Optimal Channel Assignment in Multi-hop Cellular Networks[†]

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***Abstract*—Wireless networks have made great gains in usability and popularity. However, inherent limitations on cell capacity and coverage still exist. There are also dead-spots and hotspots problems in these networks. Ad hoc multi-hop relaying enhances cell capacity and coverage, alleviates the dead-spots problem, and helps to ease congestion in hotspots. However, multi-hopping also increases packet delay. Effective channel assignment is key to reducing delay. Existing channel assignment schemes are heuristics and may not guarantee optimal solutions in terms of minimum delay. In this paper, we provide an optimal channel assignment (OCA) scheme for ad hoc TDD W-CDMA multi-hop cellular networks (MCN) to minimize packet delay. OCA can also be used as an un-biased tool for the comparison among different network topologies, network densities, and protocols. To the best of our knowledge, this is the first time that a minimum delay optimal channel assignment is proposed in a multi-hop cellular environment.**

Keywords-multi-hop; TDD; CDMA; cellular networks; optimal; channel assignment; delay

I. INTRODUCTION

Wireless networks have been a great success and will continue to play an important role in supporting user access and services. Still, the inherent limitations on cell capacity and coverage and the problems of *dead-spots* and *hotspots* exist in these networks. Dead-spots may occur in underground areas, and indoor environments where the signals are blocked from the base station (BS). Hotspots may occur in city centers and amusement parks where mobile users tend to experience higher call blocking. Recently, the concept of ad hoc multi-hop relaying for cellular networks was introduced to address these problems [2, 4, 9, and 12]. Systems of this type are called multi-hop cellular networks (MCN) and also have an enhanced cell capacity [7] and increased coverage at the expense of signal (or packet) delay. Several channel assignment schemes [1, 10, and 11] were recently proposed to address delay in a contention-free time division duplex (TDD) wideband code division multiple access (W-CDMA) MCN environment. These schemes can also be applied in the case where directional antennas are used. However, existing schemes may not guarantee an optimal solution that minimizes packet delay. In addition, it is difficult to objectively evaluate the performance of the various schemes proposed for TDD W-CDMA or TDD CDMA MCN, and more so, to evaluate quantitatively the gains in network performance from using a MCN scheme in different scenarios. In this paper, we describe an optimal scheme that computes a channel assignment minimizing the total packet relaying delay. We call our method the "Optimal Channel Assignment" (OCA) to distinguish it from other existing schemes. In addition to the benefit of minimizing delay in TDD W-CDMA MCN, OCA can assist us in studying quantitatively the performance gains achieved in different TDD CDMA MCN scenarios and also provides a benchmark to estimate the performance of different MCN schemes from the literature [8]. To the best of our knowledge, this is the first time that an optimal channel assignment is formulated for such networks.

This paper is organized as follows. In the next section, we describe the channel assignment problem. In Section 3, we present OCA scheme, our solution to the channel assignment problem. In Section 4, we describe the simulation model and the results with OCA on different network topologies and node densities.

II. CHANNEL ASSIGNMENT

In this section, we discuss the channel assignment in a TDD W-CDMA MCN environment. Then, we define the main delay component, relaying delay, in these networks. Note that the channel assignment problem described here is applicable to any TDD MCN system, such as TDD CDMA or TDMA. In these systems, mobile nodes requesting service (called source nodes) need a data connection to one of the base stations. To establish the connection, the system must assign channels to the source node and to possibly other relaying nodes.

A. Channel and Conflicts

In a TDD W-CDMA MCN environment, a channel c_i is represented by the pair (time-slot, code). A source node can have several channels; each of them is allocated for a different connection. Each connection initiation point is represented by a source point s_i. A relaying node may relay several connections. Each connection is relayed by a relay point r_i. A relaying node can also be a source node itself. Fig. 1 illustrates a typical example of channel assignment in this multi-hop cellular environment in which directional antennas are used.

When assigning a channel to a connection of a mobile node, channel conflicts need to be avoided. We define two types of channel conflicts in this environment:

- *Co-channel conflict* -

Case 1: When a relaying node receives signals from more than one transmitting node, the channels of the nodes must be different; otherwise, signal collisions occur. For example, in Fig. 1, node *D* is receiving signals from node *E* and *F*. Then, channels c_4 and c_5 have to be different from c_{11}.

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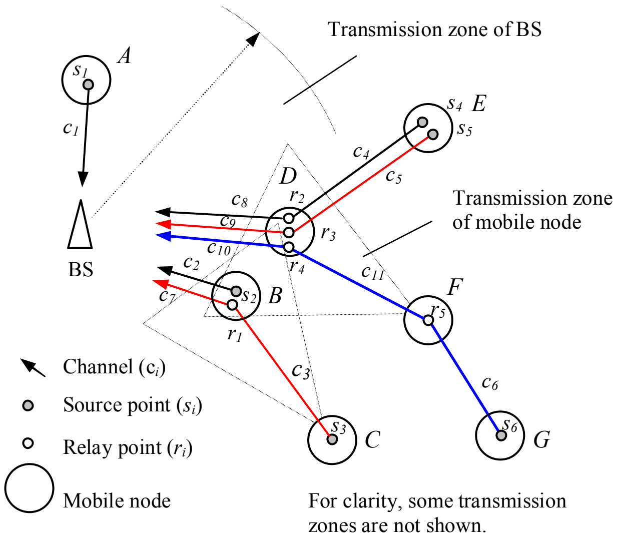

Figure 1. Topology and channel assignment in a MCN environment with directional antennas.

Case 2: When a receiving node is within the transmission zone of another transmitting node, its receiving channels have to be different from the transmitting channels of the other node; otherwise, signal collisions occur. For example, node *B* is in the transmission zone of node *F*. Then, channels c_3 and c_{11} must be different.

Case 3: A source node or relay node may serve several connections simultaneously. Each connection must use a different channel. For example, the channels, c_4 and c_5, of node *E* have to be different. Also, channels c_8, c_9, and c_{10} of node *D* must be different.

- *Co-time-slot conflict* – A node cannot physically receive and transmit data on the same time-slot using the same frequency. For example, in Fig. 1, the time-slots of the channels (c_8, c_9, and c_{10}) of node *D* have to be different from the time-slots of the channels (c_4, c_5, and c_{11}); otherwise, node *D* cannot receive the signals from node *E* and *F*.

B. *Relaying Delay*

The packet delay in a TDD MCN environment consists of four components: packet delay and time-slot waiting time at the source node, packet transmission time, packet propagation time, and time-slot waiting time at relaying nodes (see Fig. 2). Among them, the time-slot waiting time of a packet at the relaying nodes, which we call *relaying delay*, significantly affects the packet delay especially when the number of hops of a path is large. A simple way to minimize the relaying delay is to assign an immediate (consecutive) time-slot at the relaying node for a packet that just arrives at that node. This situation is similar to a perfectly pipelined condition with the assumption that the packet size is set such that the transmission and propagation time is within one time slot (see Fig. 2). Some heuristic channel assignment schemes [1, 10, and 11] for TDD W-CDMA MCN are designed based on this idea. However, in a MCN environment, source nodes and relaying nodes interact or interfere with each other. A perfectly pipelined condition for all relaying paths may not be possible. The heuristics do not guarantee a system minimum relaying delay.

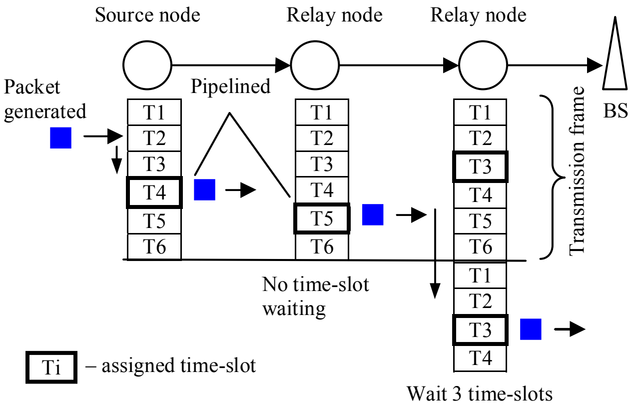

Figure 2. Relaying delay at relaying nodes in a TDD MCN environment.

III. OPTIMAL CHANNEL ASSIGNMENT

The task of finding a channel assignment is to ensure that no signal collision, channel conflict, or time-slot conflict occurs and the total packet relaying delay is minimized.

We start with the set of relaying paths from source nodes to the BS found by the routing algorithm deployed in the system. Let *V* be the set of (virtual) points that determine the relaying paths such that no two paths intersect except at the BS. Several points from set *V* may correspond to the same physical node. Fig. 3 illustrates the relaying paths and virtual points corresponding to the topology and traffic flows in Fig.1.

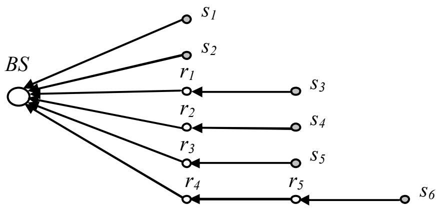

Figure 3. Virtual points of the relaying paths for the scenario in Fig. 1.

Let *S* be the set of source points, *R* the set of relaying points such that $S\cup R=V$, and let $|S|=$ n and $|R|=$ m.

We consider the time slot *t* and code *c* of a channel (*t*, *c*) to be positive integers. Let *T* and *C* be the maximum number of time-slots and codes that can be used by a network node (BS or a mobile node) in the system. For example, in the TDD mode of UMTS (WCDMA) [3], *T*=15 and *C*=16. To describe a channel assignment for the points in *V*, we define two binary {0, 1} variables:

$$x(u,t)=\begin{cases}1, & \text{if } u\in V \text{ is assigned time}-\text{slot } t\\ 0, & \text{Otherwise}\end{cases}$$

$$y(u,c)=\begin{cases}1, & \text{if } u\in V \text{ is assigned code } c\\ 0, & \text{Otherwise}\end{cases}$$

To model the co-channel conflict phenomenon, we define the collision graph $G=(V,E)$ whose vertex set is the set of all source points and relaying nodes of mobile nodes that a network controller manages. An edge in this graph exists between two vertices *u* and *v* if and only if assigning the same

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channel for transmission to both u and v leads to signal collision at some node a in the network or to a channel conflict if u and v are virtual points of the same node. For example, Fig. 4 is the collision graph for the network topology in Fig. 1. In Fig. 4, an edge exists between s_3 and r_5, s_4 and s_5, etc.

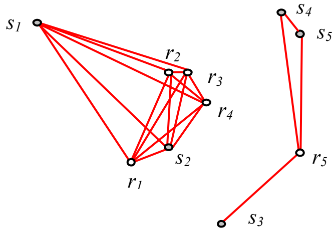

Figure 4. Collision graph for the co-channel conflicting points in Fig. 1.

Similarly, we can model the co-time-slot conflict by using a consecutive graph $G_c = (V, E_c)$. The receiving time-slots of a mobile node (i.e., the transmitting time-slots of the previous node of the node on a path) have to be different from its transmitting time-slots. An edge in this graph exists between two vertices which are in two consecutive nodes respectively along a path. Fig. 5 is the consecutive graph for the network topology in Fig. 1. In this figure, an edge exists between s_4 and r_2, s_4 and r_3, s_4 and r_4. This is because the time-slot of the transmitting channel c_4 of source point s_4 of node E has to be different from the time-slots of the transmitting channels c_8, c_9, and c_{10}, of relaying points r_2, r_3, and r_4, respectively, of node D (see Fig. 1).

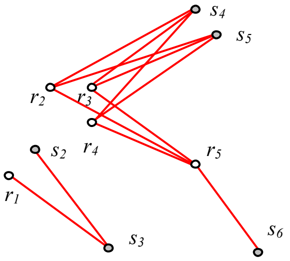

Figure 5. Consecutive graph for the co-time-slot conflicting points in Fig. 1.

We can now describe the linear constraints on variables $x(u, t)$ and $y(u, c)$ used in our Integer Programming (IP) formulation.

First, we enforce that exactly one channel (t, c) is assigned to every source point or relay point of a mobile node represented by a vertex u in V:

$$\sum_{1\le t\le T} x(u,t) = 1,\ \sum_{1\le c\le C} y(u,c) = 1,\ \forall u \in V \qquad (1)$$

Given an edge $(u, v) \in E$ from the collision graph, we have a valid channel assignment only if the vertices u and v are not assigned the same channel. For all possible channels, we can write,

$$x(u, t) + x(v, t) + y(u, c) + y(v, c) \le 3,$$
$$\forall\ (u, v) \in E,\ 1 \le t \le T,\ 1 \le c \le C. \qquad (2)$$

Given an edge $(u, v) \in E_c$ from the consecutive graph, we have a valid channel assignment only if the vertices u and v are not assigned the same time-slot. For all possible time-slots t, we can write,

$$x(u, t) + x(v, t) \le 1,\ \forall\ (u, v) \in E_c,\ 1 \le t \le T. \qquad (3)$$

Any assignment of {0, 1} values to variables x and y that satisfies constraints (1)-(3) defines a valid channel assignment. However, we are interested in a channel assignment that minimizes total packet relaying delay. The objective function that models this delay is more difficult to express. For two consecutive vertices u and v on a relaying path P, the delay incurred if distinct time slots t_u and t_v are assigned, is $(t_v - t_u) \bmod T$. For example, in Fig. 2, the packet relaying delay = (T5 – T4) mod 6 + (T3 – T5) mod 6 = 1 mod 6 + (–2) mod 6 = 1+ 4 = 5. Therefore, the packet relaying delay $\delta(u, v)$ from point u to v can be written as a quadratic expression,

$$\delta(u,v) = \sum_{\substack{1\le t_u, t_v \le T \\ t_u \ne t_v}} x(u,t_u)\cdot x(v,t_v)\cdot[(t_v - t_u) \bmod T].$$

The objective function is $F = \sum_{P\in W}\ \sum_{u,v\,\in P} \delta(u,v),$

where W is the set of paths. Function F is quadratic, but it can be linearized at the expense of increasing the problem size to make the formulation suitable for linear programming solvers. We define a new set of non-negative variables for every pair of consecutive vertices u, v on a path and every pair of time slots t_u and t_v. Our goal is to make $z(u, v, t_u, t_v)$ equal to the product of variables $x(u, t_u)\cdot x(v, t_v)$. We can achieve this goal with the following three constraints,

$$z(u, v, t_u, t_v) \le x(u, t_u),\ \text{and}\ z(u, v, t_u, t_v) \le x(v, t_v) \qquad (4)$$

$$z(u, v, t_u, t_v) \ge x(u, t_u) + x(v, t_v) - 1 \qquad (5)$$

If either one of $x(v, t_u)$ or $x(u, t_v)$ is zero, the non-negative variable $z(u, v, t_u, t_v)$ has to be zero, and when both $x(v, t_u)$ and $x(u, t_v)$ are one, $z(u, v, t_u, t_v)$ is one because of constraint (5). The IP formulation of OCA is

$$\min \sum_{P\in W}\ \sum_{u,v\,\in P}\ \sum_{\substack{1\le t_u, t_v \le T \\ t_u \ne t_v}} Z(u,v,t_u,t_v)\cdot[(t_v - t_u) \bmod T],$$

$$= \min \sum_{\substack{u,v\in V \\ 1\le t_u, t_v\le T,\ t_u\ne t_v}} Z(u,v,t_u,t_v)\cdot[(t_v - t_u) \bmod T],$$

subject to constraints (1) - (5) and $x(u, t_u)$, $y(u, c_u)$, $x(v, t_v)$, $y(v, c_v) \in \{0, 1\}$, $\forall\, u, v \in V$, $1 \le t_u \le T$, $1 \le c_u \le C$, $1 \le t_v \le T$, $1 \le c_v \le C$, $z(u, v, t_u, t_v) \ge 0$.

In practice, we use a modified version for constraint (3) which can generate a smaller number of constraints in the IP solver.

IV. PERFORMANCE EVALUATION

In this section, we will use OCA as a benchmark tool to study the performance of different network topologies and densities.

A. *Simulation Model and Parameters*

Our simulation model is a single-cell with 45 source nodes. The number of relaying nodes varies from 0 to 160 in increments of 40. We separate the role of source node and relaying node so that the case in which no mobile nodes are

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willing to relay signals can be captured. We use OCA to compare the performance of four different network topologies over which mobile nodes are uniformly distributed with various node densities (see Fig. 6).

Case 1: General - a general case having a circular region with a radius of 1km centered at the BS.

Case 2: Side-rectangle - a rectangular region (700m x1400m) on one side of the BS. This models a situation where many mobile users are moving in the same direction, for example, walking away from office buildings after work.

Case 3: Side-square - a square region (700m x 700m) overlapping a 45^{o} sector of the BS coverage region. This models a hotspot region, such as a crowd in a public square during a lunch break.

Case 4: Side-road - a long and narrow region (400m x 1400m) which is parallel to and at a distance of 100m from the BS. This can model users in a parade on a road, or bridge.

We use cases 2, 3, and 4, to study the situation of different non-uniform topologies. We assume that the traffic in these regions dominate the traffic in the rest of the areas. To focus our study on the dominating regions, we consider the other regions empty or not contributing to channel conflicts.

The simulation set-up is a true model for a TDD CDMA MCN environment. In this model, a different number of relaying nodes is used to model different node densities and traffic patterns. Table 1 shows the simulation parameters. The transmission range of the BS and mobile nodes is 250m with cell capacity of 345 kbps. Each TDD data transmission frame is 3.33 ms long and has 5 time-slots. For simplicity, we assign all 5 time-slots for the BS uplink transmission. Each time-slot can be assigned with 5 codes and each code corresponds to a data rate of 13.8 kbps [3]. Each call uses one code at a constant bit rate. The average duration of each call is 5 minutes with an exponential distribution. The maximum number of hops is set to 4. Each mobile node is equipped with a directional antenna with a 45^{o} beam angle. The simulation is implemented using OPNET Modeler 10.0A [6]. The optimization package is MOSEK version 4 [5].

OPNET Modeler generates the network topology. The collision and consecutive graphs are computed using Euclidean shortest paths as relaying paths and a given constant beam angle for the directional antenna. MOSEK is then used to compute an optimal channel assignment for each source point and relaying point. This assignment is transferred to OPNET and used in the simulation to obtain the throughput and end-to-end packet delay. Although a single-cell model is used in this simulation, it is not difficult to generalize it to a multiple cell environment as long as a proper handoff mechanism is provided.

We assume nodes to be static (or with limited mobility) because our focus is to study the performance of different network topologies and densities using OCA. We assume perfect power control, perfect physical medium, and sufficient battery capacity for relaying signals. An overhead involved in channel assignment and routing is not fixed, but is dependent on how frequent the channels and routes are updated.

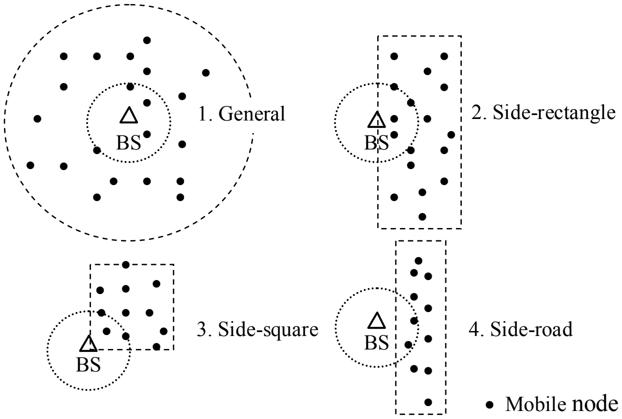

Figure 6. Four different network topologies.

TABLE I. SIMULATIONS PARAMETERS

Parameters	Value
BS or mobile range (m)	250m
BS or mobile capacity	345 kbps (or 5 slots/frame and 5 codes/slot)
Antenna	directional antenna with beam angle 45^{o}
Data rate per code	13.8 kbps
Call request rates	0.1 calls/min.
Call holding time	5 min.
Max. hop count	4

B. Performance Metrics

We use cell throughput and packet delay as the performance metrics for the evaluation of different network topologies and densities based on OCA.

Cell throughput – the number of packets that the BS receives per second. High throughput means high channel reuse and more nodes being served.

Packet delay - the time required for a packet sent from the source node to reach the BS. Low packet delay indicates the effectiveness of the channel assignment. Note that our results will always yield minimum packet delay and can indicate what scenarios are challenging in a MCN environment

C. Simulation Results

Considering Figures 7 and 8, we can generally observe that when the number of relaying nodes is zero, the network condition is reduced to a single hop case. No channel assignment optimization is necessary. The average delay in all the cases is almost the same.

When the number of relaying nodes is small (i.e., nodal density is low), many source nodes cannot reach the BS, due to the lack of relaying paths. Thus, the throughput is low. Among the four cases, the throughput of the general case appears lower than the other cases because the general case has a much larger physical area to cover compared to the other cases. That is, its node density is much lower than the other cases for the same number of relaying nodes. Hence, fewer relaying paths are available to relay the signals of the distance nodes to the BS and a lower throughput is obtained. For a denser network, the general case always achieves the highest throughput.

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When the number of relaying nodes increases to a larger value, the throughput increases because more source nodes, especially the distant nodes, have paths to reach the BS. The delay also increases as the number of hops on each path increases. Fig. 9 illustrates the delay-throughput characteristics. Note that the observed low delay at relatively high throughput is achievable due to the fact that OCA minimizes the packet relaying delay.

When the number of relaying nodes increases, the throughput increases until all the available channels are used. In this stage, the throughput value is high and relatively constant. The Side-square and Side-road cases reach this state earlier than the general and Side-rectangle cases. This is because they have a relatively higher node density for the same number of relaying nodes. As the number of relaying nodes increases, our OCA scheme manages to effectively assign channels in all the non-uniform cases such that their performance is similar to the general case.

We observed that the Side-square case has the lowest steady throughput because the relaying nodes, especially the last-hop relaying nodes to the BS, are densely located in a specific region around the BS. The relaying nodes that are close to the BS are highly congested. Hence, high co-channel and co-time-slot conflicts occur and fewer channels are available at the congested relaying nodes to relay the signals. Thus, a lower throughput is obtained.

Although the node density of the Side-road case is comparable to that of the Side-square case, the last hop relaying nodes towards the BS of the Side-road case are spread out. This avoids congestions and reduces the co-channel and co-time-slot conflicts. The small width and the orientation of the region reduce the number of hops required to reach the BS and a lower delay and higher throughput is observed. Fig. 9 shows that the Side-road case has the best delay-throughput performance.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we propose an optimal channel assignment (OCA) formulation for TDD W-CDMA MCN. OCA not only minimizes the packet relaying delay of TDD MCN networks, but also acts as an un-biased tool or benchmark for the comparison of different network conditions and networking schemes, such as routing, for these networks. Network conditions are determined by network topology, node density and traffic pattern. Indeed, we show that in several non-uniform nodal and traffic scenarios, our OCA scheme manages to effectively assign channels in all cases such that their performance is similar to a general uniform case.

Achieving minimum packet relaying delay in MCN can be considered as one important step forward. A next step could be studying of how to utilize OCA in quality of service (QoS) provisioning in MCN. OCA is computationally expensive. Its performance on a large-scale problem needs further study.

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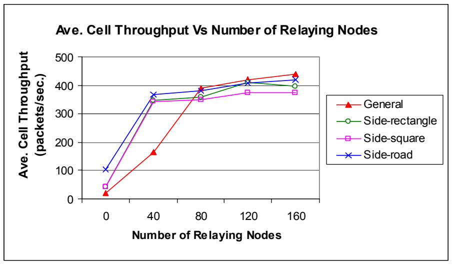

Figure 7. Average Cell Throughput.

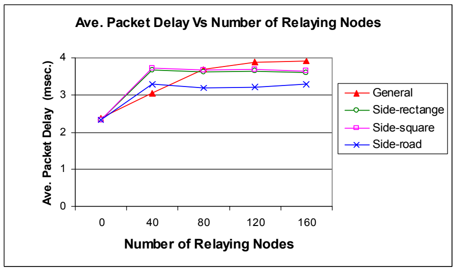

Figure 8. Average Packet Delay.

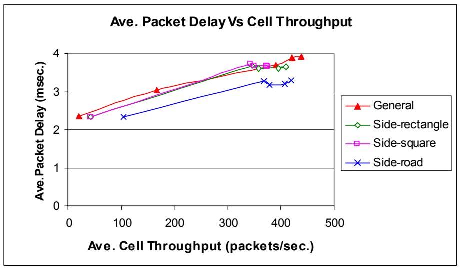

Figure 9. Packet Delay versus Cell Throughput.

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