of the cell scheme pertaining to two co-channel nodes which were in two adjacent clusters. The second evaluated the tested schemes' average throughputs defined as $\frac{\text{Total throughputs of corona } i}{\text{number of APs in corona } i}$, drop rates, jitters and network delays where total throughput is defined as the accumulated number of bits, including those in packet headers and payloads, having been successfully delivered per second by all nodes in the simulation environment. Drop rate is the percentage of dropped packets (instead of dropped bytes), and network delay consists of propagation delay and transmission delay. The third experiment evaluated system performance given different data rates. The fourth and fifth redid the third experiment but, respectively, given an AP different numbers of subordinate nodes and different packet sizes.

In the latter four experiments, the simulation environment of the interface, the random and the COMAS is a complete COMAS structure in which corona 0 to corona 3 are involved. Corona 0 has only one AP. Coronas 1, 2, and 3, respectively, have six, twelve, and eighteen APs. The numbers of subordinate nodes under a corona-0 AP, corona-1 AP, corona-2 AP and corona-3 AP are, respectively, 10, 10, 8 and 6. When simulating the case of NoACs≧24, six APs in all AP-Nod groups of corona j, $2 \le j$, were assigned six given channels, and a total of 19 channels were used. Note that as stated above if at least 5 coronas are involved, 24 channels are required. Other parameters are default values. Also, in these experiments, a sender does not retransmit a packet on packet loss, except when retransmission is required and specified. Further, before a time slot expires, if the last packet cannot be completely transmitted, or even if the packet has been completely transmitted, but the sender has not received the corresponding ACK from the receiver, we consider this is a failed transmission, called an incomplete end transmission.

Table 3
Default values of the experimental parameters.

Parameter	Default values
WiMAX/Wireless protocol	802.16e/ 802.11 abgn
Data rate of a node/an AP	50 Mbps
Packet size	1000 bytes
Max queue length of a node/an AP	50
Number of channels really used (only 15 and 19 are respectively employed in simulating WiMAX when 15≦NoACs < 24 and NoACs≧24, and 11 in simulating 802.11 when 11≦NoACs < 15)	19/15/11
Number of subordinate nodes for each AP in coronas 0 and 1	10
Number of subordinate nodes for each AP in corona 2	8
Number of subordinate nodes for each AP in corona 3	6
Time slot	8 ms
Transmitted time	1 s

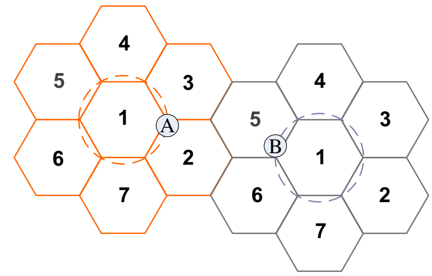

Fig. 9. In the cell scheme, nodes A and B, belonging to two different co-channel cells/APs, were located at the two AP's nearest edge points.

Table 4
The cell scheme's throughputs and drop rates.

Communication radius	Total throughput (Mbps)	Drop rate (%)
0.8*r*	107.86	0.13
0.9*r*	107.86	0.13
r	96.43	10.7
1.1*r*	93.95	13.0
1.2*r*	89.32	17.3

4.1. Interference on the cell scheme

In the first experiment, we used the topology shown in Fig. 9 as the environment to test the cell scheme. Communication radiuses range between 0.8*r* and 1.2*r*. Nodes A and B, belonging to two co-channel APs/cells, were always located at the nearest edge points of the two cells. The data rate was 54 Mbps instead of 50 Mbps.

Table 4 lists the experimental results. The drop rates range between 0.13% and 17.3% in which 0.13% comes from incomplete end transmissions instead of from signal interference. The total throughputs were between 107.86 and 89.32 Mbps. Now, we can conclude that when the communication radius is *r*, the distance between nodes A and B is not far away enough to avoid radio interference. The situation is worse when the communication range of an AP is enlarged to handle handoff.

4.2. Performance inside a corona

In this experiment, COMAS-x/2, COMAS-x and COMAS-2x, respectively, represent the simulations on 11≦NoACs < 15, 15≦NoACs < 24 and NoACs≧24. The latter two were performed in a WiMAX environment. For the former, we employed the IEEE 802.11 protocol which transmits no RTS and CTS before sending a packet. Of course, $r = 250$ m instead of 3200 m, and TDMA instead of backoff contention was used. Coronas was tested one by one to avoid simultaneously involving too many nodes. Otherwise, the system performance, particularly for packet delivery delays and drop rates, due to the load of computer hardware will be dramatically degraded.

Fig. 10 shows average throughputs and drop rates of the four tested schemes. Their corona-0 throughputs were all high because of no interference. The interface's and the random's throughputs in corona 1 were lower than those of other coronas. The reasons are as follows. In corona 1, as stated above an AP will interfere with all other APs, so the random's throughputs were the lowest. In coronas 2 and 3, the number of APs receiving interference from other APs decreased, so the throughputs were higher than those of corona 1. The interface scheme's interference occurs when the distance between two co-channel senders is not far away enough. That is why its throughputs were lower than those of the COMAS-x/2, COMAS-x, COMAS-2x and the cell scheme, but higher than those of the random. The COMAS-x/2's,

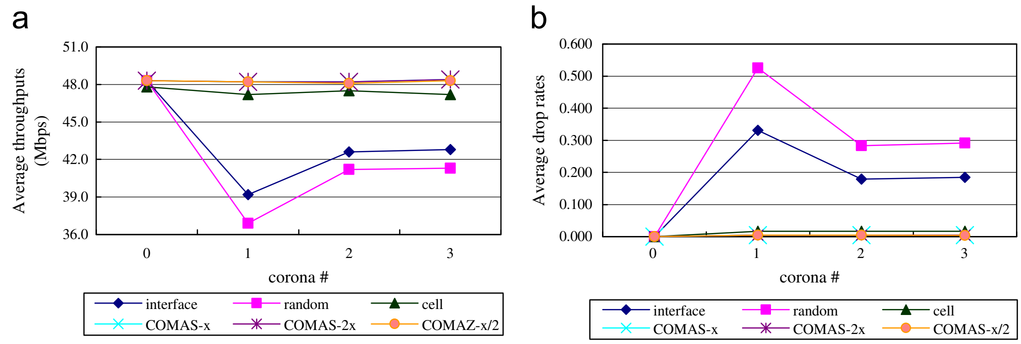

Fig. 10. Network throughputs and drop rates of the four tested schemes on different coronas: (a) network throughputs and (b) drop rates.

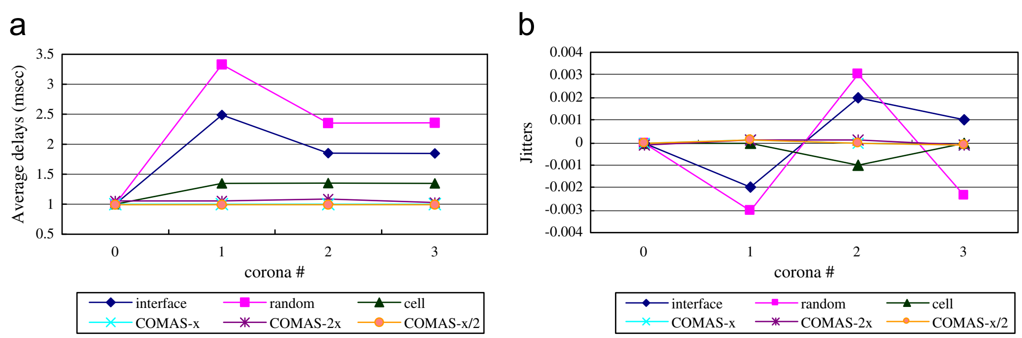

Fig. 11. Network delivery delays and jitters of the four tested schemes on different coronas: (a) average delivery delays and (b) average jitters.

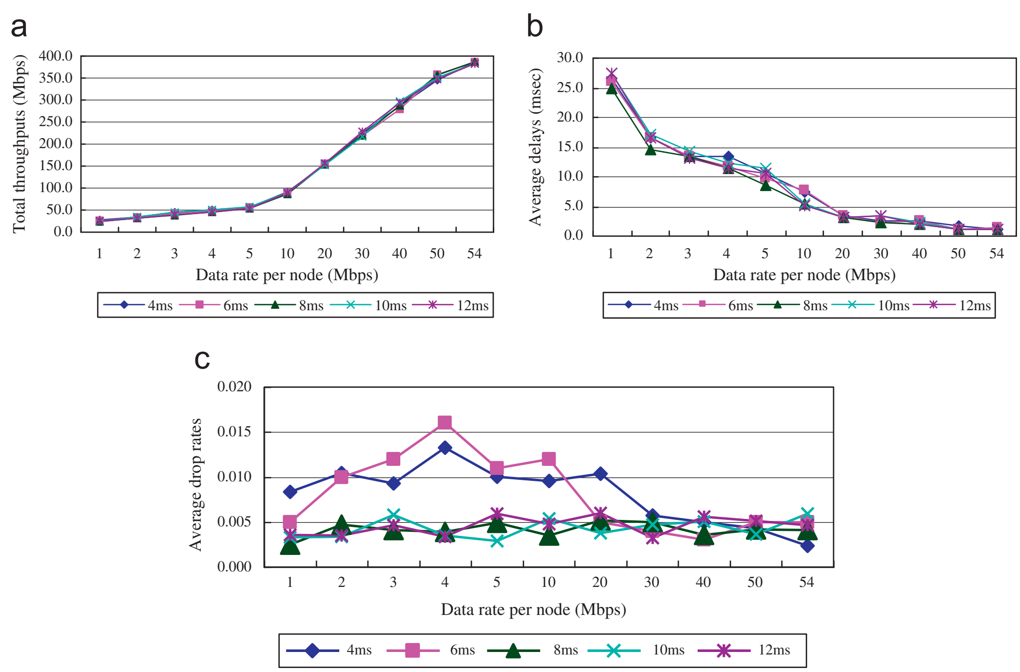

Fig. 12. Network throughputs, delivery delays and drop rates of the COMAS scheme against data rates using different lengths of time slots: (a) network throughputs; (b) average delivery delays and (c) drop rates.

COMAS-x's and COMAS-2x' drop rates as shown in Fig. 10b were stable. The cell's drop rates were a little higher than those of the COMAS-x/2, COMAS-x and COMAS-2x. Fig. 11a and b, respectively, show that the COMAS-x/2, COMAS-x and COMAS-2x due to no packet collision had less packet delivery delays, and jitters were also more stable than those of other schemes.

4.3. Performance on different data rates

In the third experiment, the data rates were increased from 1 to 54 Mbps (instead of 50 Mbps). Nodes continuously communicated with their APs, and an AP only replied to its nodes without sending messages to other APs or nodes. In the following experiments, APs and nodes do the same. We first define two cases: the period of a time slot is fixed and variable. For the former case, the periods were fixed at 4, 6, 8, 10 and 12 ms, and a node in a time slot sent a maximum of $3*data\ \ rate/1$ Mbps packets, e.g., 3 packets were sent on data rate = 1 Mbps, 6 packets on 2 Mbps, …, and 162 packets on 54 Mbps. On variable length, the time period of a time slot was $\frac{8}{(data\ \ rate/1\,\mathrm{Mbps})}$. For example, when the data rate was 1, 2 or 54 Mbps, the lengths were, respectively, 8, 4 and 0.1481 ms. Fig. 12a and b show that the total throughputs and delivery delays of the COMAS (can be COMAS-x/2, COMAS-x or COMAS-2x) scheme against data rates using different lengths of time slots are not themselves significantly different. Fig. 12c illustrates that when the length of a time slot is larger than or equal to 8 msc, the drop rates are relatively stable and low. However, longer time slots cause longer waiting time since a time sharing scheme is employed among nodes. Therefore, 8 ms is the best candidate.

Fig. 13 shows the experimental results including total throughputs and drop rates of the tested schemes. We can see that the individual throughput trends for a fixed length and a variable length schemes are similar. But, for each scheme, the fixed length's performance is better than that of the variable length, particularity when data rates are high. The reason is that when a variable length time slot is used, the time slot is relatively shorter. An incomplete end transmission packet will then yield higher drop rates. Hence, in the following experiments, we fixed the length of a time slot to 8 msec. Also, a node transmits the next packet only when it receives the ACK of the previous packet from the receiver.

Fig. 13a also illustrates that when data rates are low, e.g., 1∼10 Mbps, the total throughputs of the four schemes are not significantly different. When date rates were higher than 20 Mbps, the cell outperformed the interface and random schemes because the cell coordinated the usage of channels. Theoretically, the COMAS-x's (COMAS-x/2's) total throughputs are one half (one third) of those of the COMAS-2x since at any moment only one node in each AP pair (AP triple) transmits packets. The COMAS-2x's throughputs, owing to it being interference-free, were higher than those of the other three schemes.

From the experimental results shown above, we can conclude that the COMAS-x/2's and COMAS-x's average throughputs evaluated from nodes viewpoint are similar to those of the COMAS-2x. But, their total throughputs evaluated from a system's viewpoint are, respectively, about one half and one third of those of the COMAS-2x's. Here, we do not recommend users to adopt the COMAS-x/2, even though it works in the proposed architecture. Further, when data rates approached 54 Mbps, the throughputs of the four schemes, due to almost saturated bandwidth, did not increase as sharply as those from 10 to 50 Mbps. In the following, we will omit the evaluation on the COMAS-x/2. Also, the COMAS-x

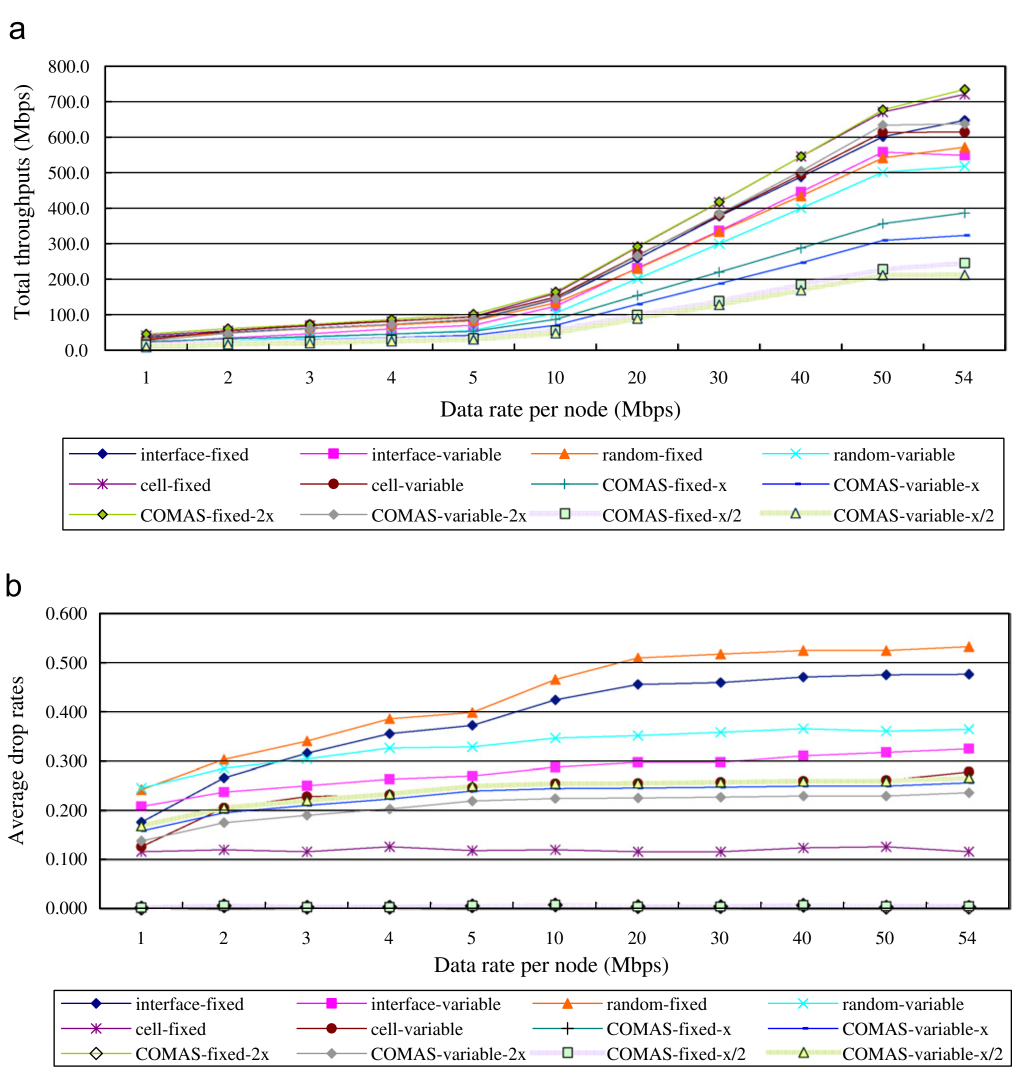

Fig. 13. Network throughputs and drop rates of the four tested schemes against data rates using fixed length and variable length time slots. Note that COMAS-fixed-x's, COMAS-fixed-2x's, and COMAS-fixed-x/2's plots are almost overlapped: (a) network throughputs and (b) drop rates.

and COMAS-2x will be separately described only when necessary. Otherwise, COMAS represents both to simplify the description.

Fig. 13b shows that the COMAS's drop rates (about 0.01) and the cell's drop rates (about 0.11) were stable. However, the interface and the random schemes' drop rates for data rate = 1 Mbps were, respectively, 0.17 and 0.24. Drop rates increase when data rate is higher because the communication link is gradually saturated. The interface scheme uses multiple channels to transmit/receive packets. But, when the distance between two co-channel nodes is not far away enough, interference will occur, resulting in poor performance. The random algorithm has the same phenomenon. Also, when data rates are higher, the number of lost packets due to incomplete end transmission is relatively lower than the number of those completely transmitted. That is why the drop rates were smoothly increased.

The COMAS's average delays, as shown in Fig. 14a, are shorter than those of the other three algorithms. When data rates are higher, delays of course decrease. Fig. 14b illustrates the jitters of the four schemes. The COMAS is relatively stable.

4.4. Performance on different numbers of subordinate nodes

In the fourth experiment, we evaluated how the number of active subordinate nodes affects network performance. The number of an AP's subordinate nodes ranges between 10 and 40 (instead of 10, 8 and 6 listed in Table 3). Nodes are randomly distributed to an AP's communication range. Each node continuously communicates with its AP in a TDMA method.

Fig. 15a shows that when the number of subordinate nodes increases, the COMAS's and the cell's total throughputs change slightly. The reason is that the time slots are fixed in length, nodes follow scheduled time slots to send packets and most packets have sufficient time to be transmitted. The interface and the random

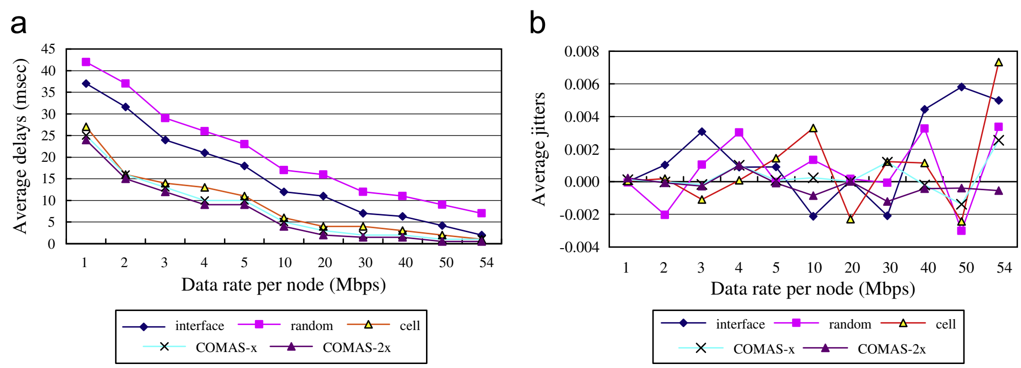

Fig. 14. Network delivering delays and jitters of an AP for the four tested algorithms against data rates: (a) average delivery delays and (b) average jitters.

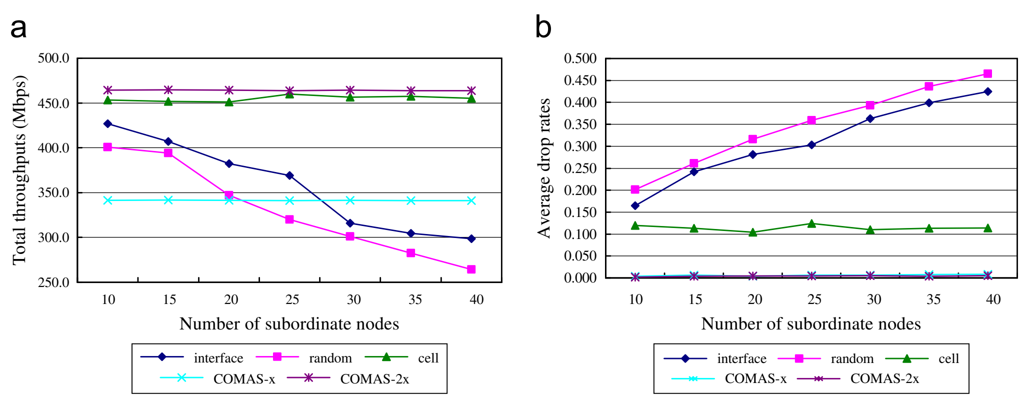

Fig. 15. Network throughputs and drop rates of the four tested algorithms against numbers of subordinate nodes: (a) network throughputs and (b) drop rates.

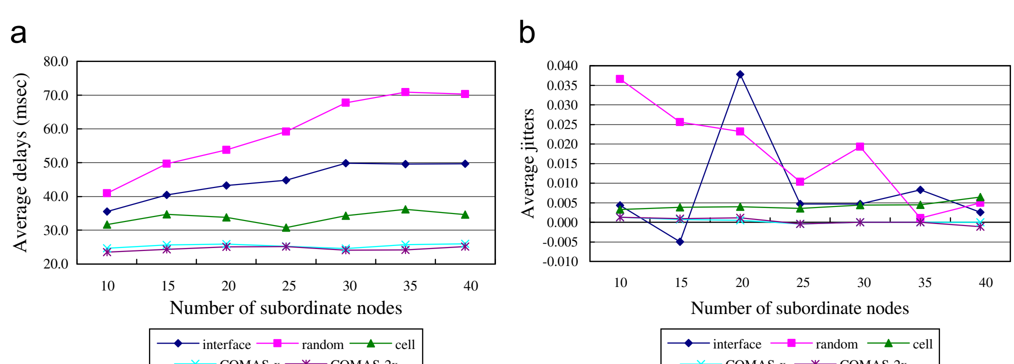

Fig. 16. Network delivery delays of an AP for the four tested algorithms against numbers of nodes: (a) average delivery delays and (b) average jitters.

schemes' throughputs decrease sharply since when the number of subordinate nodes increases, the probability that nodes choose the same channel or nodes are assigned the same channel also increases.

Fig. 15b shows that the COMAS's drop rates are lower than the other three schemes', and remain at about 0.01. The interface's drop rates, which increase from 0.17 to 0.43 when the number of subordinate nodes increases from 10 to 40, are lower than those of the random, implying fixing receiving channels and transmitting channels once they are assigned to nodes is helpful in improving system performance as compared to the drop rates of the random algorithm. The number of the COMAS's dropped packets does not significantly change when the number of subordinate nodes increases. Also, more subordinate nodes result in higher drop rates. That is why the interface's and the random's drop rates decrease sharply. With the cell scheme, the drop rates keep on 0.01.

Table 5
Packet sizes and their related information.

Packet size (bytes)	The time required to transmit a packet (ms)	No. of packets/no. of bytes that can be sent in a time slot	The effective utilization of a time slot
1000	0.16	50 pkts/50,000 bytes	1 (=8/8)
5000	0.8	10 pkts/50,000 bytes	1(=0.8 × 10/8)
10,000	1.6	5 pkts/50,000 bytes	1(=1.6 × 5/8)
15,000	2.4	3 pkts/45,000 bytes	0.9 (=2.4 × 3/8)
20,000	3.2	2 pkts/40,000 bytes	0.8 (=3.2 × 2/8)
30,000	4.8	1 pkts/30,000 bytes	0.6 (=4.8*1/8)
40,000	6.4	1 pkts/40,000 bytes	0.8 (=6.4 × 1/8)

Fig. 16a shows that the COMAS's delivery delays are more stable and shorter than those of the other schemes. The random's delays fluctuate due to randomly choosing channels. Sometimes signals collide, and sometimes signals are collision-free. Fig. 16b shows that the COMAS's jitters are stable. The cell's network delays owing to light interference are longer than those of the COMAS, and its jitters are a little unstable.

4.5. Performance on different packet sizes

In the fifth experiment, we evaluated how packet sizes affect network performance. Dropped packets will be retransmitted. So the delays of a packet will be the time period from when the sender starts to send the packet to the time point when the packet is successfully delivered. The sizes of sent packets range between 1000 and 40,000 bytes. Others parameters follow the default values. Nodes continuously transmit packets to their APs in their allocated time slots, and an AP only replies to its nodes without sending messages to other APs or nodes.

When packet size=1000 bytes, a node spent 0.16 ($=1000\times 8/(50\times 10^6)$) ms to transmit a packet. So, theoretically it can continuously transmit 50 packets in 8-ms time slot. But, due to waiting to receive an ACK from the receiver, the number is really less than 50. When packet size=30,000 or 40,000 bytes, a node can only successfully transmit a packet in a time slot, and due to the incomplete end transmission, the effective utilization of a time slot is not 100%. Table 5 lists the packet sizes and their related information which show the reason why in Fig. 17a when packet sizes range between 15,000 and 40,000 bytes, the total throughputs are lower. But the COMAS's throughputs are still higher than the other three schemes'. Fig. 17b shows the four schemes' drop rates. In fact, in a fixed-length time slot

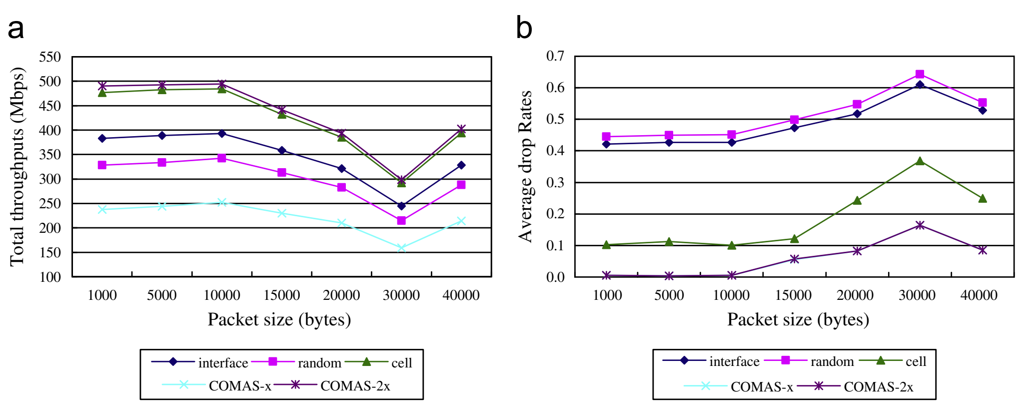

Fig. 17. Network throughputs and drop rates of the four tested algorithms against different packet sizes: (a) network throughputs and (b) drop rates.

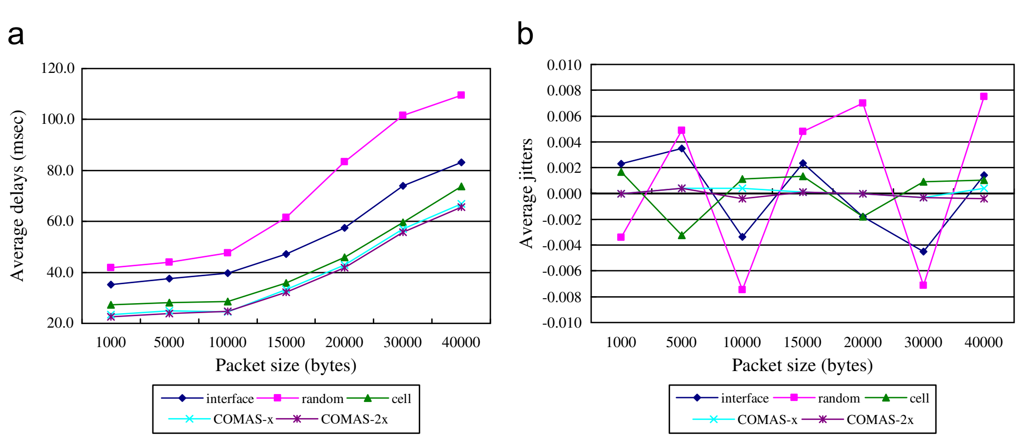

Fig. 18. Network packet delays and jitters of the four tested algorithms against different packet sizes: (a) average delivery delays and (b) average jitters.

when packet sizes increase, the number of packets transmitted will decrease, and the packet drop rates due to incomplete end transmission and packet collision will be relatively higher.

Now we can conclude that the packet size should not be large, e.g., larger than 15,000 bytes. Otherwise, the incomplete end transmission will result in poor total throughputs and high drop rates. If a message is large, it would be better to partition it into several smaller packets, like the partition for packet switching.

Fig. 18a shows that the other three schemes' delivery delays are longer than the COMAS's since collision results in retransmission. Usually, longer delivery delays cause larger jitters. That is why the COMAS's jitters shown in Fig. 18b are stable and the smallest.

5. Conclusions and future work

In this paper, we propose the COMAS to solve the multi-channel terminal problem and channel assignment problem. With the COMAS, many packets can be delivered through multiple interference-free channels in parallel so as to effectively improve network throughputs, regardless of whether the data rate is high or low. With 802.11 protocols, only 14 channels are available, (But we only used 11 channels, one for corona 0, six for corona 1, two for both coronas 2 and 3.) so three APs of an AP triple in corona j, $2 \leq j$, share only one channel to avoid radio/signal interference. But in some wireless protocols, e.g., WiMAX, LTE, etc., many channels are available, so each AP can use at least one collision-free channel to communicate with other nodes. In the experiments, we simulated four schemes, the COMAS, the interface, the random and the cell schemes. When data rates and number of nodes increase, the COMAS also preserved high throughputs and low drop rates. Given different packet sizes, the COMAS's delays are shorter and more stable than those of the other three schemes. From the experiments, we can conclude that the COMAS's performance is more stable and higher than the other schemes', and the radio/signal interference problem exists in the cell scheme. The key drawback of the COMAS is many more channels are required, 11, 15, 24 or more.

Nevertheless, due to lower total throughputs, we do not recommend the case $11 \leqq \text{NoACs} < 15$. Also, packet sizes should not be large, e.g., larger than 15,000 bytes. Otherwise, both throughputs and drop rates will be poor. However, if a message is large, it would be better to partition it into several smaller packets before delivering the message.

In the future, we would like to derive the reliability model for the COMAS so users can predict the reliability of the system before deploying it. We also plan to study how far the communication range of an AP should be extended before k mobile devices can smoothly and seamlessly hand off from an AP to another. Those constitute our future research.

References

Alnifie G, Simon R. A multi-channel defense against jamming attacks in wireless sensor networks. In: Proceedings of the ACM workshop on QoS and security for wireless and mobile networks, October 2007, p. 95–104.

Ahmed N, Kanhere S, Jha S. Multi-Channel interference in wireless sensor networks. In: Proceedings of the international conference on information processing in sensor networks, 2009, p. 367–8.

Andrews JG, Ghosh A, Muhamed R. Fundamentals of WiMAX: understanding broadband wireless networking. Prentice Hall; 2007.

Baiocchi A, Todini A, Valletta A. Why a multi-channel protocol can boost IEEE 802.11 performance. In: Proceedings of the ACM international symposium on modeling, analysis and simulation of wireless and mobile systems, October 2004, p.143–8.

Bien VQ, Prasad RV, Niemegeers I. Handoff in radio over fiber indoor networks at 60 GHz. Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications 2010;1(2/3):71–82.

Huang H, Peng Y, Li J. Joint routing and channel assignment in WMN using extended Petri net. In: Proceedings of international conference on distributed computing systems workshops, June 2008, p. 108–13.

Incel OD, Dulman S, Jansen P, Mullender S. Multi-channel interference measurements for wireless sensor networks. In: Proceedings of IEEE conference on local computer networks, 2006, p. 694–701.

Incel OD, Jansen P. Characterization of multi-channel interference. In: Proceedings of the international symposium on modeling and optimization in mobile, ad hoc, and wireless networks, 2008, p. 429–35.

Ju JH, Li VOK. TDMA scheduling design of multihop packet radio networks based on Latin squares. IEEE Journal on Selected Areas in Communications 1999;17(8): 1345–52.

Ju JH, Li VOK. An optimal topology-transparent scheduling method in multihop packet radio networks. IEEE/ACM Transactions on Networking 1998;6(3): 298–306.

Jung E, Vaidya N. A power control MAC protocol for ad hoc networks. In: Proceedings of the eighth ACM international conference on mobile computing and networking, September 2002, p. 36–47.

Kyasanur P, Vaidya NH. Routing and interface assignment in multi-channel multi-interface wireless networks. Technical report, University of Illinois at Urbana-Champaign, October 2004.

Kim SJ, Kim SY, Lee BB, Ryu SW, Lee HW, Cho CH. Multi-hop relay based coverage extension in the IEEE802.16j Based Mobile WiMAX Systems. In: Proceedings of networked computing and advanced information management, September 2008, p. 516–22.

Leu FY, Huang YT. Maximum Capacity in chain-topology wireless mesh networks. In: Proceedings of the wireless telecommunications symposium, April 2008, p. 250–59.

Le HK, Henriksson D, Abdelzaher T. A control theory approach to throughput optimization in multi-channel collection sensor networks. In: Proceedings of the international conference on information processing in sensor networks, April 2007, p. 31–40.

Leu FY, Ko ZJ. A novel network mobility handoff scheme using SIP and SCTP for multimedia applications. Journal of Networking and Computer Applications 2009;32(5):1073–91.

McGarry MP, Reisslein M, Syrotiuk VR. Access control in heterogeneous multi-channel wireless networks. In: Proceedings of the international conference on integrated internet ad hoc and sensor networks, May 2006.

Niranjan S, Pandey, Ganz A. Design and evaluation of multi-channel multirate wireless networks. Mobile Networks and Applications 2006;11(5):697–709.

NS2 Notebook. Multi-channel multi-interface simulation in NS2 (2.29), ⟨http://www.cse.msu.edu/~wangbo1/ns2/nshowto8.html⟩, February 2009.

Park SW, Jung S. A data allocation scheme for multiple wireless broadcast channels. In: Proceedings of the International conference on ubiquitous information management and communication, January 2008, p. 256–62.

USC/ISI. The network simulator—ns-2, ⟨http://www.isi.edu/nsnam/ns/⟩, February 2009.

Wang M, Ci L, Zhan P, Xu Y. Multi-channel MAC Protocols in wireless ad hoc and sensor networks. In: Proceedings of the international colloquium on computing, communication, control, and management, August 2008, p. 562–6.

Wang H, Yow KC. Qos routing in a multi-channel multihop wireless network with infrastructure support. In: Proceedings of the international conference on integrated internet ad hoc and sensor networks, May 2006.

Wormsbecker I, Williamson C. On channel selection strategies for multi-channel MAC protocols in wireless ad hoc networks. In: Proceedings of wireless and mobile computing, networking and communications, June 2006, p. 212–20.

Xu W, Trappe W, Zhang Y. Channel surfing: defending wireless sensor networks from interference. In: Proceedings of the international conference on information processing in sensor networks, April 2007, p. 499–508.

Zhou H, Yeh C, Mouftah HT. Multi-channel busy-tone multiple access for a scalable wireless mesh network. In: Proceedings of advanced information networking and applications workshops, May 2007, p. 27–9.