私立東海大學資訊工程與科學研究所

碩士論文

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同心圓式無線網路 AP 佈署與協調式多通道分配策略

A Coordinated Multiple Channel Assignment Scheme and AP Deployment for Channels Reuse in Wireless Networks

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摘要

在無線網路環境下，使用單一通道會導致隱藏節點及訊號干擾等的問題，也是網路效率降低的主要原因。而隱藏節點亦是因訊號干擾所引起的問題。現今有許多研究，利用多通道來解決訊號干擾的問題。多通道雖然能解決單通道的問題，但也衍伸出其他問題，例如:多通道隱藏節點及通道該如何配置的問題。實際上，一個好的通道配置演算法，不但可以提昇無線網路的效能，更可以解決多通道隱藏節點的問題。因此在本研究中，我們提出一個演算法，藉由協調周圍各 AP 的通道，來降低訊號干擾所產生的影響，並藉此提升 AP 與節點之間傳輸的效能。在我們提出的無線通訊網路中，將 AP 以同心圓的方式佈置並分群，通道亦分群並配置給各 AP，以避免多通道隱藏節點的問題。實驗結果顯示，此演算法確實可以增進無線網路的單位時間內的傳輸量及效能。

關鍵字： 無線網路, 電波/訊號干擾, 多通道配置, 隱藏節點, 多通道隱藏節點

Abstract

In a wireless network, if single channel is employed, hidden terminal and radio interference problems may occur. The two problems are the two main factors that cause low network throughput. In fact, the hidden node problem results from radio interference. Up to present, many researchers have used multi-channel schemes to solve the interference problem. However, multi-channel results in other problems, e.g., multi-channel hidden terminal problem, and channel assignment problem. Actually, a well-defined channel assignment can effectively solve the former. Therefore, in this paper, we proposes a multi-channel assignment system, called corona-oriented multi-channel assignment system (COMAS), which coordinates channel usage in wireless networks to decrease radio interference among APs and nodes so as to improve network throughput and efficiency, particularly when many nodes are connected to APs. In 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 occuring among adjacent AP groups and among APs in a group. Simulation results show that COMAS can effectively improve wireless-network throughput, efficiency and channel utilization.

Keywords: wireless network, signal/radio interference, multi-channel assignment problem, hidden terminal problem, multi-channel hidden terminal problem

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

Recently, wireless networks have increasingly become pervasive. More and more wireless devices, such as notebook, smart phone, sensor networks, etc., 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., hidden node problem [1], radio collision [2], and multi-channel hidden terminal problem [3], need to be solved before we can efficiently enjoy wireless network convenience.

A. Baiocchi *et al.* [4] compared wireless network transmission throughputs for single channel and multiple channels given a hidden-node scenario and a non-hidden-node scenario. The best throughput is on 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. [1] claimed that hidden node problem truly exist in the real world.

[5] and [6] defined different channel assignment algorithms for wireless networks to improve their network throughputs, and avoid signal interference and hidden node problem. Nevertheless, when many nodes are connected to an AP, or two or more APs are equipped near by or even at the same location, the two schemes can not avoid radio interference between/among nodes which are connected to the APs. To solve signal interference problem, several problems and challenges should be conquered, including how to coordinate transmission between/among neighbor nodes [21][22][23][24], which channel should be switched to when collision occurs [12], and how to interleave the transmission if two nodes have to share a channel [20]. But, it also same disadvantages: (1) the coordinating area is not extensive [20]; (2) interference also occurs when nodes change the communication channel

[12] [22].

In this study, we propose a multi-channel assignment system, called corona-oriented multi-channel assignment system (COMAS) which can be deployed by a wireless environment, 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 (AN-group for short). Each AN-group is assigned several interference-free channels. The purpose is to avoid radio interference. The details will be described and defined later. In each AN-group, the interference-free channels are shared by APs and nodes. So, to further avoid interference, we need to schedule the use of the channels with a time-sharing method. Experimental results show that network throughput, efficiency, and channel utilization of our approach outperforms other current state-of-the-art systems.

Contributions of this study are as follows.

(1) We organized APs into concentric coronas, and grouped APs in different methods to avoid signal interference among APs.

(2) Due to limited number of available channels, nodes under an AP are scheduled to share a single channel so nodes can fairly transmit their packets. Such can also avoid signal interference among nodes, and improve channel utilization and throughput.

(3) When a mobile device would like to hand off from an AP to another AP, its connection may not be disconnected if the COMAS as the wireless environment is used.

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

Chapter 2. Background and Related Work

2.1. IEEE 802.11 Protocol

In a network, two or more neighbor or nearby nodes may transmit packets simultaneously, resulting in radio interference. IEEE 802.11 uses contention window (or CW) [2][7] to solve contention problem. When a node wants to transmit data to another node, it initially generates a random number ranging from 0 to 31 as the CW size. If collision occurs, the node generates another random number ranging between 0 and $2^n - 1$, where n is the preceding random number. Figure 1 shows an example. When the first collision occurs, the new range is between 0 and 63. Upper limit of the range is 1023, i.e., after the fifth retransmission, CW size keeps ranging from 0 to 1023 until there is no more collision.

However, using contention window to control node contention wastes too much time, particularly when many nearby nodes contest the commutation channel at the same time. Researchers [9][10] solved this problem by deploying k channels ($k > 1$) to avoid collisions. This has shown effectively improving system performance.

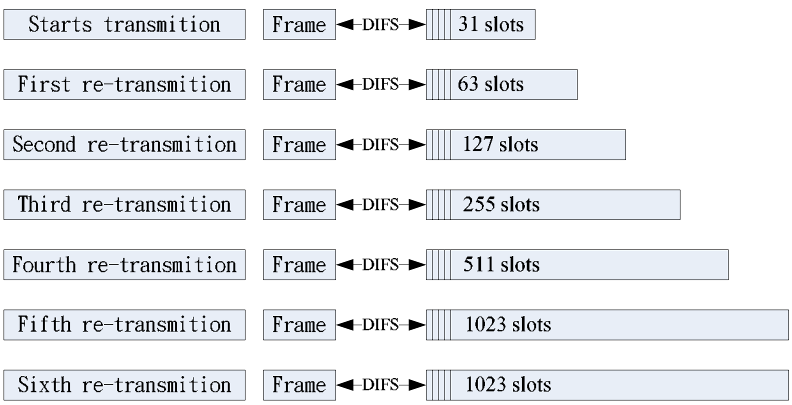


Figure 1 IEEE 802.11 contention window

2.2. Multi-channel Hidden Terminal Problem

The hidden node problem [1] exists in multi-hop networks. As shown in Figure 2, nodes A and D can not send data to B and E, respectively, at the same time because B is within D's interference range.

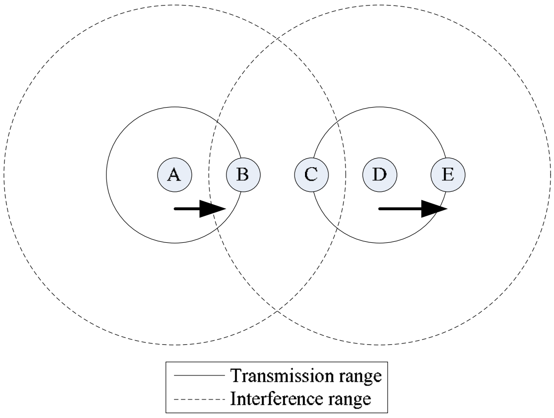


Figure 2 Hidden node problem (A is a hidden node of D)

Let's check the case shown in Figure 3. Nodes X and Y are communicating with each other through, e.g., channel 1. Initially, node X transmits a Request to Send (RTS) to node Y, and node Y replies a Clear to Send (CTS). Meanwhile, node A transmits a RTS to node B, and node B replies a CTS both through, e.g., channel 2. There is no communication interference between the two pairs of nodes. If now node Y transmits RTS to node A through channel 1, node A cannot hear the RTS from node Y. However, when node A transmits RTS to node Y, and node X transmits data to node Y, both using the same channel simultaneously, e.g., channel 2, then collision occurs. This phenomenon is called multi-channel hidden terminal problem. To avoid the problem, McGarry *et al.* [11] reserved a channel, called control channel, through which nodes can exchange messages, e.g., RTSs and CTSs, and continuously monitor statuses of all other nodes.

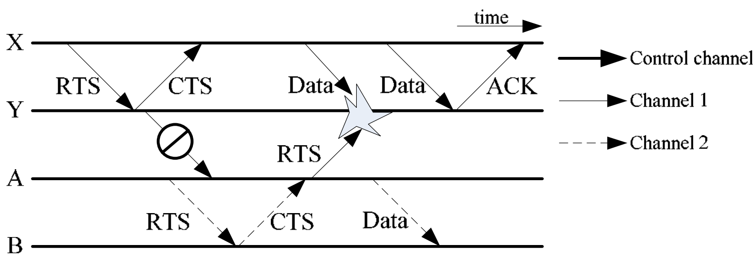


Figure 3 Multi-channel hidden terminal problem

The studies [3][4][11][12] did the same. However, [3] mentioned that the control channel would decrease performance when the network traffic is heavy.

2.3. Multi-channel Systems

Kyasanur *et al.* [6] proposed a multi-channel assignment using multi-interface for wireless networks, called the interface algorithm. With the algorithm, a node is equipped with several channels. It uses a "fixed" channel to receive packets and the remaining channels to transmit packets. For example as shown in Figure 4, there are three completely connected nodes, e.g., nodes A, B and C, in which node A uses channel 1 to receive packets from nodes B and C. Nodes B and C respectively receive packets through channels 2 and 3. However, interference occurs when nodes B and C to transmit packets to node A at the same time.

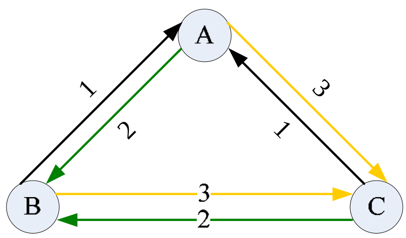


Figure 4 Both nodes B and C transmit packets to node A through channel 1, and nodes A and C (both nodes A and B) transmit packets to node B (node C) through channel 2 (channel 3).

Recently, the GSM (Global System for Mobile communications) and wireless networks deployment follow the cellular system [8]. Figure 5 shows the cellular system. Seven cells cluster a group, and the channel assignment scheme is the same among/between each group. So, every cell use different channels among/between its neighbor cells. But the system exist the radio/signal interference problem.

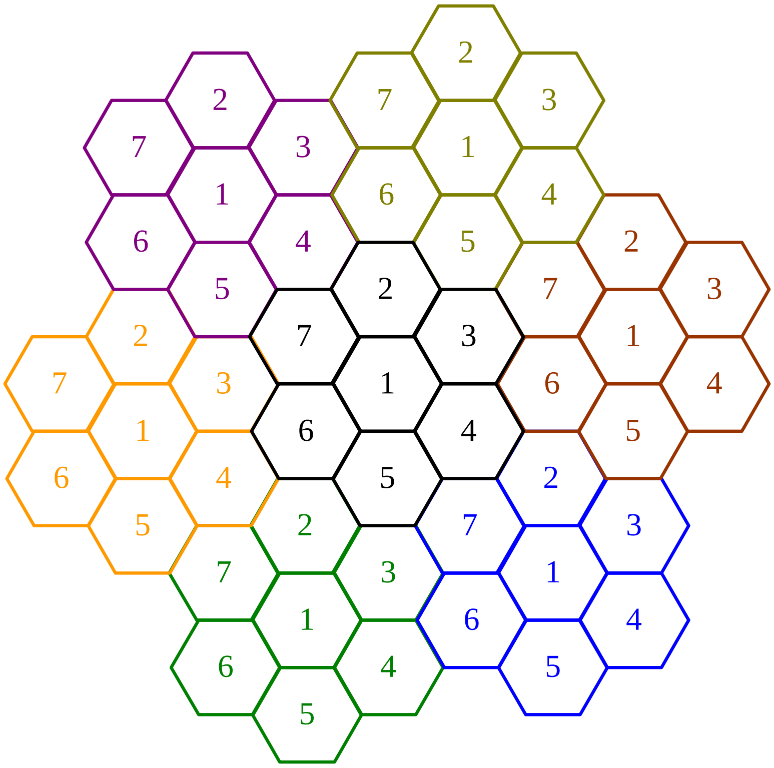


Figure 5 The cellular system. Seven cells cluster a group, and the channel assignment scheme is the same among/between each group.

The studies [19][20] used multi-channel systems to improve the original systems. Park *et al.* [19] used placement-based allocation algorithm (PBA) to classify independent data items, and scheduled these items to channel's time slot. The algorithm can be used to process stock-price data, traffic data, etc. Zhou *et al.* [20] proposed a multi-channel medium access control protocol for wireless mesh networks by using busy tones to prevent data packet from collisions. If a node is neither transmitting nor receiving packets, it randomly selects a free data channel to listen to. 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 and telling A which channel is available. Then, A transmits packets to B through the channel. This can truly avoid packet collision. However, if two nearby wireless environments due to no coordination may result in collision.

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

2.4. Related Work

Niranjan *et al*. [5] designed and evaluated a multi-channel multi-rate protocol on a wireless network. The authors experimented 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 reduce down other high-rate link segments if a routing path consists of several link segments. The authors proposed Data Rate Adaptive Channel Assignment (DR-CA) algorithm to improve a wireless network. The main idea is assigning heavy traffic to high data-rate links. The studies [4][13] also claimed that multi-channel improves the wireless network throughput. Xu *et al.* [12] used multi-channel to avoid channel interference. The authors proposed two schemes: coordinated channel switching and spectral multiplexing. When the coordinated channel switching scheme is used, and packets are jammed or interference occurs, a node switches its channel and announces the switch to its neighbors. The authors also proposed a synchronous spectral multiplexing algorithm and a round-robin asynchronous spectral multiplexing algorithm. The main idea of the asynchronous one is all nodes periodically switch channels to communicate with their own child nodes. The idea of the synchronous one is 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 problem, and traffic jam so as to improve system performance. But, it is hard for us to design the corresponding scheduling algorithm, since nodes switch channels frequently, particularly when traffic is busy.

Wang *et al.* [3] introduced several multi-channel MAC protocols, and reserved a dedicated control channel with which time synchronization can be achieved. The disadvantage is requiring a dedicated channel, and decreasing network efficiency since the control channel is often a communication bottleneck. In a time division scheme, channel communication is divided into alternating sequence of control phase and data exchange phase. During the control phase, all nodes transmit RTS and CTS packets to negotiate with others for channels. During the data exchange 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. The authors of [3] also proposed a multiple transceivers approach with which each node has several transceivers. Each transceiver uses an individual channel. So a node can transmit packets through different channels simultaneously. However, the cost is high.

Chapter 3. System Architecture

Figure 6 shows deployment of APs of the COMAS's wireless environment/network, in which coronas from the inmost to the outmost are numbered as coronas 0, coronas 1, coronas 2, …, coronas *n*-1, where *n* is number of coronas that the environment has. Also, an AP, except those in the outmost coronas, is surrounded by six APs.

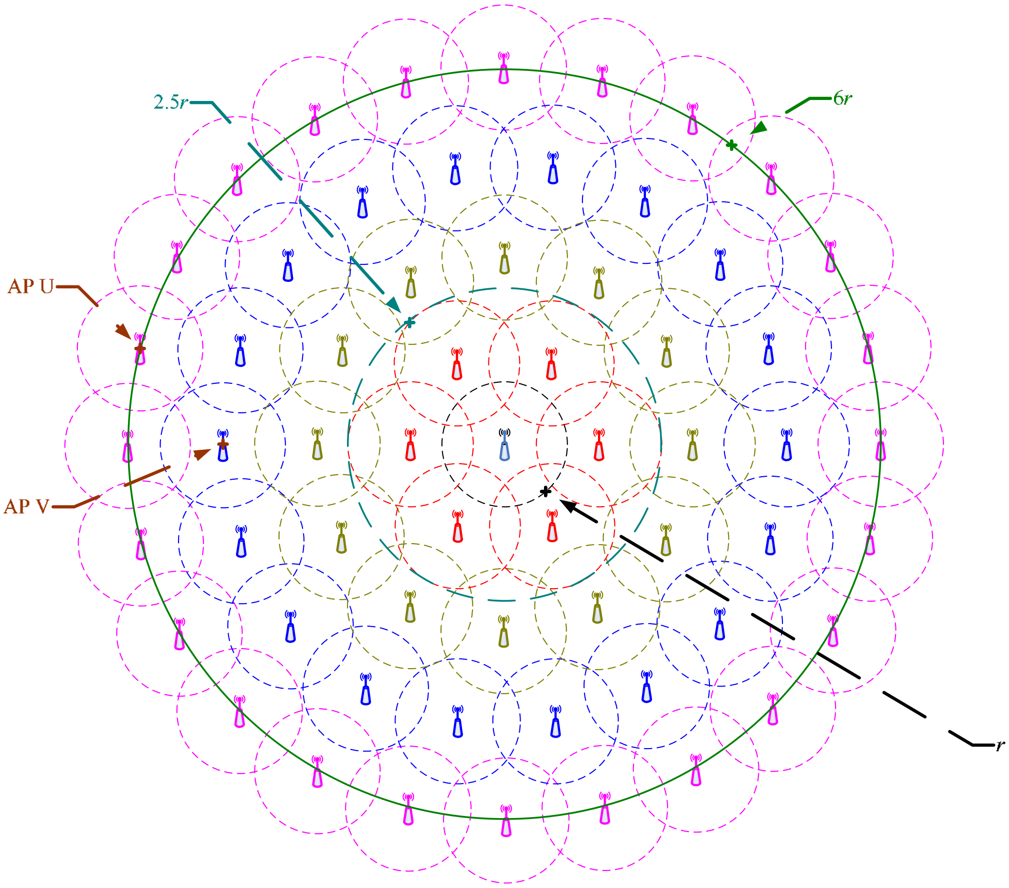


Figure 6 Environment of the COMAS's wireless network.

Also, from the inmost to the outmost, every four adjacent coronas form an adjacent corona group (AC-group for short), i.e., coronas 0~3 belong to AC-group 0, coronas 4~7 together are AC-group 1, … coronas 4*m*~4*m*+3 belong to AC-group *m*, …, and the remaining coronas form group $\left\lceil \frac{n}{4} \right\rceil - 1$, where corona *j*, $0 \le j \le n-1$, is assigned to AC-group *k*, if

$k = \left\lceil \frac{j+1}{4} \right\rceil - 1$. In addition, we divide all coronas into four corona groups (CO-groups for short), in which coronas 0, 4, 8, 12, 16, … 4*m* … belong to CO-group 0, coronas 1, 5, 9, … 4*m*+1 … form CO-group 1, and so on.

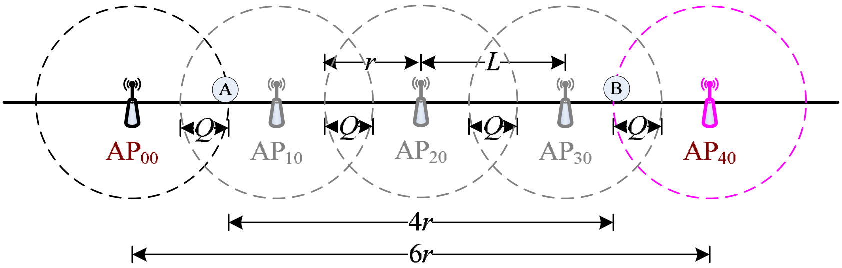


Figure 7 *L* is the line segment connecting two adjacent (inner and outer) APs, and *Q* is the line segment of *L* in the overlapped communication range of the two APs.

3.1. AP-Deployment Scheme

The communication range of an AP, also of a node, is the range inside a circle of *X* meters in radius, e.g., 250m in an 802.11 AP. Let L be the line segment connecting two adjacent APs (see Figure 7), and Q be the line segment of L in the overlapped communication range of the two APs. According to [1][4][11][14], the interference range of an AP or a node is about 2.5r. To avoid hidden node problem, the authors of [1] claimed that two APs (or two nodes), e.g., AP Q and AP S, should be separated at least 3.5*r*, and the distance between the two APs' subordinate nodes, e.g., node A under AP Q and node B under the AP S, of course is longer than or equal to 2.5*r*. As shown in Figure 8, if node C and node D can send packets without interfering each other, the distance between APs X and Y should be at least 5.5*r*. Between the two APs, if $|Q| = 0$, 1.75 ($= \frac{3.5r}{2r}$) APs can be inserted. That means at least two coronas are required to connect the coronas that the two APs belong to if we would like to transmit packets between APs X and Y. According to [15], if a car's driving speed is 100 $^{km}/_{hr}$ and its passengers' mobile devices can successfully hand off between two APs without their connections being disconnected, it should be that $|Q| \geq 39\text{m}$ (40m).

$$\frac{40m}{250m} = 0.16r \qquad (1)$$

$$2 \times 2r - 3 \times 0.16r \cong 3.52r > 3.5r \qquad (2)$$

where r is communication range of an AP, and $2 \times 2r$ and $3 \times 0.16r$, as shown in Figure 8, imply that there are two APs and three Qs (i.e., three overlapped regions) located between APs X and Y.

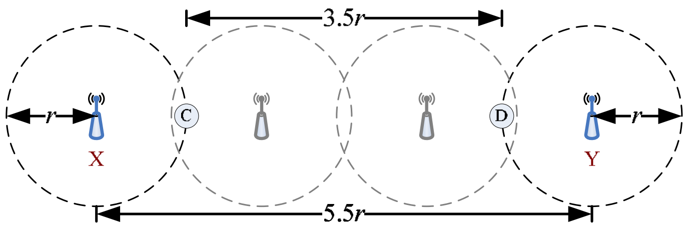


Figure 8 Originally the distance between APs X and Y is 5.5*r*, and the distance between nodes C and D is 3.5*r*.

3.2. Cross-corona Signal Interference

For handoff consideration, two APs are enough to connect APs X and Y. However, such will result in the fact that radio coverage of the whole area shown in Figure 6 will not be 100%, where current $|Q| = \frac{r}{2}$. If $|Q| = 0.16r$, then the distance between two adjacent APs, e.g., nodes U and V, will be longer than what they are right now, and the area between the two APs will be uncovered by radio. In fact, $Q = 39\text{m}$ is proposed under the assumption that there is no channel contention during handoff. If *k* cars, *k*>1, would like to hand off from one AP to another AP at the same time, *Q* should be longer than 39m. So, for handoff and communication coverage consideration, three APs are deployed to connect APs X and Y, and $|Q| = \frac{r}{2}$. Now, the distance between nodes A and B shown in Figure 7 is 4*r* and that between

AP_{00} and AP_{40} is 6*r*, which also imply nodes A and B can communicate with their opposite nodes without interfering each other. In other words, AP_{00}'s subordinate nodes when communicating with other nodes or with AP_{00} will not interfere AP_{40} and AP_{40}'s subordinate nodes. They only interfere nodes in coronas 1 to 3. This can explain why from corona 0 to corona *n*-1 every four coronas are grouped as an AC-group since interference will not go across four coronas. Now, we can conclude that channels can be reused for every AC-group.

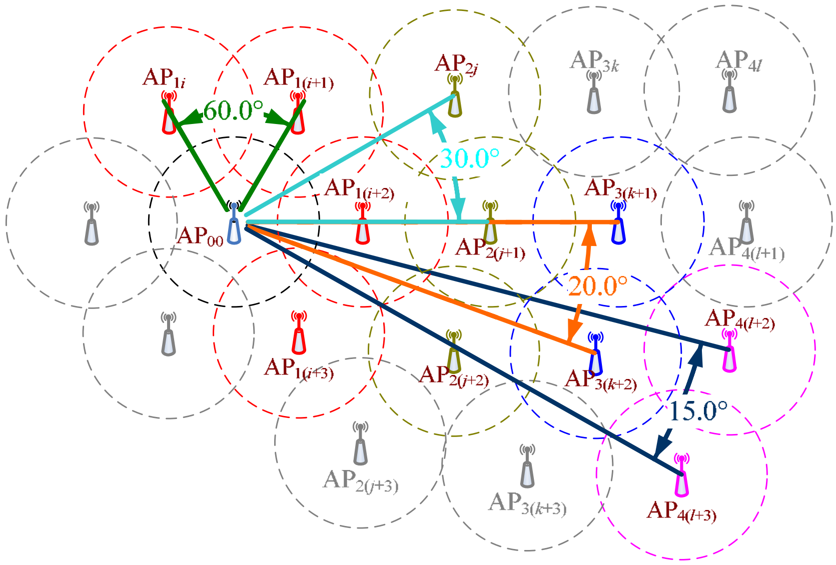


Figure 9 The angles among APs in corona 0 ~ corona 3. The angle between $\overline{AP_{1i}AP_{00}}$ and $\overline{AP_{00}AP_{1(i+1)}}$ is 60°, and the angle between $\overline{AP_{2j}AP_{00}}$ and $\overline{AP_{00}AP_{2(j+1)}}$ is 30°(360°÷12), that between $\overline{AP_{3(k+1)}AP_{00}}$ and $\overline{AP_{00}AP_{3(k+2)}}$ is 20°(360°÷18), and that between $\overline{AP_{4(l+2)}AP_{00}}$ and $\overline{AP_{00}AP_{4(l+3)}}$ is 15°(360°÷24), and so on.

As illustrated in Figure 9, there are six corona-1 APs that surround AP_{00}, and the angle of two adjacent APs, e.g., AP_{1i} and $AP_{1(i+1)}$, to AP_{00} is 60°(360°÷6). There are twelve APs in corona 2, the angle between $\overline{AP_{2j}AP_{00}}$ and $\overline{AP_{00}AP_{2(j+1)}}$ is 30°(360°÷12). There are eighteen and twenty-four APs in corona 3 and corona 4, respectively. So, the angle between $\overline{AP_{3(k+1)}AP_{00}}$ and $\overline{AP_{00}AP_{3(k+2)}}$ is 20°(360°÷18), and that between $\overline{AP_{4(l+2)}AP_{00}}$ and

$\overline{AP_{00}AP_{4(l+3)}}$ is 15°(360°÷24). The number of APs in corona *j* can be derived as:

$$\left|\mathrm{AP}_j\right| = \begin{cases} 1, \text{ if } j = 0 \\ 6 \times j, \text{ if } n-1 \geq j \geq 1. \end{cases} \qquad (3)$$

where *n* is number of coronas in the concerned environment. In corona *j*, the angle between two adjacent APs, e.g., AP_{ji} and $\mathrm{AP}_{j(i+1)}$, to AP_{00}, i.e., $\overline{AP_{ji}AP_{00}}$ and $\overline{AP_{00}AP_{j(i+1)}}$, is $\frac{360°}{6 \times j}$, where $n-1 \geq j \geq 1$.

3.3. Joint Node

A node which locates in the overlapped area of two adjacent APs' communication ranges is called a joint node. The two APs can be in the same corona or different coronas. An example of the latter is AP_{jx} in corona *j* and $\mathrm{AP}_{(j+1)y}$ in corona *j*+1. A joint node uses Multi-input Multi-output (MIMO) technique [16] to send and receive packets through different channels. MIMO can achieve better communication throughput and efficiency than those of Single-input Single-output (SISO) and Single-input Multi-output (SIMO) in wireless networks. A joint node, no matter its APs belong to different coronas or the same corona, can select either AP as its coordinating AP.

To relay packets for APs, a joint node A broadcasts a packet to its neighbor APs, e.g., APs P and Q, to announce that it can bridge packets for them. Each of the two APs on receiving the announcement allocates a time slot for A, regardless of whether they belong to the same AP-pair or not, so that A can transmit packets to and receive packets from each of them. When a mobile node newly joins an AP or departs from an AP, the AP needs to readjust its time slots and then exchanges its time slots with its AP-pair partner so as to synchronize communication within the AP-pair. A joint node's arrival and departure follow this rule.

3.4. Relay Scheme

A node N may transmit packets to another node M, where N and M may be under the same AP or different APs. In this environment, we connect all APs with a wired link so that communication among/between APs can go through the wired link or wireless links. The latter should be accomplished by joint nodes. Figure 10 shows how packet relay is performed through the wired link. Generally, wireless links are used to communicate an AP and its subordinate nodes. When node E would like to transmit packets to node Z, it firstly transmits packets to AP P, which relays the packets to AP S through the wired link. After that, AP S sends the packets to node Z through a wireless link.

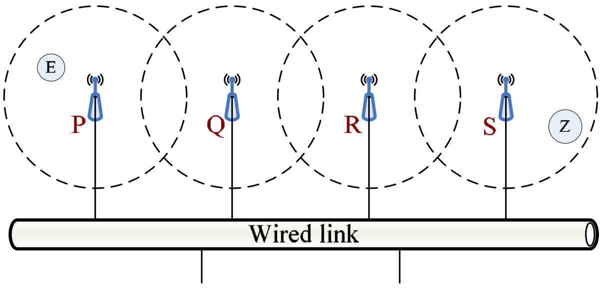


Figure 10 Node E (node Z) connects itself to AP P (AP S) through a wireless link, and APs relay packets for their subordinate nodes via a wired link.

Assume each AP has routing capability, i.e., each AP is a mobile router. So, when the wired link fails, joint nodes can relay packets for APs. Figure 11 shows the process of packet relay through wireless networks. When node E would like to transmit a packet to node Z, it firstly transmits the packet to its AP, e.g., AP P, in the allocated time slot. If the wired link is still functioning, AP P sends the packet to AP S through the wired links. This time, node E as shown in Figure 13 transmits the packet to AP P. AP P checks to see whether there are joint nodes, e.g., in the overlapped region between its communication range and that of the AP on the best routing path. If yes, e.g., node F, AP P sends the packets to node F. Otherwise AP P sends the packets to other joint nodes with dynamic routing approach. If no joint nodes can relay the packets, node E returns an error message. Now, node E and AP P are isolated from their outside world until there comes a joint node or the wired network recovers from failure. Other APs on receiving the packets process the packets by using the same method until the packet arrives at node Z, or there is an error.

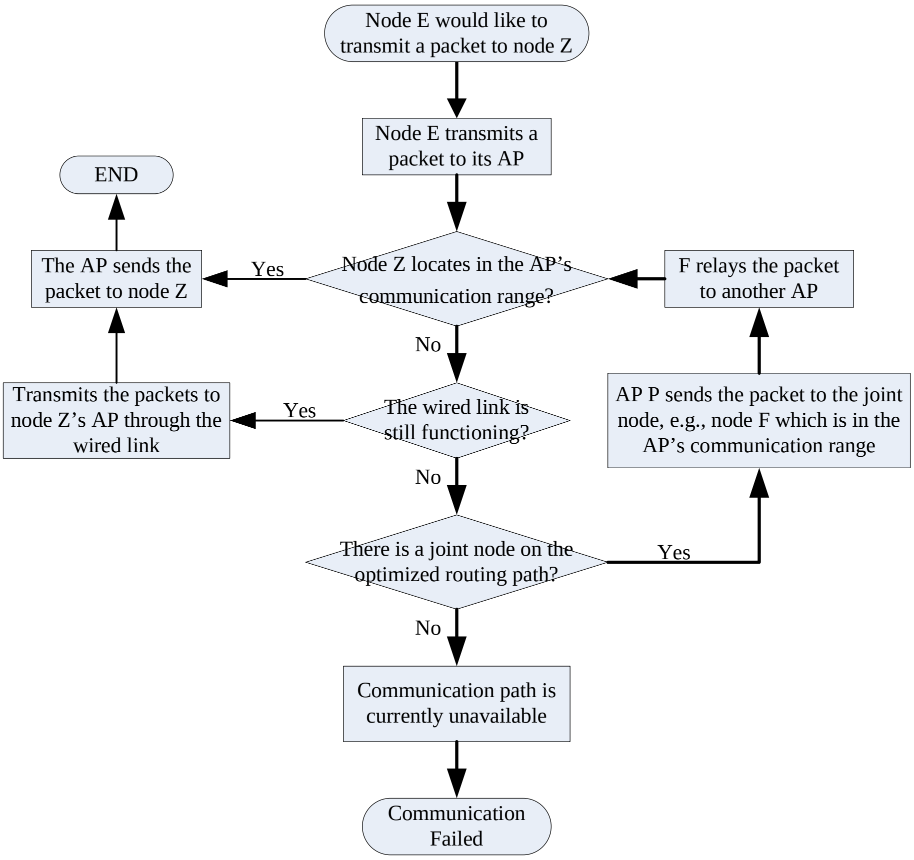


Figure 11 The process of packet relay through a wireless link.

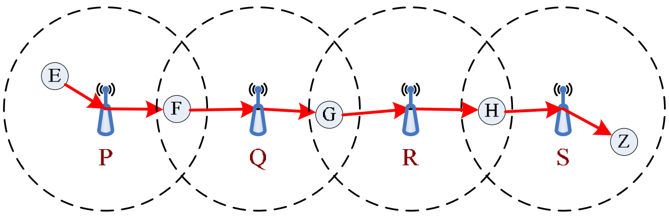


Figure 12 AP P relays packets to AP Q through joint node F. Q relays the packets to AP R through node G. and AP R relays the packets to AP S through node H. AP S sends the packets to node Z.

3.5. Signal Interference

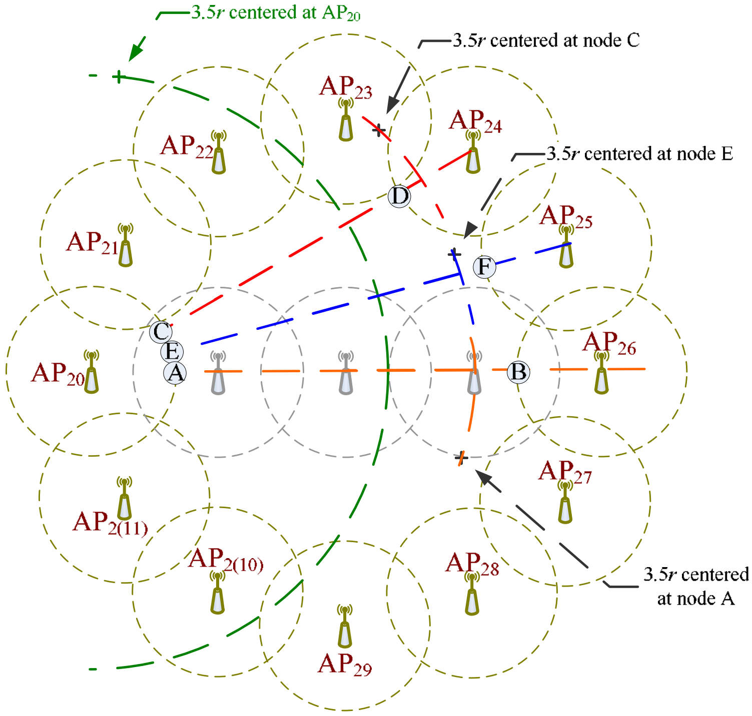


Figure 13 The interference range of AP_{2i}, e.g., AP_{20}. AP_{21}, AP_{22}, and AP_{23} are in AP_{20}'s interference range, so are $AP_{2(11)}$, $AP_{2(10)}$, and AP_{29}. Node D is in node C's interference range. But, nodes B and F are respectively out of node A's and E's interference ranges.

As shown in Figure 13, interference range of node A under AP_{2i}, e.g., AP_{20} in corona 2, covers communication ranges of AP_{21}~AP_{24} and $AP_{2(11)}$~AP_{28}. These APs' communication ranges are also interfered by nodes C and E. From this point, we can realize that the interference range of an AP in corona 1 (instead of corona 2) covers all APs in corona 1. In Figure 14, AP_{31}~AP_{33} in corona 3, excluding AP_{34}, in corona 3, 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_{30}'s and its subordinate nodes' interference ranges. In an outer corona, e.g., corona *k*, $k \geq 4$, the distance between AP_{k0} and AP_{k4} is longer than that between AP_{30} and AP_{34} since in a relatively outer corona, e.g., corona *k*, the relationship between AP_{k0} and AP_{k4}, approaches a straight line. Please compare the relationship between AP_{20}~AP_{24} in Figure 13 and AP_{30}~AP_{34} in Figure 14. Now, from what has been shown in the two figures, we can conclude that AP_{24} is out of

AP_{20}'s interference range, and AP_{k4} is out of AP_{k0}'s and AP_{k0}'s subordinate nodes' interference ranges, where $n-1 \geq k \geq 3$.

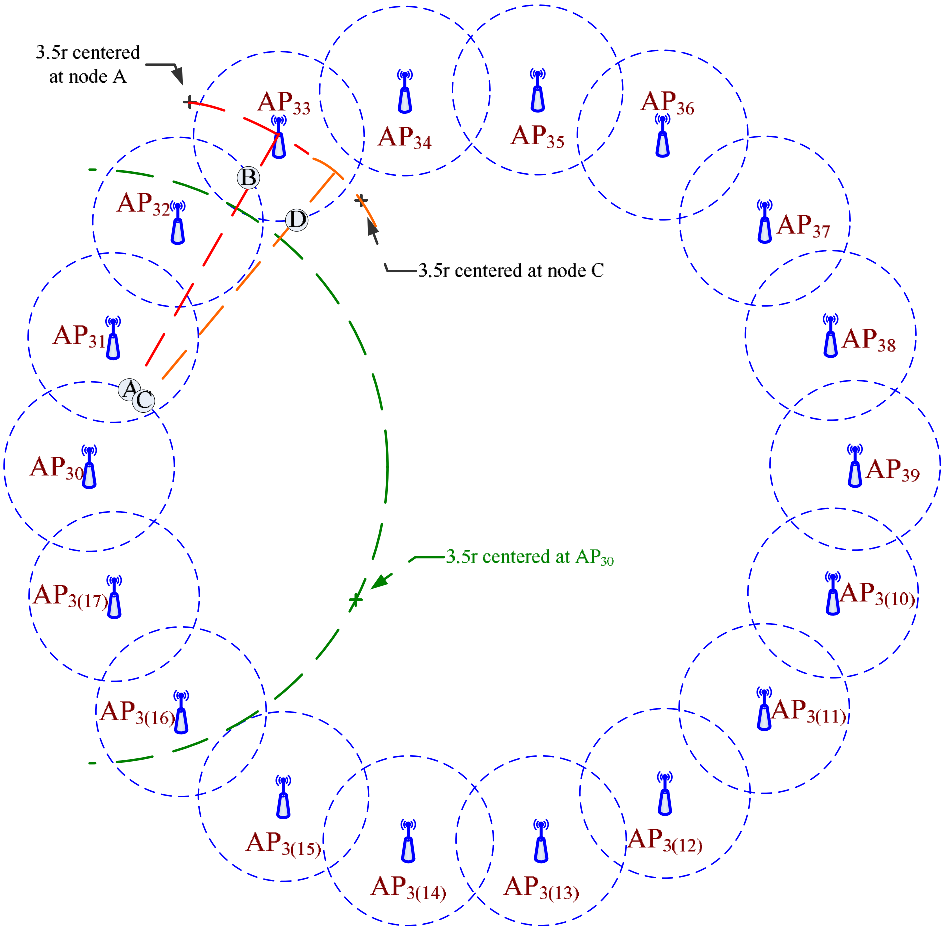


Figure 14 The interference range of AP_{3i}, e.g., AP_{30}. (AP_{31}, AP_{32}, and AP_{33} are in AP_{30}'s interference range, so are $AP_{3(17)}$, $AP_{3(16)}$, and $AP_{3(15)}$. Node B (node D) is in node A's (node C's) interference range.)

The COMAS employs 12 of 14 Wi-Fi 802.11 channels, and divides the 12 channels into four channel groups (CH-group for short). Channel 0~2 form CH-group 0, channels 3~5 belong to CH-group 1, channels 6~8 form CH-group 2, and the remaining 3 channels are CH-group 3. CH-group *i* is assigned to each element of CO-group *i*, *i*=0, 1, 2, 3, e.g., elements of CO-group 2, including coronas 2, 6, 10, 14 … 4*m*+2, …, are all given CH-group 2.

From an AC-group viewpoint, CH-group j (j=0, 1, 2, 3) as shown in Figure 15 is assigned to corona q where $j = q \bmod 4$. For example, in AC-group1, CH-groups 0, 1, 2 and 3 are respectively assigned to coronas 4, 5, 6 and 7. The purpose is to avoid interference among coronas in an AC-group and in two adjacent AC-groups. Table 1 shows the relationship of channel assignment among AC-groups and CO-groups.

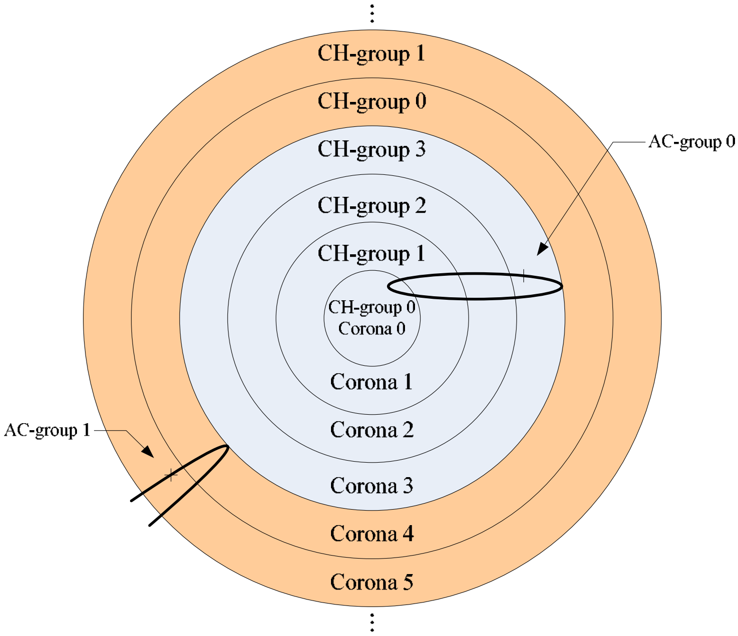


Figure 15 The assignment of CH-groups to coronas in the COMAS.

Table 1 Channel assignment among AC-groups.

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

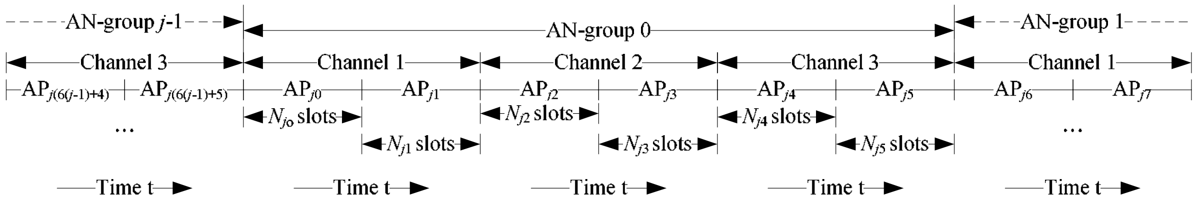
Here, we would like to formally define an AN-group. For $j \geq 2$, six adjacent APs in corona j are clustered into a subgroup, i.e., AP_{j0}~AP_{j5} form subgroup 0, named AP-subgroup 0, AP_{j6}~AP_{j11} form AP-subgroup 1, …, $AP_{j(6(k-1))}$~$AP_{j(6(k-1)+5)}$ belong to AP-subgroup k-1, …, $AP_{j(6(j-1))}$~$AP_{j(6(j-1)+5)}$ are grouped as AP-subgroup j-1, where $2 < k < j$, even though in each subgroup, e.g., AP_{j0}~AP_{j5}, the last two APs, e.g., AP_{j4} and AP_{j5}, are not interfered by the first AP, e.g., AP_{j0}, $n-1 \geq j \geq 2$. In other words, corona j has j AP-subgroups. Corona 0 itself is an AP-subgroup which has only one AP. An AP-subgroup, e.g., AP-subgroup j, and all its subordinate nodes together are called an AN-group, e.g., AN-group i, $0 \leq j \leq n-1$.

In order to avoid interference within an AN-group and between adjacent AN-groups, channels are assigned to elements of an AN-group as follows. In an AN-group, the first two, the second two and the third two APs respectively share the first, the second and the third channel of the given CH-group. Every AN-group does the same. For example, in corona j, AP_{j0} and AP_{j1} in AN-group 0, AP_{j6} and AP_{j7} in AN-group 1, $AP_{j(12)}$ and $AP_{j(13)}$ in AN-group 2, … are given the first channel. Table 2 shows how channels are allocated to AP pairs of AN-groups in corona j. The second and the third channels have the similar assignment. We call each pair of adjacent APs that share the same channel an AP pair.

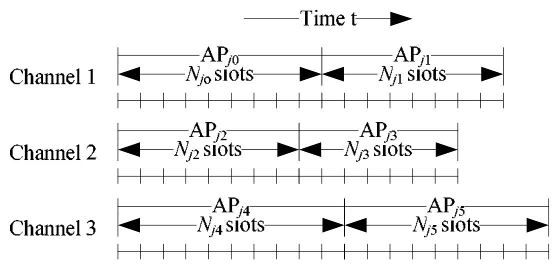
Table 2 An AP pair in corona j and the channel assignment, where corona j has 6j APs, $1 \leq j \leq n-1$, n is number of coronas that the underlying environment has, and the assigned channel group is CH-group ($j \bmod 4$).

	Channel 1 of CH-group (j mod 4)	Channel 2 of CH-group (j mod 4)	Channel 3 of CH-group (j mod 4)
AN-group 0	AP_{j0}, AP_{j1}	AP_{j2}, AP_{j3}	AP_{j4}, AP_{j5}
AN-group 1	AP_{j6}, AP_{j7}	AP_{j8}, AP_{j9}	AP_{j10}, AP_{j11}
⋮	⋮	⋮	⋮
AN-group (k-1)	$AP_{j(6(k-1))}$, $AP_{j(6(k-1)+1)}$	$AP_{j(6(k-1)+2)}$, $AP_{j(6(k-1)+3)}$	$AP_{j(6(k-1)+4)}$, $AP_{j(6(k-1)+5)}$
⋮	⋮	⋮	⋮
AN-group (j-1)	$AP_{j(6(j-1))}$, $AP_{j(6(j-1)+1)}$	$AP_{j(6(j-1)+2)}$, $AP_{j(6(j-1)+3)}$	$AP_{j(6(j-1)+4)}$, $AP_{j(6(j-1)+5)}$

Now, we can further conclude that an AN-group in a corona, e.g., AN-group k in corona j, will not be interfered by any AN-groups in all coronas, including other AN-groups in corona j. Since the channel that AP_{ji} uses is reused by those coronas at least four coronas/APs away and at least four APs away, i.e., coronas j-4, j+4, j-8, j+8, …, those AP pairs, in corona j that are assigned the same channel are at least four APs away, and coronas j+1 ~ j+3 and j-1 ~ j-3 use other three CH-groups. All are far enough or use different CH-groups so no mutual interference may occur. The only possible interference that may occur is between the two APs of an AP pair. To further avoid interference between the two APs, and among their subordinate nodes, an AP pair follows Time Division Multiple Access (TDMA) scheme to assign its only channel to their subordinate nodes. As shown in Figure 16, AP_{j0} and AP_{j1} share channel 1 of CH-group ($j \bmod 4$). The channel is further divided into $N_{j0}+N_{j1}$ time slots, where N_{j0} and N_{j1} are numbers of AP_{j0}'s and AP_{j1}'s subordinate nodes, respectively. The working process is as follows. There is an AP pair, e.g., AP_{ji} and $AP_{j(i+1)}$, in which AP_{ji} ($AP_{j(i+1)}$) establishes a scheduling table to assign N_{ji} ($N_{j(i+1)}$) time slots to its N_{ji} ($N_{j(i+1)}$) nodes. It also sends the table to $AP_{j(i+1)}$ (AP_{ji}). $AP_{j(i+1)}$ (AP_{ji}) 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. So, the proposed scheme can truly avoid interference. Of course, if an AN-group can be assigned at least six channels, then the TDMA can be performed individually by each AP (instead of by an AP pair) and its subordinate nodes.



(a) Channel assignment represented by using a spatial distribution scheme in a corona, e.g., corona j.



(b) Channel assignment represented by using a time distribution scheme in an AN-group.

Figure 16 Channel distribution schemes in which an AP pair shares the same channel. An AP further divides its own time period into k subslots if the AP has k subordinate nodes which are nodes within the AP's communication range.

Chapter 4. Experimental Results

In this study, we used *ns-2* [17] as our simulation tool, and enhanced the tool by integrating it with a modified version of the multi-channel model introduced by [18] to make the tool be one with multi-channel capability. In the following experiments, the compared schemes include the interface assignment algorithm (interface algorithm for short) [6], the random channel assignment algorithm (random algorithm for short) and the cellular system (cell algorithm for short). With the random algorithm, a node is connected to an AP with a randomly chosen channel. With the interface algorithm, a node is equipped with several interfaces/channels. It uses a “fixed” channel to receive packets and the remaining channels to transmit packets. The test environment of the four schemes is the same, but the channel assignment approaches are different. In the following experiments, we use a special IEEE 802.11 protocol which does not involve RTS and CTS, and a sender does not retransmit a packet when the packet is dropped.

A total of six parameters were performed in this study. The first experiment evaluated how data rates affect the tested schemes’ network throughputs, efficiencies, drop rates, network delays and jitters. Efficiency is defined as number of packets received over number of packet sent, and delay time consists of propagation delay and transmitting delay. The second and third redid the first experiment but given an AP with different numbers of subordinate nodes and given different packet sizes, respectively. During the experiments, we assume that number of each AP’s subordinate nodes is the same, and all APs as stated above are connected by wired links. In the fourth and fifth experiments studied packet relay delays which include those delays between a node and its AP, and between two APs. In the fourth, like that in experiments 1~3, and APs are connected by wired links. In the fifth, all communication links are wireless. Moreover, a sender will retransmit a packet when the packet is dropped in the fourth and fifth experiments.

The default values of the parameters used in the experiments are shown in Table 3. But the values will be changed if necessary. Figure 17 shows the experimental environment in which due to retaining *ns-2* simulation performance number of nodes involved should be limited. So, only 13 APs, but with losing its generality, are involved, and each AP has 10 subordinate nodes.

Table 3 Default values of the experimental parameters

Parameter	Default values
Wireless protocol	802.11abgn
Data rate	50 Mbps
Packet size	1000 bytes
Max queue length of a node/AP	50
Number of channels really used (12 are used in our system, but only 7 are employed in the following experiment)	7
Number of subordinate nodes for each AP	10
Time slot	8 msec
Transmitted time	1 second
Experimental time	1 second

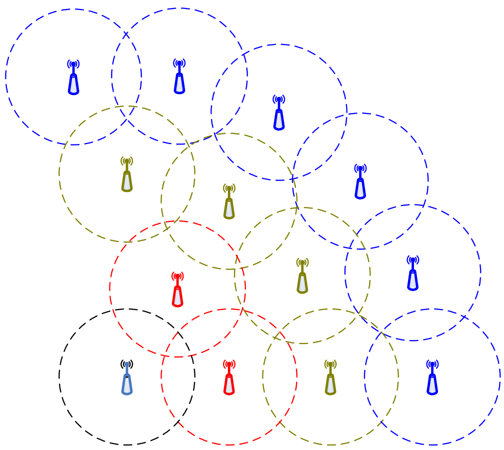


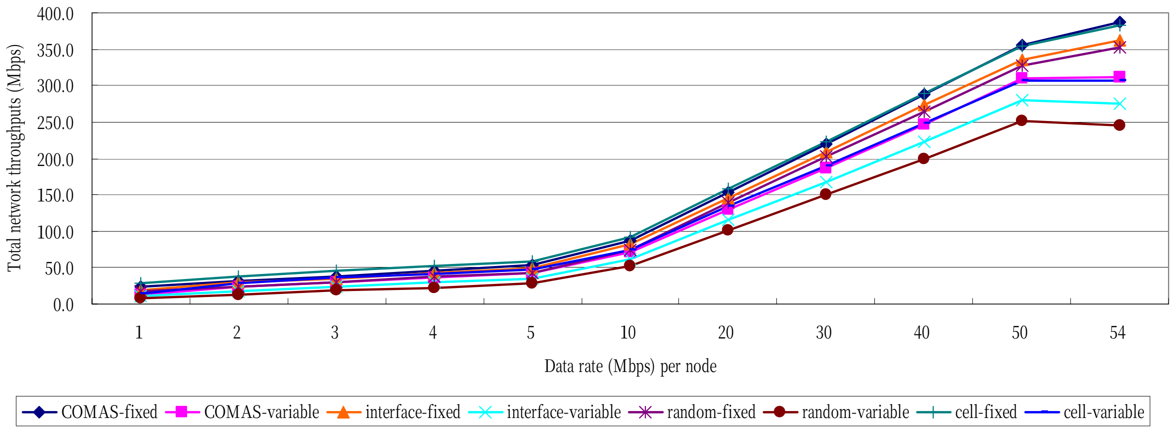
Figure 17 Four coronas from corona 0 to corona 3 were employed to test the three schemes.

Corona 0 deployed an AP, corona 1 deployed two APs, corona 2 deployed four APs and corona 3 deployed six APs. So, in the following experiments only 7 channels are required, even 12 channels are involved in the previous description.

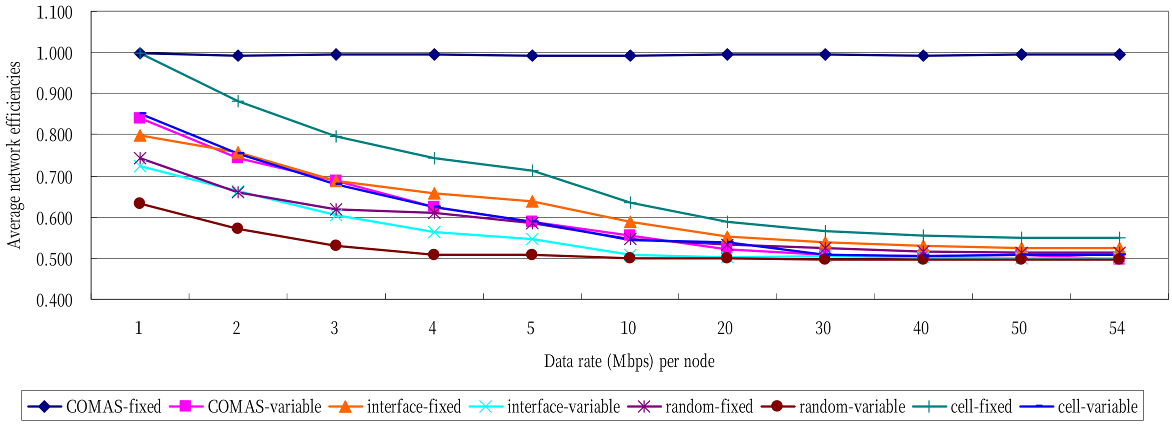
4.1. Performance on Different Data Rates

In the first experiment, the data rates are from 1 to 54 Mbps (instead of 50 Mbps) shown in Table 3. Nodes continuously communicated with their APs, and an AP only replies its nodes without sending messages to other APs or nodes. We firstly defined two cases: the period of a time slot is fixed and variable. For the former case, the period is fixedly 8 msec, and each node sends maximum of $3*\textit{data rate}$ packets in a time slot, e.g., 3 packets are sent on data rate=1 Mbps, 6 packets on 2 Mbps, …, and 162 packets on 54 Mbps. When variable length is used, the time period of a time slot is $\frac{8}{\textit{data rate}}$. For example, when data rate=1 Mbps, the length is 8 msec, when data rate=2 Mbps, the length is 4 msec … and when data rate=54 Mbps.

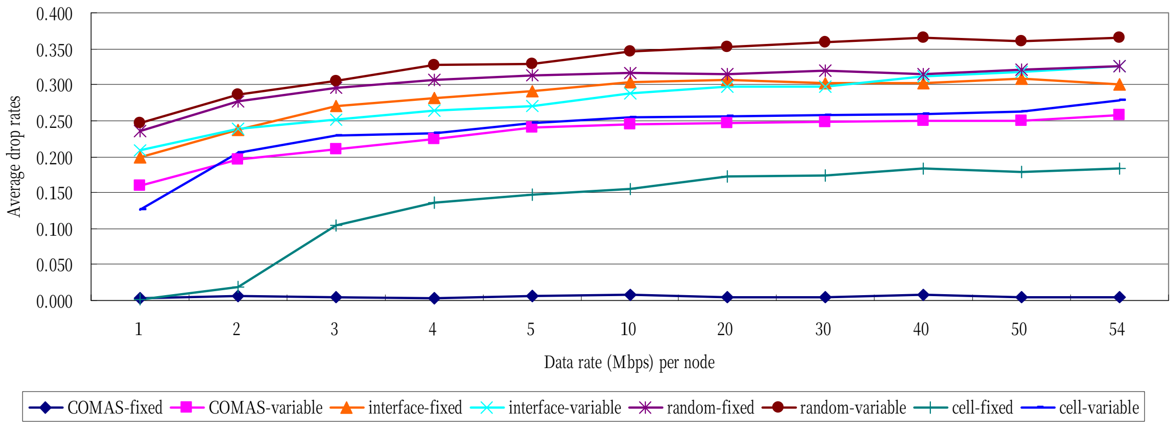
Figure 18 shows the experimental results including network throughputs, efficiencies and drop rates. We can see that the individual performance trends between fixed length and variable length are themselves similar, but the fixed length's throughputs, efficiency and drop rates are better than those of the variable length, particularity when data rates increase. The reason is due to using variable length time slot when the time slot is shorter, and date rates increase, it may occur that a packet, particularly the last packet transmitted in a time slot can not completely transmitted and receive the corresponding ACK message from the receiver. To avoid occurrence of this problem, in the following experiments, we fixed the length of a time slot to 8 msec, a node transmits a new packet only when it receives the ACK massage of the previous packet from the receiver.



(a) Network Throughputs



(b) Network Efficiencies



(c) Drop rates

Figure 18 Network throughputs, efficiencies and drop rates of the four tested schemes against data rates using the fixed length and variable length of time slots.

In Figure 18a, when data rates are low, e.g., 1 to 10 Mbps, the network throughputs of the three schemes are almost the same. However, when date rates are higher than 20 Mbps, the COMAS outperformed the other two schemes because the COMAS coordinates the usage of channels. No interference occurs among/between AN-groups in the same corona or different coronas. The interface scheme uses multiple channels to transmit/receive packets. But, when the distance between two nodes is not far enough, and the two nodes use the same channel to transmit/receive packets at the same time, interference will occur, resulting in poor performance. The random algorithm does not coordinate channel usage so the interference problem is serious. With data rates approach 54 Mbps, the throughputs of the three schemes do not increase due to saturated bandwidth. In the cell scheme, the cell scheme outperformed the interface and the random schemes. The reason is that the cell scheme has been designed to avoid radio/signal interference. But the distance is not far between two nodes which use the same channel, so the interference occurs slightly.

Figure 18b and Figure 18c respectively show the network efficiencies and drop rates. The COMAS's efficiencies and drop rates are stable on 0.99 and 0.005. The drop rates are not due to interference or packet collision. They result from the fact that when a time slot expire the last packet transmitted in a time slot can not completely transmitted and receive the corresponding ACK. However, the interface and the random schemes' efficiencies in data rate=1 Mbps are 0.84 and 0.74, and drop rates are all over 0.2. The network efficiencies fall down and drop rates increase when data rate increases because communication link is gradually saturated. Due to coordinated usage of channels, the COMAS outperformed the other two. With the cell scheme, the efficiency and drop rate are respectively 0.99 and 0.01 on data rate=1 Mbps. But the data rates increase, the efficiency decreases to 0.55 and the drop rate increases to 0.18 when data rate=54 Mbps. The reason is also the interference problem.

As respectively shown in Table 4, the COMAS's average, maximum and minimum delays are all shorter than those of the other two algorithms. When date rates increase, the average and maximum delays of the three schemes are almost steady. In other words, delays are not influenced by data rates. But, the COMAS's are the lowest. The COMAS conducted the least standard deviations. Table 5 illustrates the jitters of the three schemes. Like those of network delays, the COMAS is relatively stable with less average jitters.

Table 4 Network delays of the four tested algorithms against data rates using the fixed time slot.

Scheme	Average (ms)	Maximum (ms)	Minimum (ms)	Standard deviation
COMAS	24	78	12	0.014
Interface	41	127	13	0.031
Random	59	183	12	0.045
Cell	31	97	12	0.053

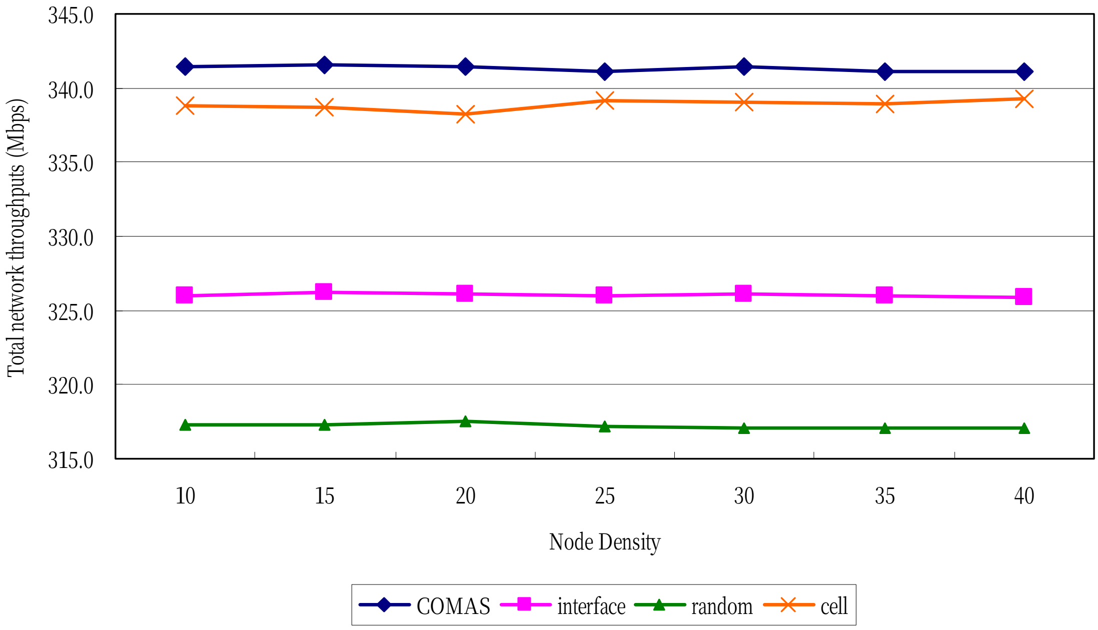
Table 5 Network jitters of the four tested algorithms against data rates using the fixed time slot.

Scheme	Average	Maximum	Minimum	Standard deviation
COMAS	1.2E-05	0.057	-0.050	0.018
Interface	0.0008	0.109	-0.093	0.045
Random	0.0041	0.157	-0.135	0.064
Cell	-1.9E-06	0.098	-0.069	0.028

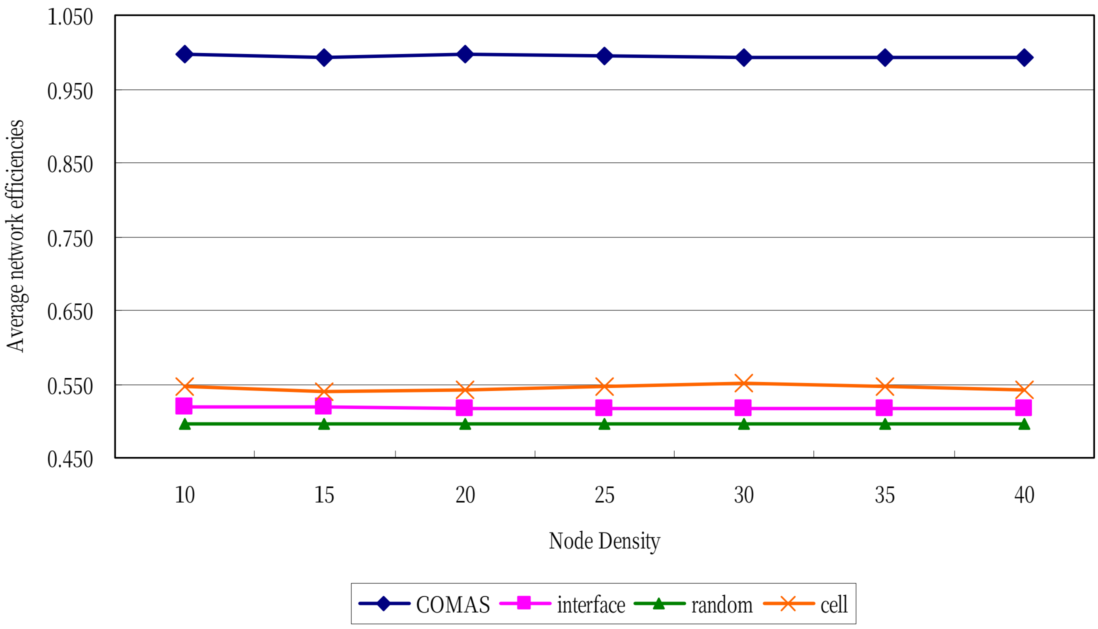
4.2. Performance on Different Number of Subordinate Nodes

In the second experiment, we evaluated how number of subordinate nodes affects network throughputs, efficiencies, drop rates, delays, and jitters. The data rate of each node=50 Mbps, the number of an AP's subordinate nodes ranges between 10 and 40 (instead of 10 shown in Table 3), and the time slot is fixed to 8 msec. Each node continuously communicates with its AP, and an AP only replies its nodes without sending messages to other APs or nodes.

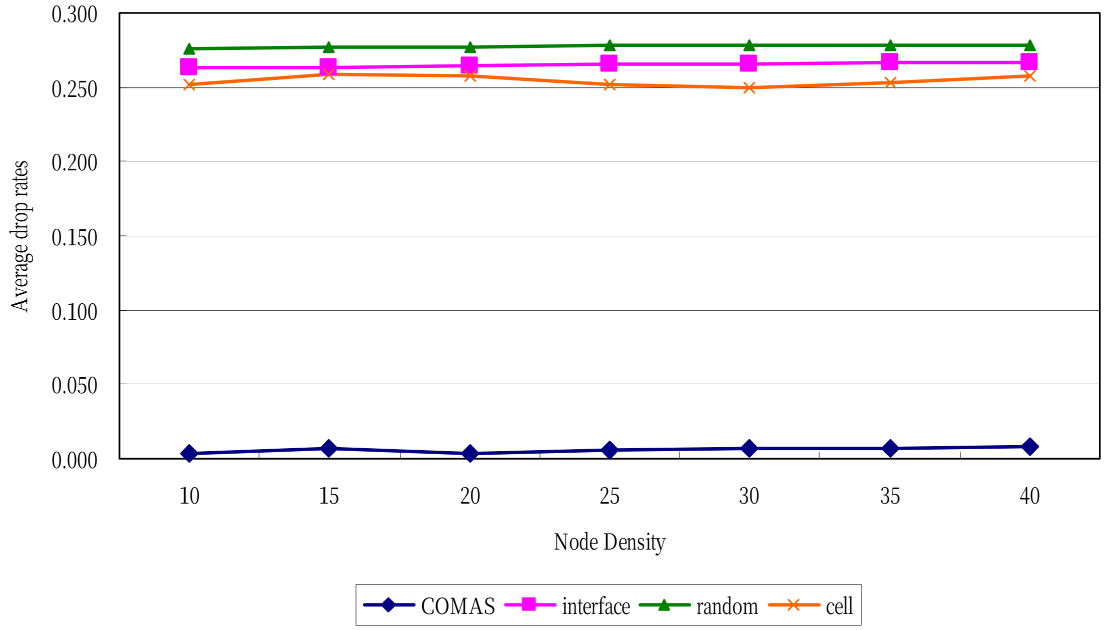
Figure 19a shows that when number of subordinate nodes increase from 10 to 40, the three schemes' throughputs are all smoothly because the time slots are fixed in length, i.e., 8 msec. Each node has efficient time to transmit a packet within a time slot. The COMAS outperformed the other three owing to interference-free. Figure 19b and Figure 19c respectively shows how network efficiencies and drop rates of the three schemes are affected by number of subordinate nodes. The COMAS's efficiencies are higher than other two schemes, and keeps on about 0.5. With the interface, the efficiencies decrease from 0.5 to 0.4965 when subordinate nodes increase. But the interface's efficiencies outperformed the random. The variation of The COMAS's drop rates is not clear when subordinate node increases. However, the interface and the randoms' drop rates rise when subordinate node increases. With the interface algorithm, a receiving node used a fixed channel to receive packets. So, the interference occurs, only when two or more nodes transmit packets to the same node simultaneously. However, with the random algorithm, a node fixedly uses the same channel (initial selection is random) to transmit packets to its AP. With the cell scheme, the efficiency keeps on 0.55 and the drop rate is about 0.25. The cell scheme outperformed the interface and the random schemes. When number of nodes is high, the packet collision probability is also higher. So, the radio interference problem in the random algorithm is more severe than those of the interface algorithm and the COMAS.



(a) Network throughput of a node



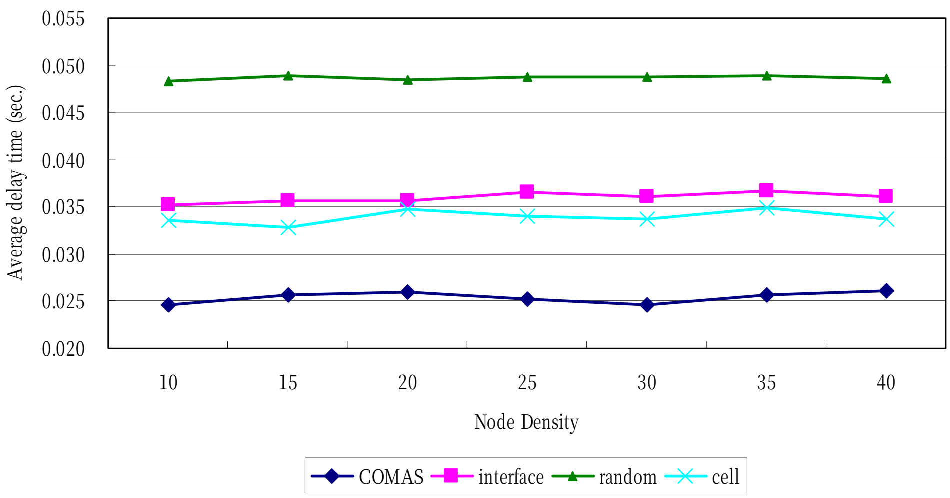
(b) Network efficiencies



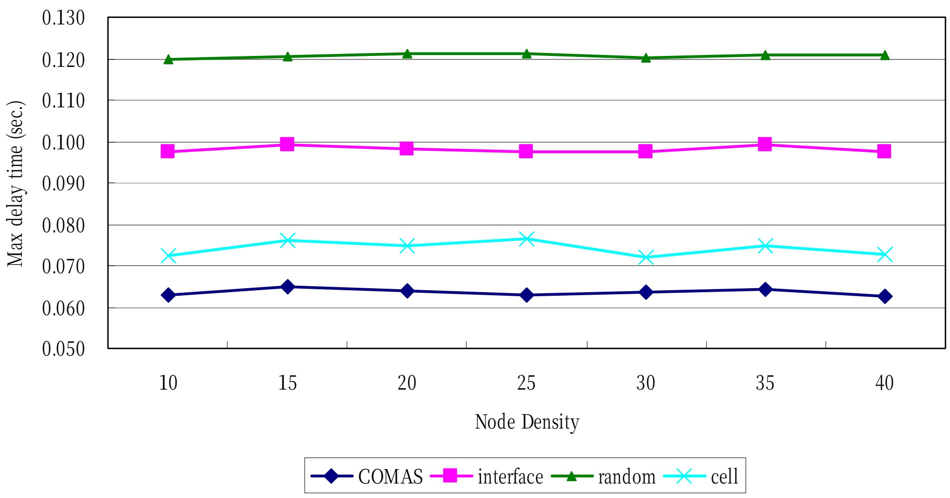
(c) Drop rates

Figure 19 Network throughputs, efficiencies and drop rates of the four tested algorithms against number of nodes.

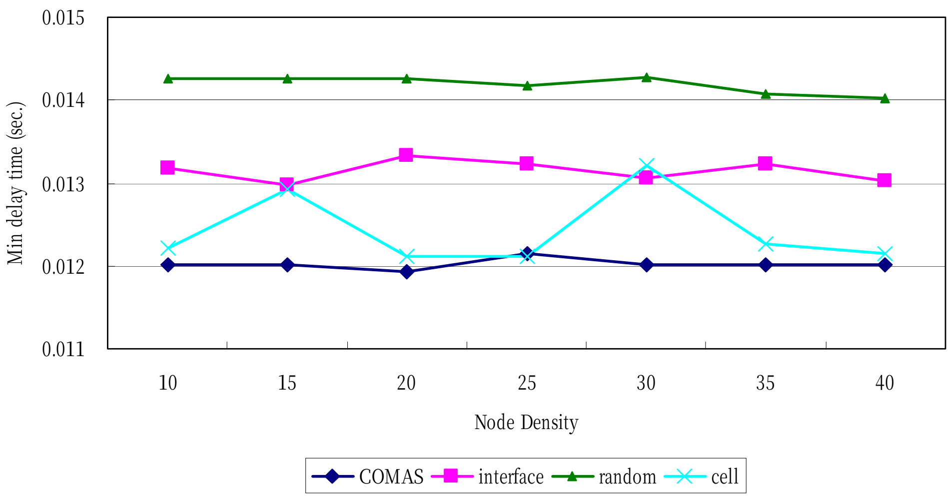
Figure 20a to Figure 20c respectively show average, maximum and minimum delivering delays, and Figure 20d illustrates the standard deviations. The average, maximum and minimum delays of the COMAS algorithms are all outperformed the other three. When number of nodes is high, e.g., up to higher than 25 nodes, the interface, the random and the cell schemes due to interference increase more sharply. Figure 21a to Figure 21d illustrate the plots of jitters of the four schemes. Like those of network delays, the COMAS is stable with less average jitters. But, the other two algorithms' are higher when number of nodes increase. With the interface and the random algorithms, the packet delivery delays owing to interference change differently. That is why their jitters are relatively higher.



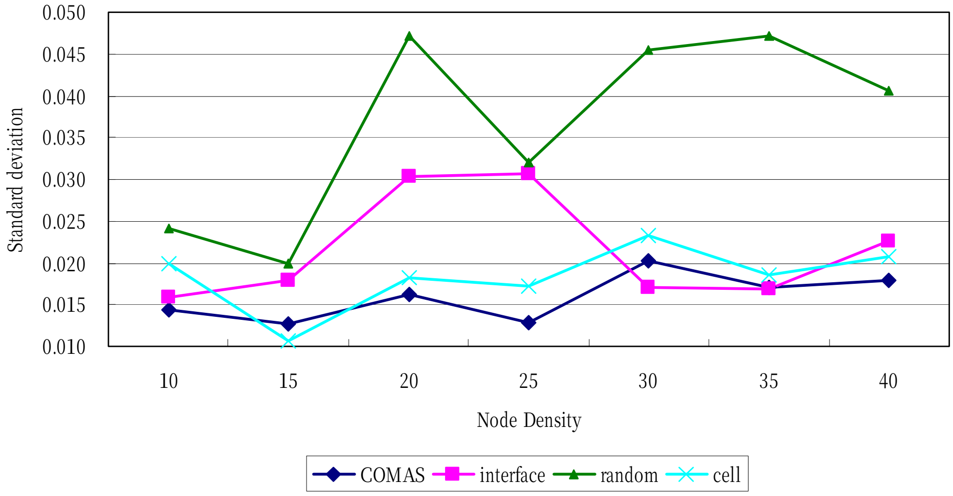
(a) Average delivering delays



(b) Maximum delivering delays

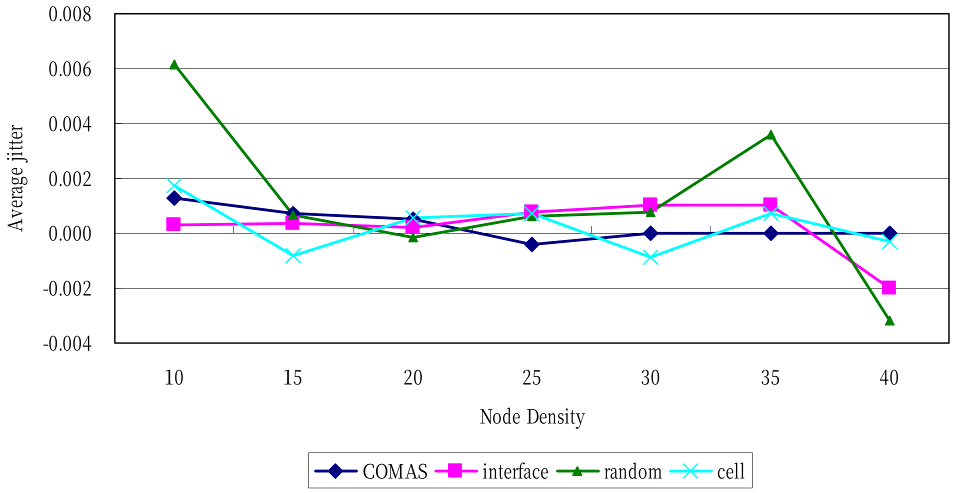


(c) Minimum delivering delays

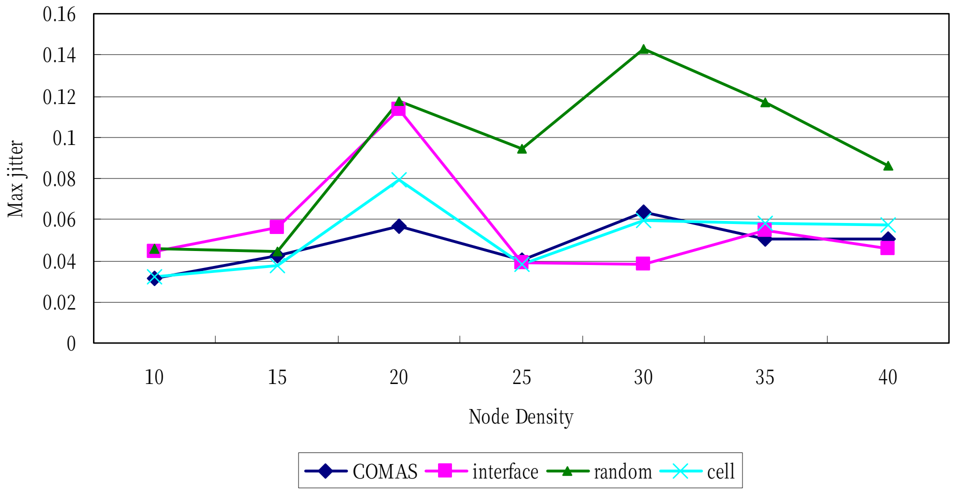


(d) Standard deviations of delivering delays

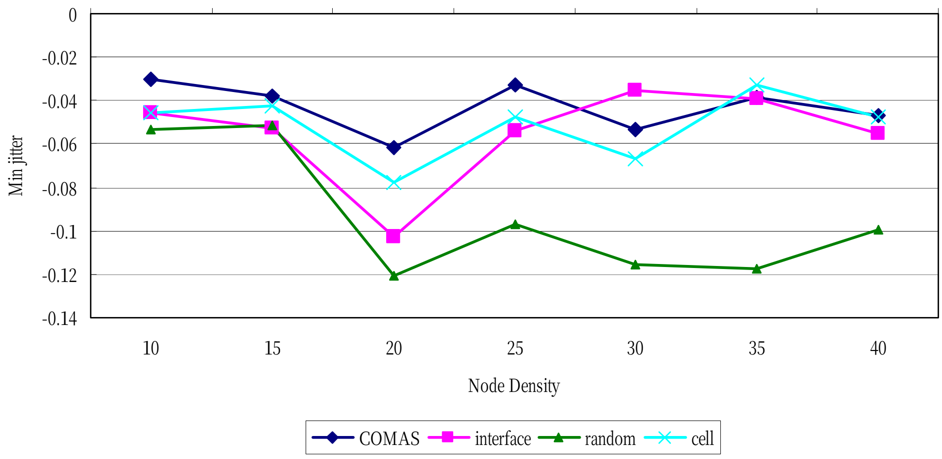
Figure 20 Network delivering delays of an AP for the four tested algorithms against number of nodes.



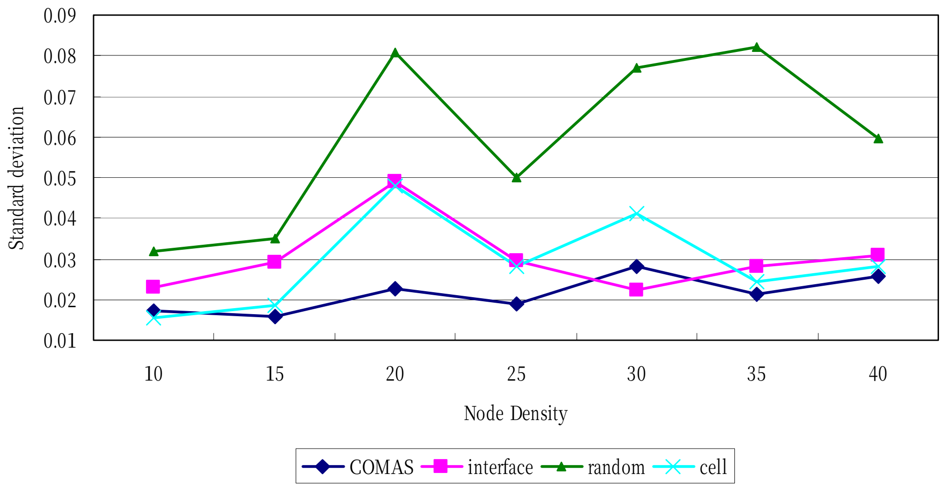
(a) Average jitters



(b) Maximum jitters



(c) Minimum jitters



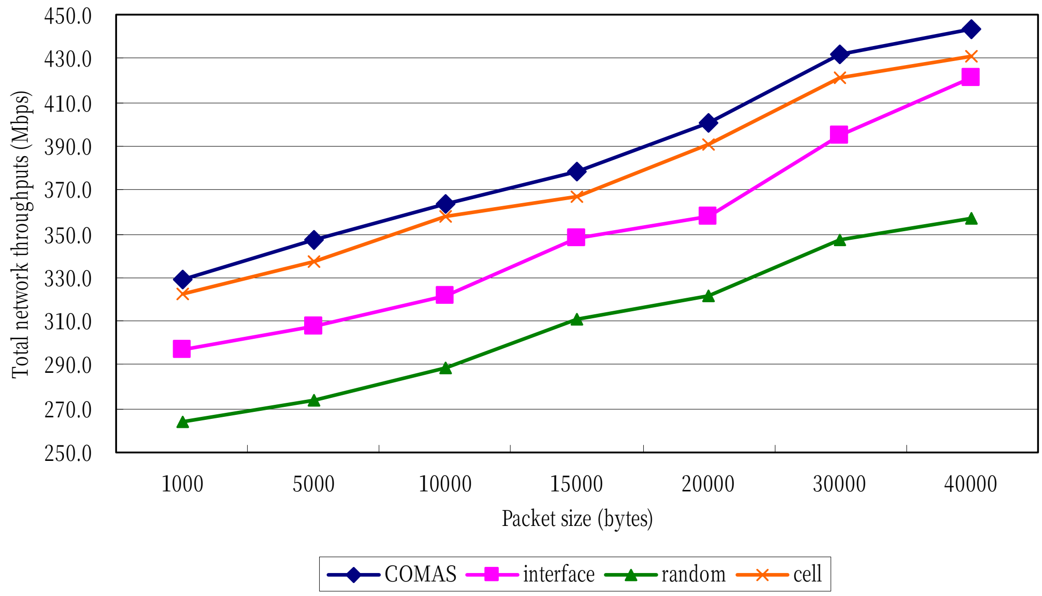
(d) Standard deviations of jitters

Figure 21 Network jitters against number of nodes for the four tested algorithms.

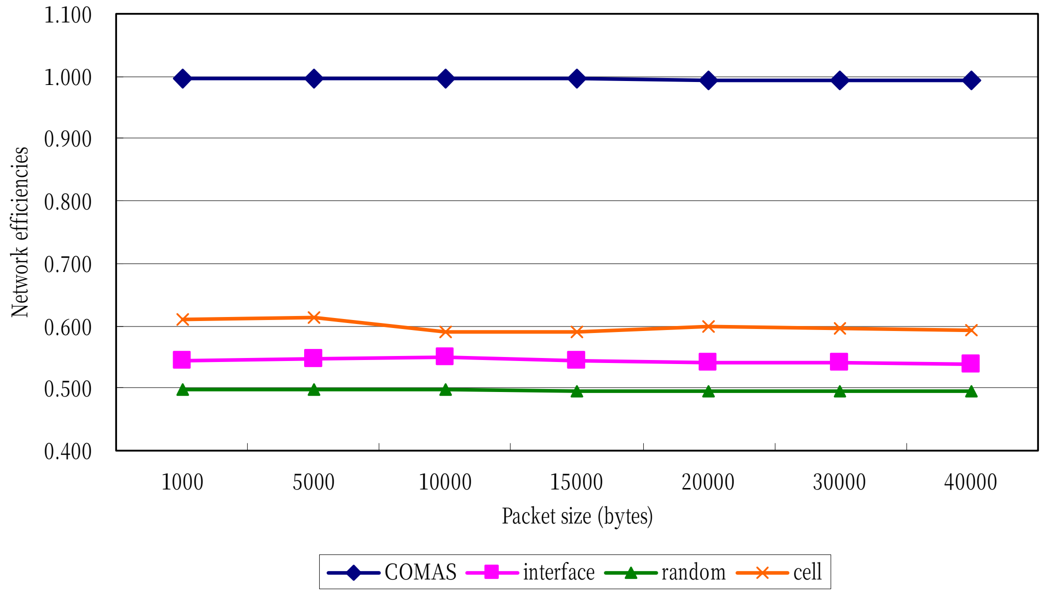
4.3. Performance on Different Packet Sizes

In the third experiment, we evaluated how packet sizes affect network throughputs, efficiencies, drop rates, delays, and jitters. The data rate as like the default values is 50 Mbps, the sizes of sent packets range between 1000 and 50000 bytes, and others parameters follow the default values. Nodes continuously communicate with their APs, and an AP only replies its nodes without sending messages to other APs or nodes.

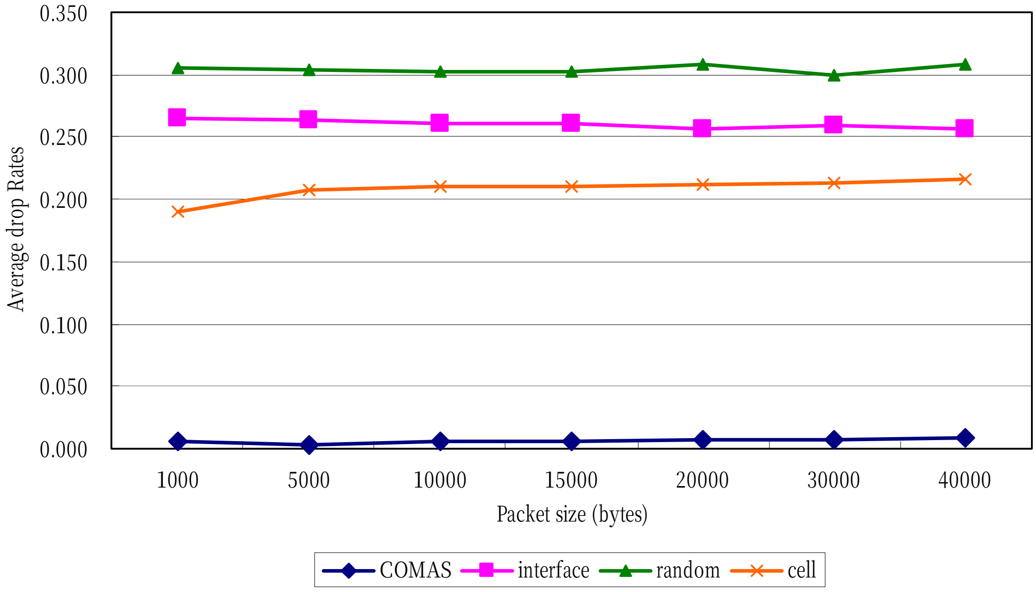
Figure 22a shows that the throughputs of the three schemes. The COMAS's throughputs are higher than the other two schemes'. When packet size=1000 bytes, a node spent 0.16 ($=\frac{1000*8}{50*10^6}$) msec to transmits a packet. So, it can transmit 50 packets in a time slot of 8 msec. And a node can only transmit a packet when packet size=40000 bytes. But, due to waiting for receiving an ACK message from the receiver, a node does not continue to transmit packets. In fact, the number of packets which a node transmits are less than 50 when packet size=1000 bytes. Figure 22b and Figure 22c show respectively the network efficiencies and drop rates on different packet sizes. The three schemes' efficiencies and drop rates descend obviously when packet sizes increase. With the drop rats, because of packet sizes increase, the transmitted time becomes longer, the transmitted packets decrease in fixed time, so the drop rates of the three schemes decrease.



(a) Network throughputs



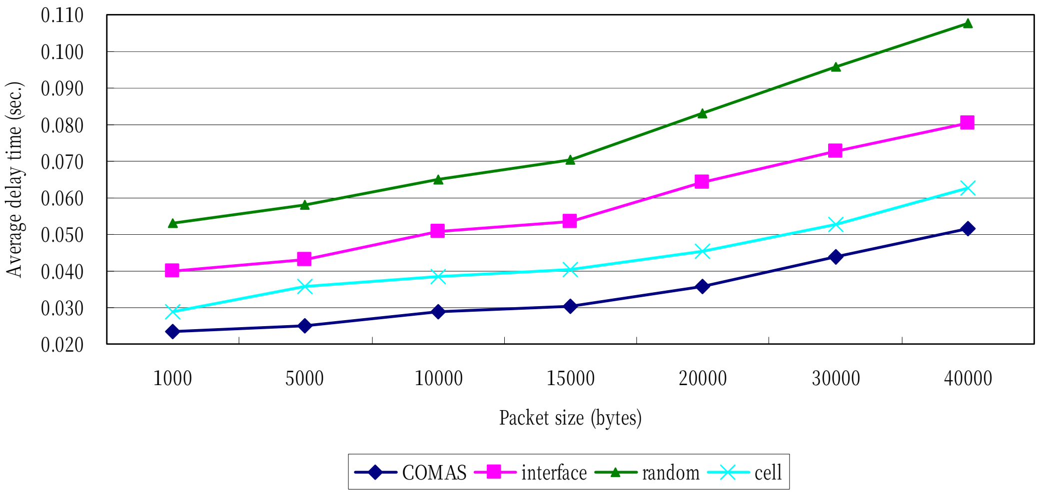
(b) Network efficiencies



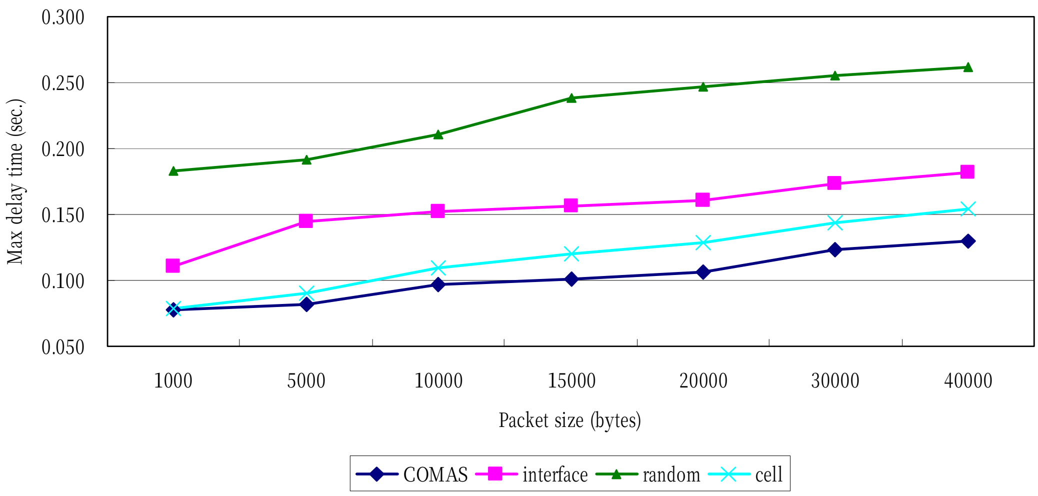
(c) Drop rates

Figure 22 Network throughputs, efficiencies and drop rates of the four tested algorithms against different packet sizes.

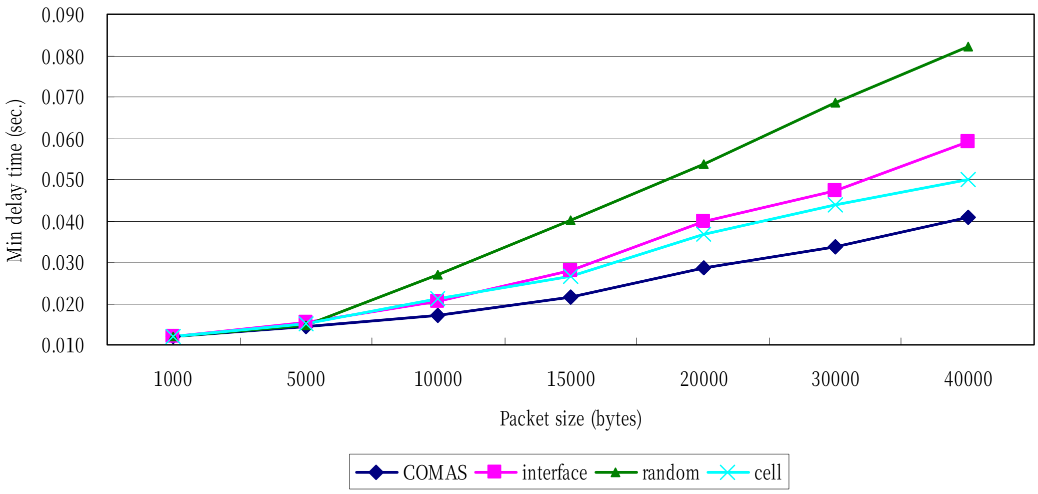
Figure 23a and Figure 23d respectively show the average delays, maximum delays, minimum delays and their standard deviations given different packet sizes. It is clear that the COMAS's outperformed the other two schemes. The interface and the random schemes spent more time than the COMAS to transmit packets because of the interference problem. Figure 24a to Figure 24d respectively show the average jitters, maximum jitters, minimum jitters and their standard deviations given different packet sizes. Due to shorter delay time, the COMAS is more stable than the other two schemes.



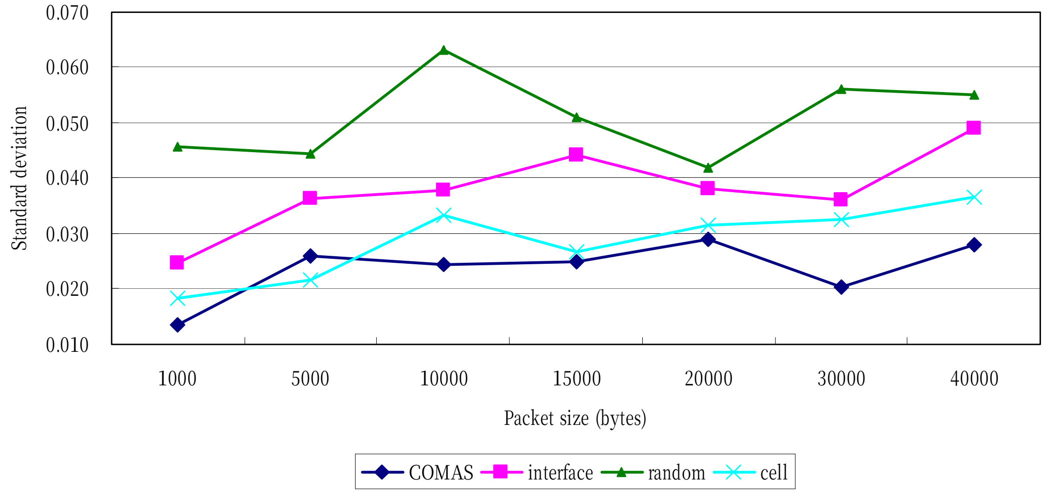
(a) Average packet delays



(b) Maximum packet delays

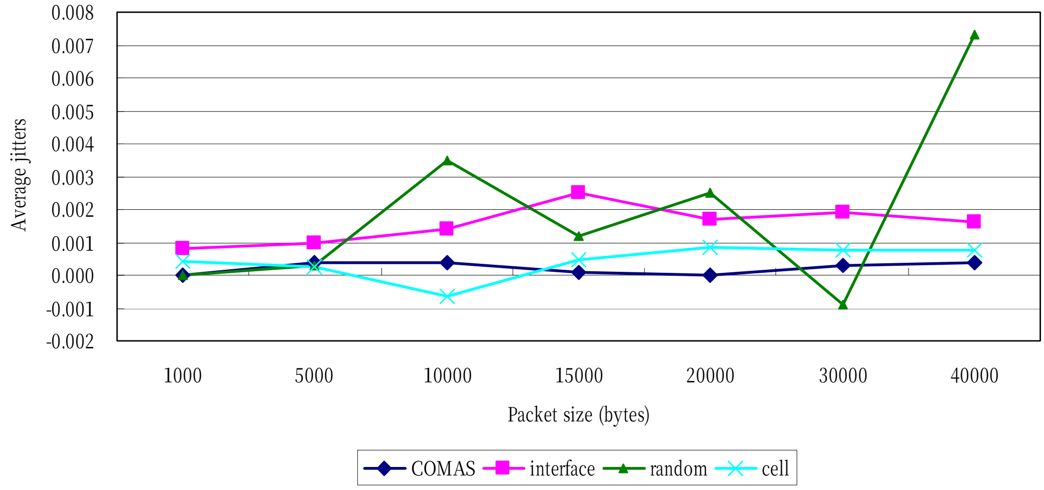


(c) Minimum packet delays

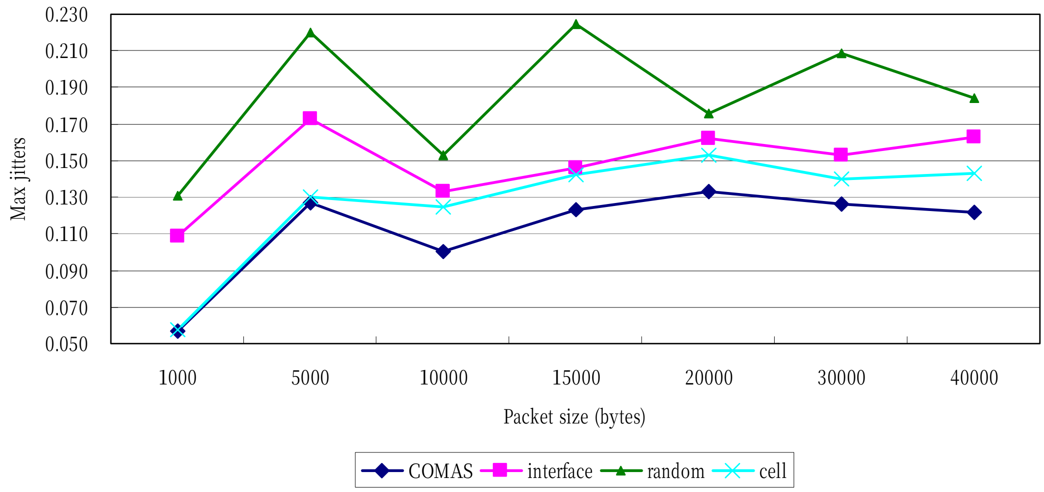


(d) Standard deviations of packet delays

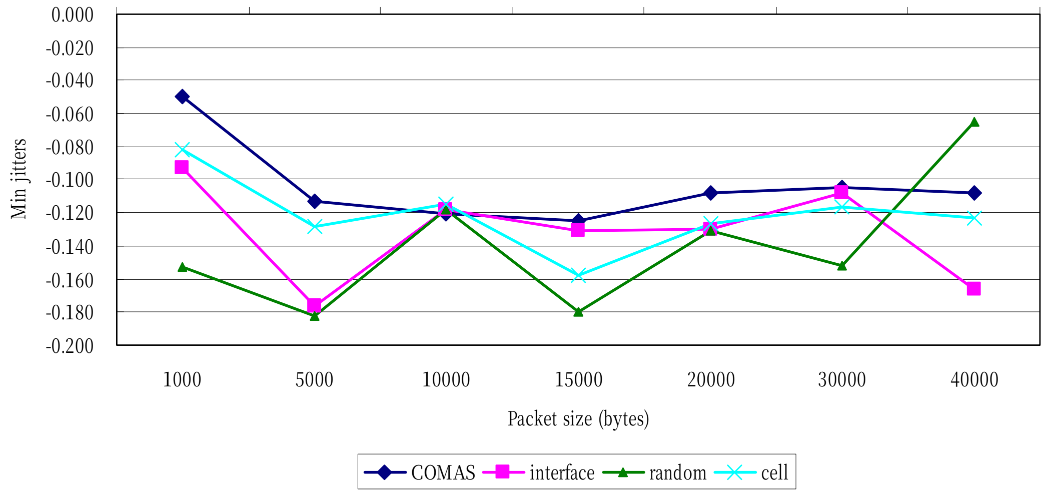
Figure 23 Network packet delays of the four tested algorithms against different packet sizes.



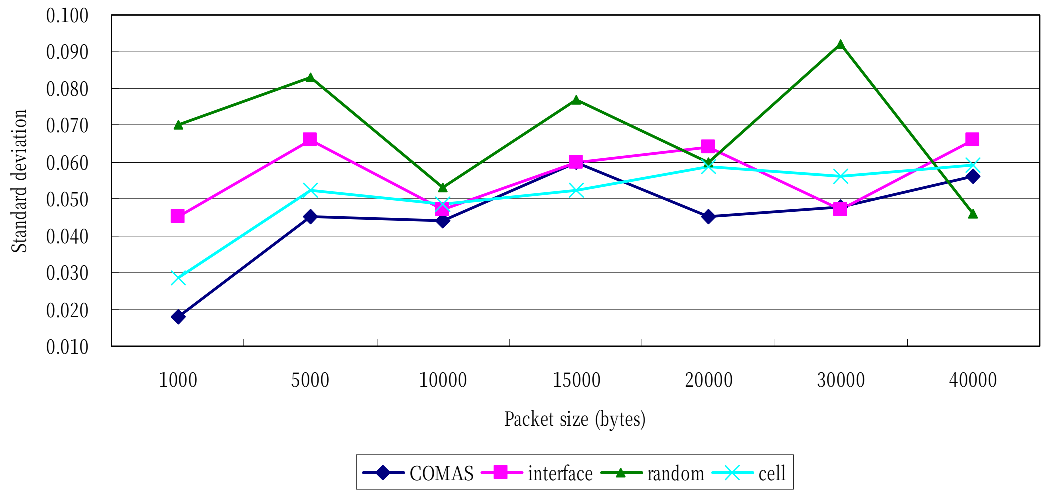
(a) Average jitters



(b) Maximum jitters



(c) Minimum jitters



(d) Standard deviation of jitters

Figure 24 Network jitters of the four tested algorithms against different packet sizes.

4.4. Cost of Relaying Packets through a Wired Link

In the fourth experiment, we evaluated the relaying delays of the four tested schemes. In this experiment, each AP has 10 subordinate nodes, and all APs in coronas 0 to 3 randomly communicated with their subordinate nodes (not shown) and node A under AP_{33} (see Figure 25) continuously communicate with node E under AP_{00}. The connection between AP_{33} and AP_{00} is a one Mbps wired link. APs have to content the wired link before they can transmit packets to other APs. The length of a packet is randomly generated to simulate the fact that messages of different lengths are delivered between the two nodes. The communication distance between nodes A and E is the farthest inside an AC-group, even it is not geographically the farthest. In the wired link, we used two different bandwidths, 1 Mbps and 100 Mbps, to evaluate how different wired bandwidths affect network throughputs, efficiencies, drop rates, delays, and jitters. In this experiment, when the wired bandwidth is 1 (100) Mbps, the data rate in the wired link is 1 (100) Mbps.

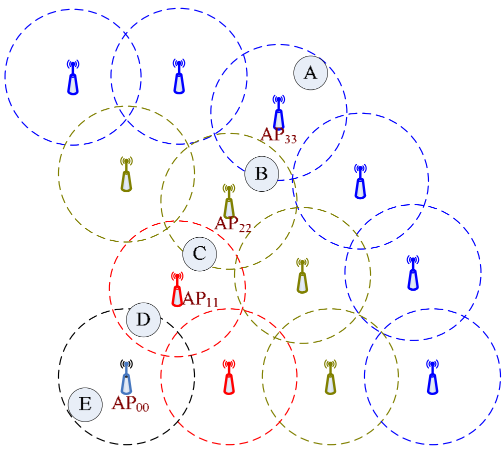
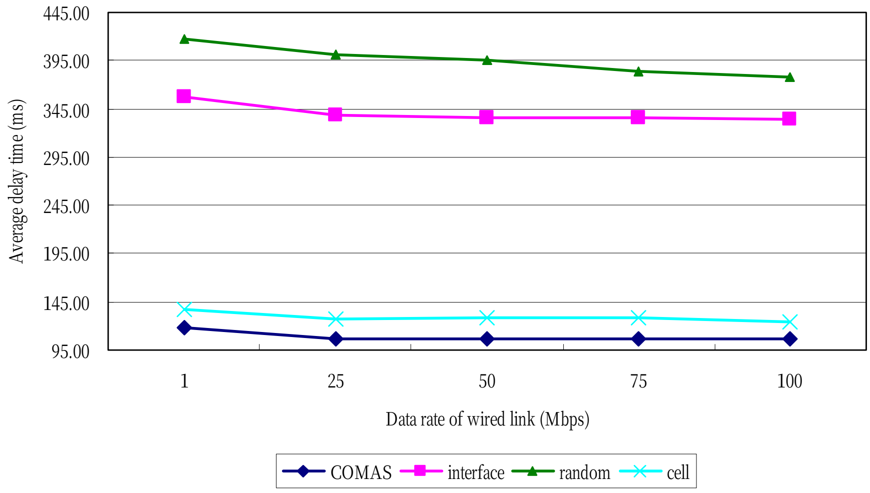


Figure 25 Node A (E) communicates with AP_{33} (AP_{00}) with a wireless link of 50 Mbps bandwidth, and AP_{00} connects to AP_{33} with a wired link of 1 (100) Mbps bandwidth.

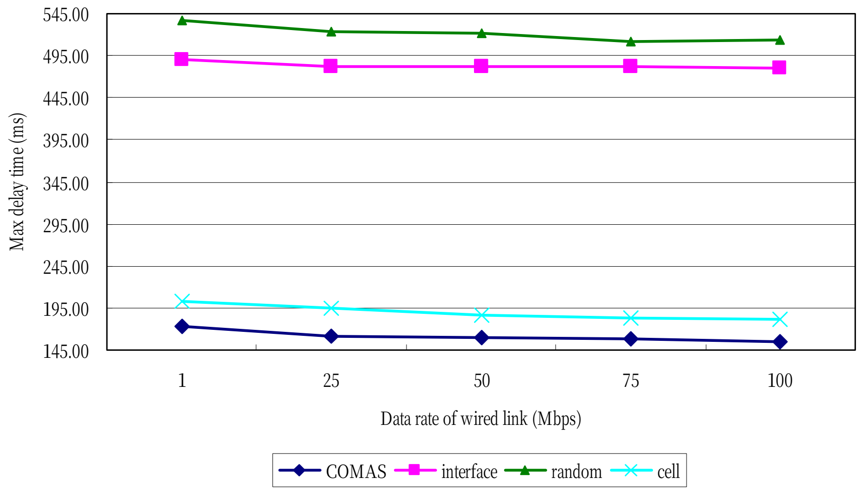
The experimental results of delivery delays and jitters are respectively shown in Figure 26 and Figure 27. When the wired link is 1 (100) Mbps, the random and the interface schemes respectively spent 546.92 (265.55) msec and 634.63 (306.16) msec to transmit a packet. Theoretically, we need 8.32 ($= \frac{1000*8*2}{50*10^6} + \frac{1000*8}{10^6}$) msec to deliver a packet (1000 bytes) through two wireless links and one wired link when the wired link's bandwidth is 1 Mbps, and spent 0.4 ($= \frac{1000*8*2}{50*10^6} + \frac{1000*8}{100*10^6}$) msec on the 100 Mbps wired link. The worst case of the COMAS in wireless portion is the case when a node has to wait for a round of time slots of an AP pair before the node can transmit/receive the next packet, so it spent 320 ($= 8*20*2$) msec to wait, where 20 means an AP pair has 20 subordinate nodes and 2 stands for two ends of the wired link, and the best case is 16 ($= 8*2$) msec. So, the worst cast of the COMAS is 328.32 (320.4) msec, and the best case is 24.32 (16.4) msec when the wired link's bandwidth is 1 (100) Mbps. Theoretically, no matter whether the bandwidth of wired link is 1 or 100 Mbps, the consumed times in the COMAS's worst case are not significantly different since Figure 26 lists the simulation results in which the COMAS.

Figure 26 lists the simulation results in which on 1 Mbps wired link the COMAS spent 117.45 msec to deliver a packet. So, the average wired link contention time is 93.13 (=117.45-16-8.32) msec, where 16 msec is the best time that a node of the COMAS waits for the next time slot. When 100 Mbps wired link is employed, the contention time is 90.39 (=106.79-16-0.4) msec. However, with the interference, the interface and the random schemes spent more time than the COMAS scheme, it respectively 356.90 (333.94) msec and 417.26 (377.30) msec.

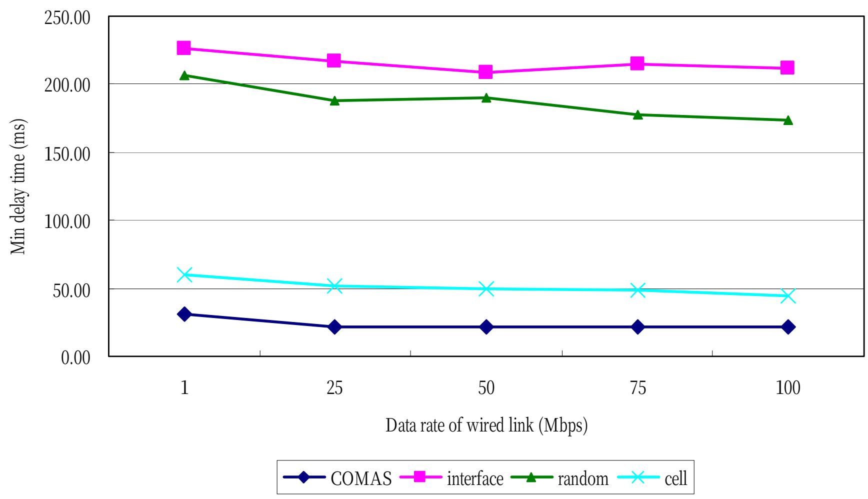
Figure 27 shows the jitters of this experiment. The COMAS scheme is also less than the interface and the random schemes. Figure 28 shows the drop rates, throughputs and efficiency. In Figure 28a and Figure 28b, the COMAS's throughputs and efficiency are higher than other two schemes. The COMAS's delays time is shorter than the other two schemes, so node A can transmit many packets to node E. Figure 28c shows the network drop rates that the COMAS is the lowest among the three schemes.



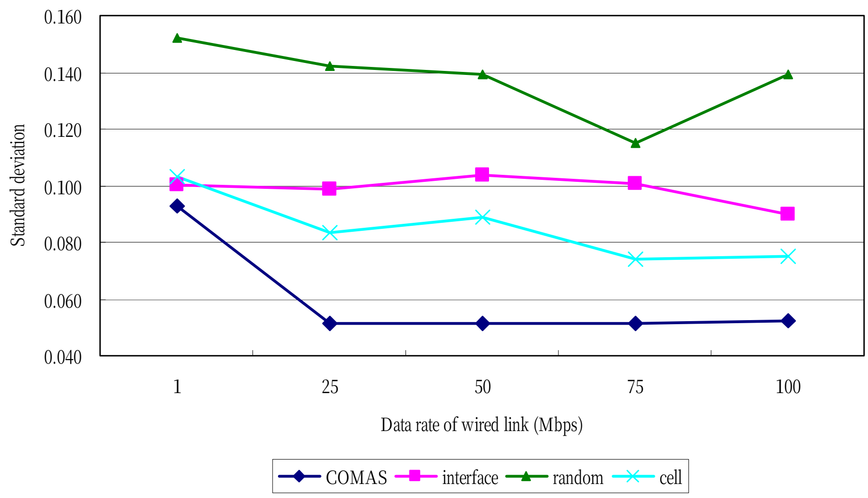
(a) Average packet delays



(b) Maximum packet delays

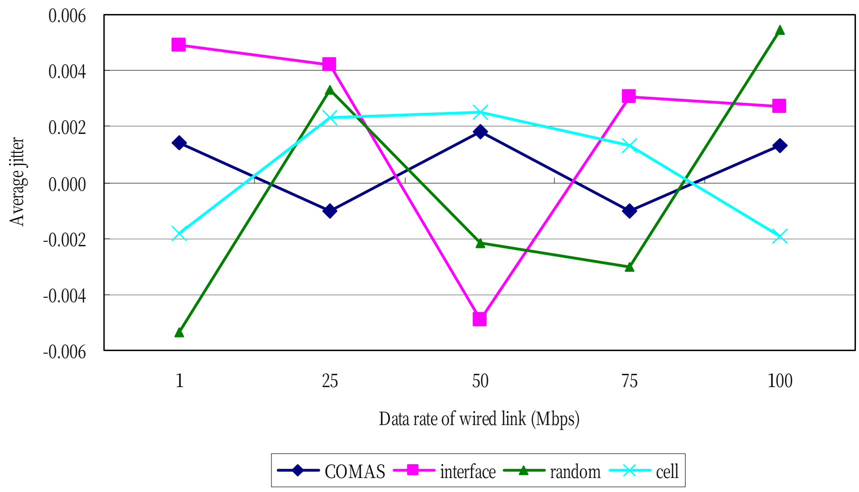


(c) Minimum packet delays

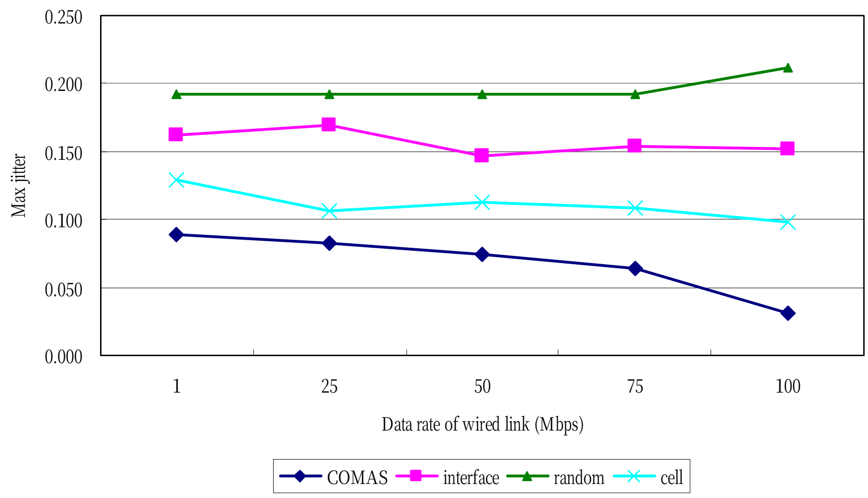


(d) Standard deviation of packet delays

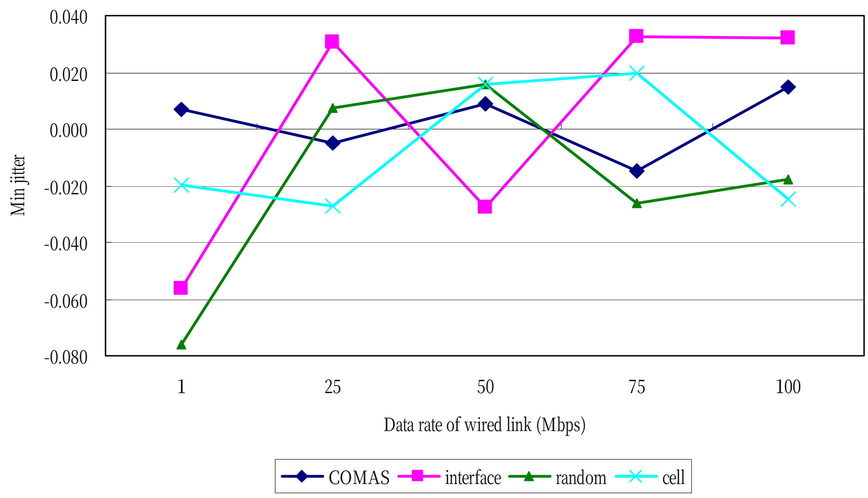
Figure 26 The delivery delays between node A and node E using the four tested schemes. The wireless channels used by AP_{00} and AP_{33} in the COMAS are different. But they may be the same or different when the other two schemes are used.



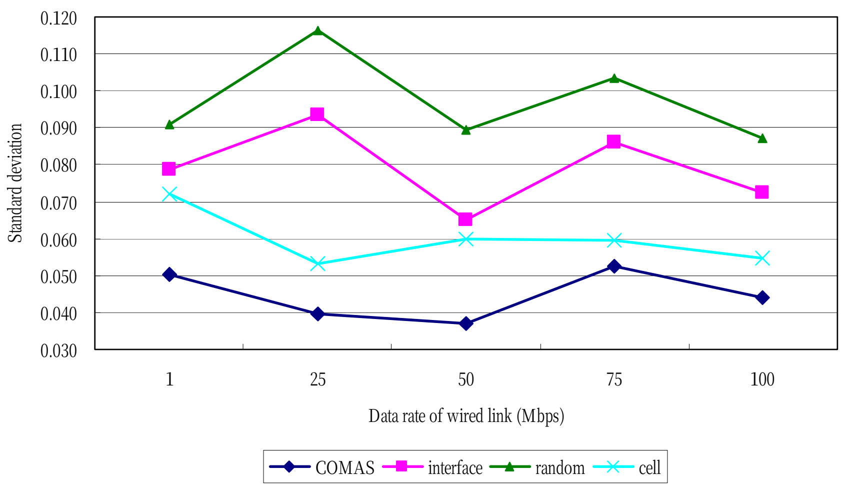
(a) Average jitters



(b) Maximum jitters

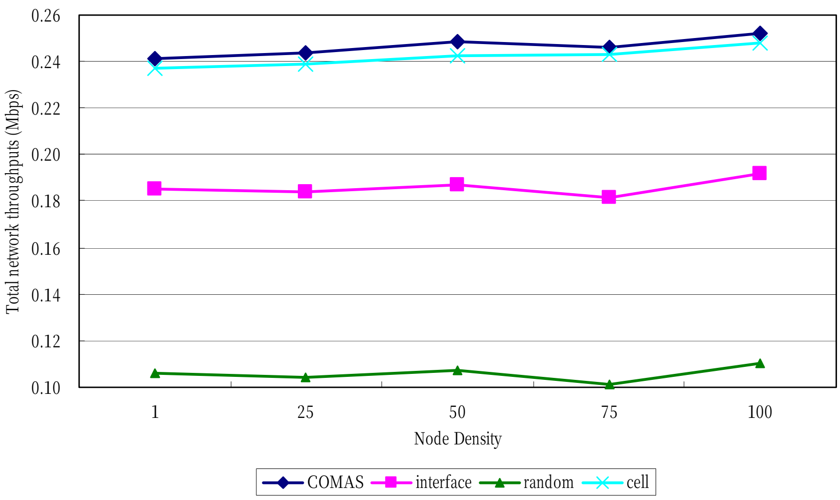


(c) Minimum jitters

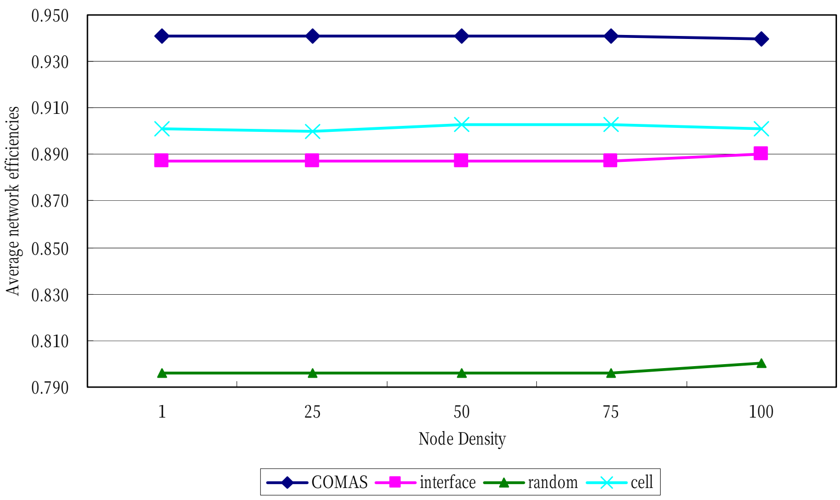


(d) Standard deviation of jitters

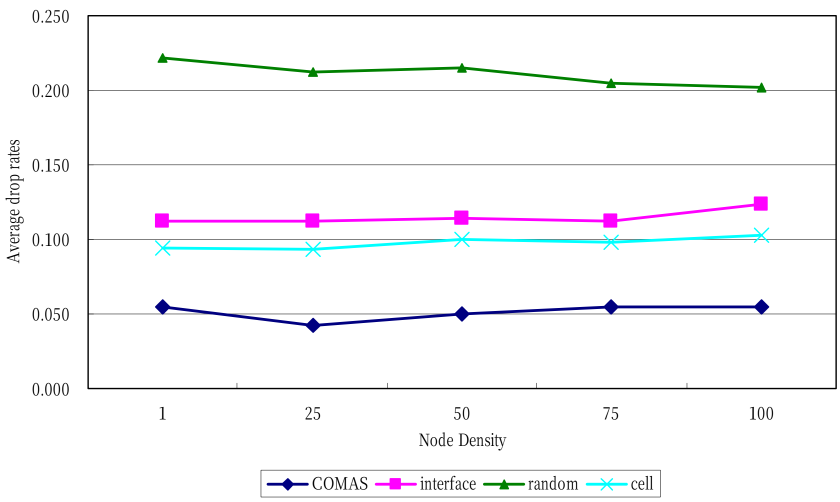
Figure 27　The jitters of the communication between node A and node E using the four tested schemes.



(a) Network throughputs



(b) Network efficiencies



(c) Drop rates

Figure 28 The drop rates, throughputs and efficiencies of the communication between node A and node E using the four tested schemes.

4.5. Cost of Relaying Packets through a Wireless Link

This fifth experiment is different from the fourth in that in the fifth experiment the communication between two APs is through a wireless environment. Figure 25 gives an example in which AP_{33} sends packets to AP_{22} for node A through joint node B. On receiving the packets, AP_{22} relays them to AP_{11} through node C. and AP_{11} relays the packets to AP_{00} through node D. At last, AP_{00} sends the packets to node E. The parameters are listed in Table 3. Meanwhile, the wireless link's surrounding APs are also shown in Figure 25.

Table 6 and Table 7 respectively list the delivery delays and jitters. In Table 6, the COMAS's average delay is 594.78 msec, but the interface and the randoms' are 1352.96 and 1748.81 respectively. With the COMAS scheme, there are a total of 8 hops on the link between node A and node E, node C, AP_{11}, node D and AP_{00}. The worst case of the COMAS is that a node/AP has to wait for 160 msec (=8*20), e.g., a round of a time slot before it can transmit a packet to next AP/node. So the total waiting time of the 8 hops is 1280 msec. The best case is that a node/AP can transmit a packet to the next AP/node immediately right after it receives the packet. So, the packet only spent 64 msec (=8*8) to arrive at its destination. The average is 672 msec, and the measured is 594 msec. So, with the COMAS, the average waiting delay on a node is 66.25 msec ($\frac{594-64}{8}$).

Table 8 shows the drop rates, throughputs and efficiencies of the three schemes. We can see that the COMAS's drop rate, throughput and efficiency are all less than those of the interface and the randoms' schemes.

Table 6 The delivery delays between node A and node B.

Scheme	Average (ms)	Maximum (ms)	Minimum (ms)	Standard deviation
COMAS	594.78	909.31	181.31	373.94
Interface	1352.96	1567.49	1045.37	273.22
Random	1748.81	2594.55	1160.94	750.79
Cell	622.32	912.55	183.72	254.89

Table 7 The jitters of the communication between node A and node B.

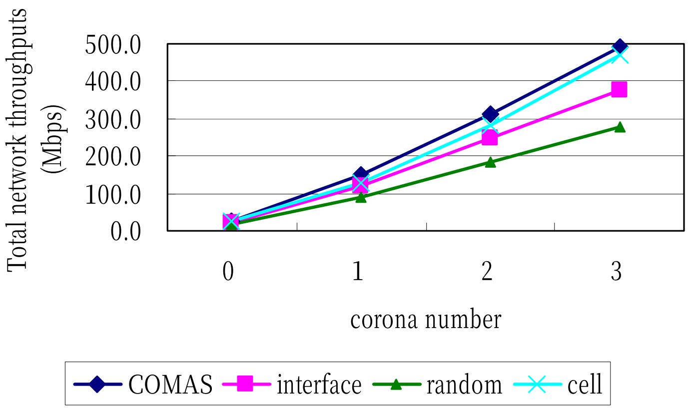
Scheme	Average	Maximum	Minimum	Standard deviation
COMAS	-0.108	0.512	-0.728	0.877
Interface	0.200	0.522	-0.121	0.455
Random	-0.552	0.330	-1.434	1.247
Cell	0.133	0.517	-0.423	0.637

Table 8 The drop rates, throughputs and efficiencies of the communication between node A and node B.

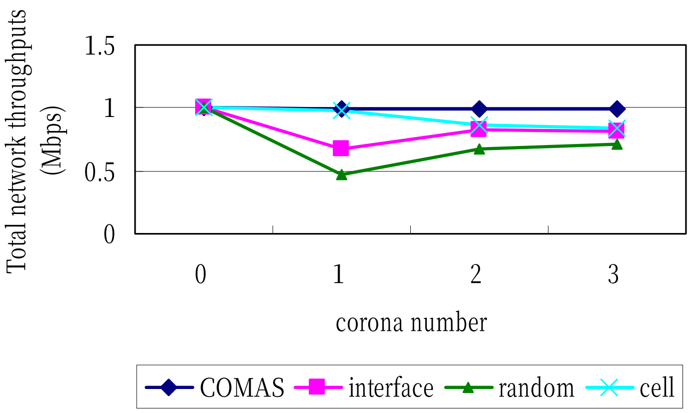
Scheme	Drop rate (%)	Throughput (Mbps)	Efficiency
COMAS	0.35	0.347	0.994
Interface	19.3	0.303	0.729
Random	27.5	0.230	0.583
Cell	5.44	0.335	0.932

4.6. Performance on Different Coronas

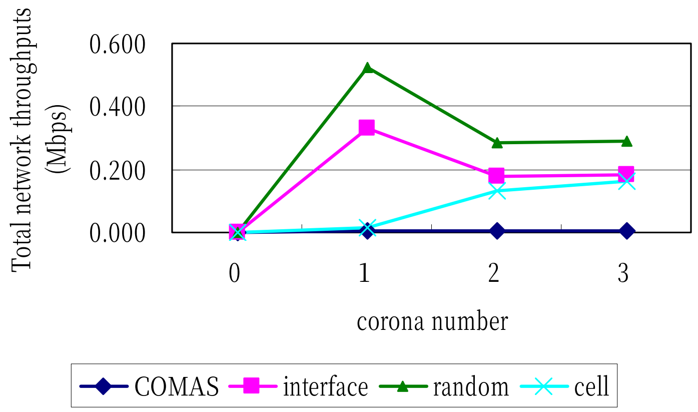
In this experiment, the coronas numbers are from 0 to 3 respectively. There is an AP in corona 0, six APs in corona 1, twelve APs in corona 2, and eighteen APs in corona 3. And other parameters are default values. Figure 29 shows the network throughputs, efficiencies and drop rates on different coronas. In Figure 29a, the three schemes' throughputs increase because of the number of APs increase. But the interface and random schemes' efficiencies and drop rates are all less than the COMAS. An AP in corona 1 will interfere other APs, so the random's efficiency is the lowest. But in corona 2 and corona 3, the number of interfered APs decreases, so the efficiencies are higher than corona 1. In the interface scheme, the interference occurs because of the distance is not far between two senders which used the same channel, so the interface's efficiencies are lower than the COMAS, but higher than the random. However, the COMAS's efficiencies and drop rates are stable. From Figure 29b and Figure 29c, it shows that each corona can avoid the interference problem. So, we used Figure 17 to do the latter experiments.



(a) Network throughputs



(b) Network efficiencies



(c) Drop rates

Figure 29 Network throughputs, efficiencies and drop rates of the four tested schemes against different coronas.

4.7. Interference Tested on the Cell Scheme

In this experiment, we tested the cell scheme that node A and B used the same channel, two nodes located on its AP's rim as shown on Figure 30 and shows the throughput, efficiency and drop rate as shown on Table 9. The data rate of each node is 50 Mbps and the other parameters are default values.

In Table 9, the efficiency in the cell scheme is 0.602 and the drop rate is 20.35%. The cause is that the distance between node A and B is not far, the radio/signal interference problem occurs. So, it can forecast that node A and C transmit packets to node B and D in the same time, the radio/signal interference problem become seriously.

Table 9 The cell scheme's throughput, efficiency and drop rate.

Throughput (Mbps)	Efficiency	Drop rate (%)
96.43	0.602	20.35

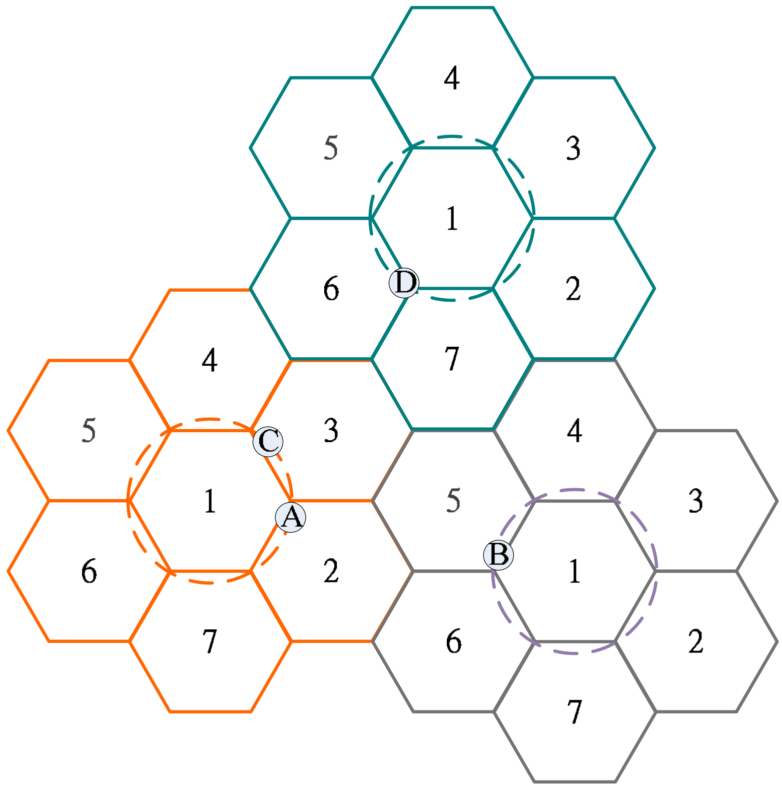


Figure 30　In the cell scheme, node A, B, C and D used the same channel in different clusters, and two nodes located on its AP's rim.

Chapter 5. Conclusions and Future Work

In this paper, we proposed the COMAS to solve 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 throughput, regardless of whether data rate is high or low. When data rate and number of nodes increase, the COMAS also preserved high throughputs and efficiencies. Given different packet sizes, the COMAS's delays are shorter and more stable than the interface and random schemes.

In the future, we would like to mathematically derive behavior and reliability models for the COMAS so users can predict the behavior and reliability of the environment before using it. We would also like to develop a method to calculate network throughput and efficiency by involving some other factors, e.g., distance between two nodes, number of available channels, interference range, and other factors which influence network throughput and efficiency.

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