Optimal Cell Size in Multi-hop Cellular Networks†

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***Abstract* - 3G-based Multi-hop cellular networks (MCNs) inherit a special characteristic of 3G systems, namely the relationship between a cell's coverage and its capacity. At the planning stage, a cell may be statically set to have small coverage with high capacity, a large coverage with small capacity, or some other fixed settings in between. Such static settings, however, do not adapt to the projected dynamic nature of users in 3G – especially in an MCN environment. In this paper, we propose the Optimal Cell Size (OCS) scheme for a 3G TDD W-CDMA MCN multi-cell environment. Given the cell capacity function, users' distribution and demands, OCS yields optimal cell sizes that maximize the system throughput through balancing coverage and capacity. Not only can OCS cope with dynamic network conditions, but it can also be considered as an aid to the network planning process. To the best of our knowledge, this is the first multi-cell optimal cell size scheme in the context of MCNs.**

Keywords - multi-hop; TDD; CDMA; cellular networks; optimal; cell size; throughput

I. INTRODUCTION

In a cellular network, the coverage of a cell is basically the cell size or the communication range of BS. The cell capacity is usually measured by number of admitted calls or maximum supportable data rate in the cell. In third generation (3G) systems, a cell's coverage is inversely proportional to its capacity. During the planning stage, if a large coverage is required, a small interference margin [3], which corresponds to a low cell capacity, is allocated so that a larger margin can be allocated for the propagation loss [3]. If a large cell capacity is required, a large interference margin is allocated to allow a high capacity whereas the margin for propagation loss is reduced which corresponds to the cell size. Obviously, such a static approach cannot cope with the dynamic nature of users in 3G.

In MCNs [1, 2, 5, 9, 10], where connectivity to the base station (BS) may be through one or more intermediate nodes, the coverage not only depends on the cell size but also the availability of mobile nodes for relaying. To achieve high cell capacity without deteriorating the coverage or network reachability, some MCN proposals, e.g. ad hoc cellular architecture (A-Cell) [9], assume a small cell size and a dense network. A smaller cell size allows higher cell capacity whereas a dense network provides sufficient relaying nodes for relaying signals. However, in practice, a dense network may not always be the case. When the network is sparse, the performance of MCN could be greatly degraded because distant mobile nodes may not find relaying paths to reach the BS to use the available capacity. If a large cell size is set, more nodes can reach the BS, but the resulting cell capacity may not meet the demands.

In order to overcome the drawbacks of static cell size assignments, we recently introduced the concept of optimal cell size [10] in a 3G time division duplex (TDD) wideband code division multiple access (W-CDMA) multi-hop cellular system. A limitation of the work presented in [10] is that it only applies to a single-cell case, and cannot be directly extended to a multi-cell environment. In this paper, we propose the Optimal Cell Size (OCS) scheme for finding the optimal cell sizes that maximize the system throughput in a multi-cell TDD W-CDMA MCN environment. OCS can determine the cell size dynamically and can be considered as a network planning aid in cellular networks and MCNs. Note that a cellular network is a mere special case of MCN. To the best of our knowledge, ours is the first work on multi-cell optimized cell size in MCNs.

In the next section, we discuss the cell size in MCNs. In Section III, we introduce the OCS scheme. In Section IV, we present the simulation model and discuss the results.

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II. CELL SIZE

In this section, we describe the importance of cell size and the concept of optimal cell size in a single-cell and a multi-cell MCN environment. Fig. 1 shows a typical single-cell TDD W-CDMA or CDMA MCN environment and a graph for illustrating the optimal cell size.

A. The Importance of Cell Size

In Fig. 1, we represent a connection (call or session or traffic flow) in a source node by a virtual point called source point s_i. Each source point s_i is assigned exactly one channel with a demand of traffic $\mu(s_i)$. Each source node may have several source points; each supports a different connection for a different service. A connection is relayed by relaying points r_j in relaying nodes on a relaying path. A relay node may have several relaying points for relaying different connections. The BS only needs to communicate with the last-hop node on a relaying path for a source point s_i. For example, nodes *A*, *B*, and *D* are last-hop nodes. A source node can be a relaying node and a last-hop node itself (see node *B*). If the cell size is not large enough to cover the last-hop nodes of the source nodes, the demands of source nodes cannot reach the BS. Cell size also affects the cell capacity. The smaller the cell size, the higher the cell capacity can be achieved. Thus, the cell size is an important design factor that ultimately affects the total demands that can be served which gives the system throughput.

B. Optimal Cell Size - Single-Cell Case

To explain the concept of optimal cell size, a Capacity-demand model [10] is used. The *capacity* represents the cell capacity of the CDMA technology and is a decreasing function over the cell size. The *demand* represents the total data rate requested by the source nodes and is an increasing step function over the cell size.

In the graph in Fig.1, there are three demand segments (μ_1, μ_2, and μ_3); the value of each segment represents the cumulated

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demand of the source nodes having their last-hop nodes within the corresponding range of the BS. Two capacity functions, U and U', are used to illustrate two typical cases.

In the first case, the curve of the capacity function U intersects with the demand segment μ_2 which is the total demand originated from source nodes A, B and C. The demand of node C is relayed through node B to the BS. The optimal cell size is at range R_2 because, at this range, the demand that can be served is maximized and equal to μ_2 and the remaining capacity ($U(R_2)$ - μ_2) for future calls is also maximized.

In the second case, the curve of the capacity function U' is in-between the demand segments μ_2 and μ_3. In this case, if the total demands that can be served by the capacity corresponding to the range R_3 is more than μ_2, then R_3 is the optimal cell size; otherwise, the optimal cell size is at R_2. This problem is actually a knapsack problem [4] which involves selecting a number of objects (each of them has a value) into a bag which has a capacity such that the total value is maximized. In this case, the objects are the demands. Each demand has a value which is the data rate requested by a corresponding source point. The cell capacity corresponds to the bag's capacity.

The capacity function may be obtained through on-line computation, prediction or experiments. Table 1 shows sample uplink ranges with respect to the uplink capacity (data rates) in a suburban area for W-CDMA networks [3]. We use curve fitting to approximate the capacity function $U(R)$ as a continuous function over the range R by a degree 4 polynomial.

$$U(R) = 245.56R^4 - 2717.13R^3 + 11245.43R^2 - 20736.4R + 14511.99.$$

TABLE I. UPLINK RANGE vs. CAPACITY

Range (km)	1.1	1.4	1.75	2.25	2.7	3.1
Capacity (kbps)	2048	1024	384	144	64	32

C. *Optimal Cell Size - Multi-Cell Case*

In a multi-cell environment, the task not only requires the computation of the cell sizes, but also involves the selection of a BS among several possible BSs for a connection (source point) of a source node. The decision is dependent on the availability of relaying paths (each path ends at a different neighboring BS), the locations of the last-hop nodes of the paths, the cell sizes, and the corresponding cell capacities. For example, in Fig. 2, connection s_7 requested by node I can be assigned to BS b_2 or b_3. Assigning the connection to b_3 gives a lower overall system capacity compared to that of assigning it to b_2 because the cell size of b_3 needs to be larger to cover the last-hop node J of the relaying path for the connection in node I. Assume that a source point has one path per each BS. The distance between the last-hop node of the path and the BS is an important input parameter for determining the optimal cell size.

III. OPTIMAL CELL SIZE

Given a set of relaying paths, a set of demands, and the capacity function of the cell, the task is to find the optimal cell sizes to maximize the system throughput.

We denote by V the set of (virtual) points that determine the relaying paths, which do not intersect with one another except at the BSs. Several points from set V may be in the same physical node. Let S be the set of source points $\{s_1, s_2, \ldots, s_m\}$ and L be the set of relaying points $\{r_1, r_2, \ldots, r_k\}$, and B be the set of BSs $\{b_1, b_2, \ldots, b_n\}$ such that $S \cup L \cup B = V$.

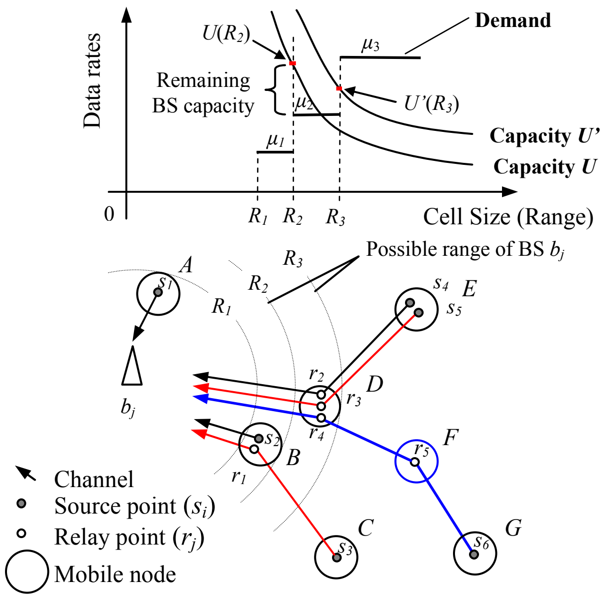

Figure 1. Capacity-demand model

Each source point may have several relaying paths; each path has a different nearby BS as target. In other words, for each BS, there is a set of relaying paths; each path relays the signals of a unique source point to the BS.

To determine whether or not a source point can reach the BS, we just need to know the distance of the last-hop node of the relaying path for the source point from the BS. Assume a routing protocol provides a set of relaying paths for each source point for each BS, the topology in Fig. 2 can be translated into three sets of relaying paths; each set of paths ends at a different BS. From these paths we can construct a bipartite distance graph G (V_h, E) for each BS where V_h is the set of vertices representing the last-hop relaying points towards to the BSs and E is the set of edges connecting a vertex in V_h to a BS. Each edge is weighted by the distance $d(v(s_i), b_j)$ of the last-hop relaying node having the last-hop relaying point $v(s_i)$ on the path reaching the BS b_j. If no relaying path is found for a source point for a BS, the distance of that source point to that BS is set to infinite (∞). Fig. 3 shows the distance graph for the BS b_1 for the scenario in Fig. 2. For example, for s_3 in Fig. 3, $v(s_3) = r_1$ and $d(v(s_3), b_1) = d(r_1, b_1) = d_3 = 4$.

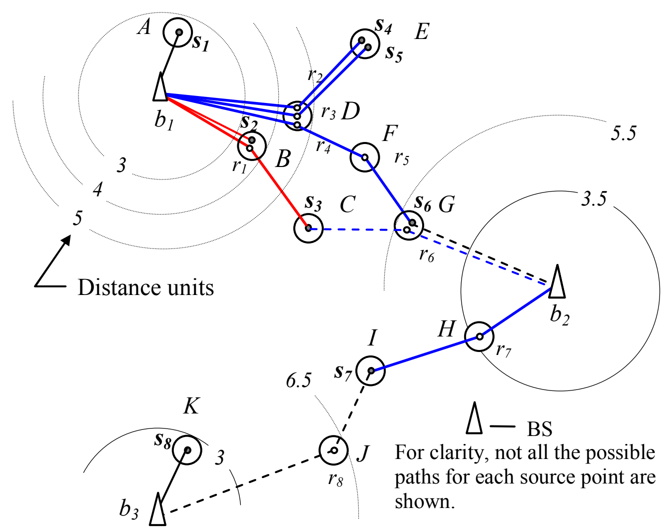

Figure 2. Cell size in a multi-cell environment

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Let $R(b_j)$ be the set of communication ranges $\{R_1, R_2, \ldots, R_k\}$ of BS b_j in non-decreasing order where R_k represents the distance between the BS and the last-hop node of the relaying path for a source point s_i to the BS. The ranges can be obtained based on the distance graph G. For example, in Fig. 3, the set of the ranges for BS b_1 is {3, 4, 5} where the number represents the units of distance. Note that the set of ranges can also be a set of predetermined values, e.g., {1, 2, 3, 4, 5, 6, 7}, depending on the standard and/or configuration of the system in practice.

As mentioned in Section II.A, $\mu(s_i)$ represents the demand (data rate) of the source point s_i. We seek to maximize the total demand that can be served. More specifically, we need to decide (i) what communication range (cell size) to use for each BS and (ii) which BS to assign to a connection request.

To solve for optimal cell size, we formulate the problem as an Integer Linear Programming (ILP) problem.

To model the assignment of the connection of a source point s_i of a mobile node to a BS b_j, we use a connection assignment variable $x(b_j, s_i)$. For example, if s_4 is assigned to b_1, then $x(b_1, s_4)$ is equal to 1.

$$x(b_j, s_i) = \begin{cases} 1, & \text{if } s_i \text{ is assigned to } b_j \\ 0, & \text{Otherwise} \end{cases}$$

To ensure that a source point is assigned to no more than one BS, the total sum of the values of the variables x is constrained to be less or equal to 1. For example, the sum of the values of $x(b_1, s_1)$, $x(b_2, s_1)$, and $x(b_3, s_1)$ must be less than or equal to 1. The sum is zero if s_1 cannot be assigned to any of the BSs (b_1, b_2, b_3) due to insufficient capacities of the BSs or lack of a relaying path to the BSs.

$$\sum_{b_j \in B} x(b_j, s_i) \le 1, \ \forall b_j \in B, \forall s_i \in S \qquad (1)$$

To model a communication range of a BS b_j, we define a range variable $y(b_j, R_k)$. The value of $y(b_j, R_k)$ is 1 if R_k is less than or equal to the chosen communication range R_c of the BS; otherwise, $y(b_j, R_k)$ is 0. For example, in Fig. 3, the set of possible ranges is {3, 4, 5}. If the R_c is 4, then $y(b_1, 3)$ and $y(b_1, 4)$ are equal to 1 whereas $y(b_1, 5)$ and $y(b_1, \infty)$ are equal to 0.

$$y(b_j, R_k) = \begin{cases} 1, & \text{if } R_k \le R_c \\ 0, & \text{Otherwise} \end{cases}$$

The relationship between the ranges of a BS b_j can be expressed in a set of k-1 inequalities in a compact from as follows.

$$y(b_j, R_1) \ge y(b_j, R_2) \ge \cdots \ge y(b_j, R_c) \ge \cdots \ge y(b_j, R_k), \forall b_j \in B, \qquad (2)$$

where $R_1 < R_2 < \ldots < R_c < \ldots < R_k$.

To relate the range variable y to the connection assignment variable x, we formulate the third constraint as follows. A source point s_i can be served by a BS b_j only if the BS has chosen a communication range which is able to reach the last-hop node of the relaying path for the source point. For example, if the distance $d(v(s_i), b_j)$ between the last-hop node having the relaying point $v(s_i)$ for the source point s_i and the BS b_j is less than or equal to a chosen range R_c, then $x(b_j, s_i)$ can be 1 or 0 depending on whether or not it is admitted by BS b_j. If $d(v(s_i), b_j)$ is larger than R_c, then $x(b_j, s_i)$ must be equal to 0.

$$x(b_j, s_i) \le y(b_j, R_k), \forall b_j \in B, s_i \in S(b_j, R_k), \qquad (3)$$

where $S(b_j, R_k)$ is a set of source points s_i with $R_{k-1} < d(v(s_i), b_j) \le R_k$. Sets $S\{b_j, R_k\}$ are disjoint for different values of R_k and thus there is at most one constraint (3) for every pair of BS and source point. For example, in Fig. 3, $S(b_1,3)=\{s_1 \mid 0 < d_1 \le 3\}$,

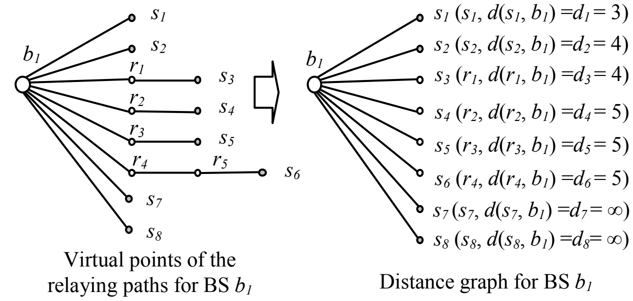

Figure 3. Distance graph for base station b_1

then $x(b_1, s_1) \le y(b_1, 3)$. $S(b_1,4)=\{s_2, s_3 \mid 3 < d_2 \le 4, 3 < d_3 \le 4\}$, then $x(b_1, s_2) \le y(b_1, 4)$; $x(b_1, s_3) \le y(b_1, 4)$. If the chosen range R_c is 4, then $y(b_1, 4)$ is equal to 1. Since $y(b_1, 3) \ge y(b_1, 4)$ in constraint (2), $y(b_1, 3)$ is also equal to 1. In this case, $x(b_1, s_1)$ can be 1 or 0 depending on whether or not s_1 is assigned to b_1. The same rationale applies to $x(b_1, s_2)$ and $x(b_1, s_3)$.

To ensure that the total demand of the source points served by a BS is not larger than the capacity of that BS for the chosen range, knapsack inequalities are used. Let $U(b_j, R_k)$ be the amount of capacity of BS b_j that decreases when the communication range of BS b_j is increased from range R_{k-1} to range R_k. In particular, we denote by $U(b_j, 0)$ the maximum capacity of the BS corresponding to the smallest possible communication range. By convention, we choose $U(b_j, R_k)$ to be positive. The summation of the product between the value of each variable $x(b_j, s_i)$ and its demand $\mu(s_i)$ (data rate) has to be less than or equal to the capacity at that chosen range R_c of b_j. For example, assume $U(b_1,0)=25$, $U(b_1,R_k)=5$ $\forall k$, and $R_c=4$, then the capacity is $25-5\cdot y(b_1,3)-5\cdot y(b_1,4)-5\cdot y(b_1,5)=25-5(1)-5(1)-5(0)=15$.

$$\sum_{s_i \in S} \mu(s_i) \cdot x(b_j, s_i) \le U(b_j, 0) - \sum_{1 \le k \le R(b_j)} U(b_j, R_k) \cdot y(b_j, R_k), \forall b_j \in B \qquad (4)$$

The objective is to maximize the total demand that can be served which is dependent on the number of reachable requests, the data-rate of each request, and the cell capacity. Thus, the objective function is to maximize the value of the summation of the products of each variable x and its corresponding demand $\mu(s_i)$ (data rate) for all BSs. The ILP formulation of OCS is

$$\max \sum_{b_j \in B, s_i \in S} \mu(s_i) \cdot x(b_j, s_i),$$

subject to constraints (1) - (4) and $x(b_j, s_i)$, $y(b_j, R_k) \in \{0,1\}$, $\forall s_i, b_j \in V$, and $R_k \in R$.

In the optimal solution, a variable $x(b_a, s_b)$ having value of 1 represents the source point s_b assigned to BS b_a. For example, if $x(b_1, s_1)=1$, $x(b_1, s_2)=0$, and $x(b_1, s_3)=1$, then s_1 and s_3 are assigned to BS b_1 whereas s_2 is not. Range variable $y(b_c, R_d)$ having a value of 1 in the optimal solution where R_d is the largest determines the optimal range of BS b_c. For example, if $y(b_1, 3)=1$, $y(b_1, 4)=1$, and $y(b_1, 5) = 0$, then the optimal cell size of BS b_1 is 4.

In this scheme, all mobile nodes are assumed to use a fixed short transmission range except the last-hop nodes, e.g., nodes A, B, D, G, H, J, and K in Fig. 2, that are within the communication range of the BS. The nodes can communicate at a flexible range as large as the BS range. Using a fixed transmission range for general mobile nodes helps simplify the relay architecture whereas using short transmission range helps reduce transmission power and, hence, the interference.

Directional antennas are assumed to help reduce the fading and interference among nodes. Short range multi-hop relaying helps alleviate dead spots where strong shadowing occurs. Note that OCS is not a power control scheme and once OCS computed the optimal cell sizes, an effective power control mechanism is assumed to maintain the cell sizes until the traffic pattern or network topology is changed. The change triggers the cell size computation and adjustment process. The mechanism for this function is the subject of future work.

IV. PERFORMANCE EVALUATION

We quantify the performance gain of OCS with respect to a small cell size multi-hop (SCS) case and a general large cell size single-hop case. The settings of SCS are the same as OCS except that the cell size of SCS is small and fixed.

A. Simulation Model and Parameters

Our simulation model is a 3-Cell model (see Fig. 4). Each cell has 25 source nodes and a number of relaying nodes varying from 0 to 160 in increments of 40. The source nodes and relaying nodes are uniformly distributed over a circular area with a radius of 1.1 km centered at each BS. The role of source node and relaying node are separated so that the case of no mobile nodes willing to relay signals can be captured.

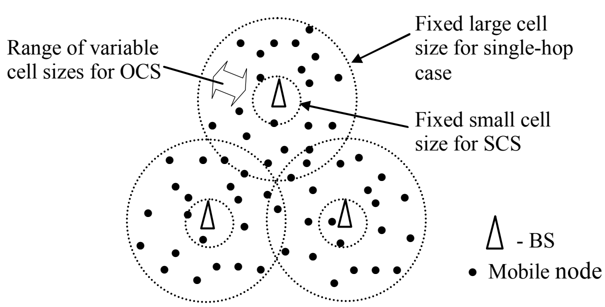

Figure 4. 3-Cell model

In this model, we vary the number of relaying nodes to model different nodal densities, traffic patterns and network topologies. Table II shows the simulation parameters. The cell ranges for SCS and the single-hop case are 250m and 1.1 km, respectively. For OCS, the cell size ranges from 250m to 1.1 km. The capacities corresponding to ranges are shown in Table III. The values in the table are obtained by using the approximated capacity function $U(R)$ in Sub-section II.*B*. We scale down the capacity values by a factor of 9.5 to reduce the simulation time. Since our interest is in the relative throughput gain of OCS as compared to that of SCS, the absolute value is less significant in this case. For both OCS and SCS case, the communication range of the mobile nodes is fixed at 250m with a capacity of 1035 kbps unless they are the last-hop nodes. Each data transmission frame is 10ms long and consists of 15 time-slots [3]. Each time-slot can be assigned at most 5 codes and each code corresponds to a data rate of 13.8 kbps [3]. Each call uses three slots and one code per slot at a constant bit rate. The duration of each call is 5 minutes. The maximum number of hops is set to 7 to avoid excessive delay. Each mobile node is equipped with a directional antenna with a 45° beam angle to increase the spatial reuse. The duration for the simulation is 5 minutes. The simulation is modeled with OPNET Modeler 10.0 [7]. The optimization package used is MOSEK version 5 [6].

The OPNET Modeler is used to generate the network topology. The distance graph is computed using the Euclidean shortest paths as relaying paths and is input to MOSEK to compute the optimal cell sizes and the connection assignment of each source point. The optimal cell sizes and connection assignments are transferred back to OPNET for the simulation to obtain the throughput and the other performance metrics.

TABLE II. SIMULATIONS PARAMETERS

	OCS	SCS	Single-hop
BS or last-hop mobile range	250 ~ 1100 m	250 m	1100 m
Mobile range	250 m		1100 m
Number of slots/ frame	15		
Data rate per code	13.8 kbps		
Call request rates	0.2 calls/min.		
Call holding time	5 min.		
Max. hop count	7		
Antenna	directional antenna with beam angle 45°		
Simulation duration	5 min.		

TABLE III. CAPACITY CORRESPONDING TO THE CELL RANGE

Range (m)	250	390	560	780	1100
Capacity (kbps)	1035	828	621	414	207
Capacity (codes/ slot)	5	4	3	2	1

In this simulation, our focus is to quantify the relative throughput between OCS and the other cases. We assume the mobile nodes to be static (or with limited mobility). High mobility may cause frequent disconnections and may require updating of the paths by routing and the cell sizes by OCA. This increases the control overhead, but does not affect the optimality of OCA. We assume a heuristic channel assignment scheme from [11] for channel assignment. A channel represents by a time-slot and code pair. We assume perfect power control so that the cell capacity function remains unchanged during the simulation. We also assume perfect physical medium, and sufficient battery capacity of mobile nodes for relaying signals.

B. Performance Metrics

We use the following metrics to evaluate the performance of OCS, SCS, and the single-hop case.

Cell throughput – the number of packets received at BSs receives per second. ***Call acceptance ratio*** (*AR*) – the ratio between the number of accepted calls and the total number of calls. High throughput and/or high call acceptance ratio represents a good cell size that balances the cell capacity and network reachability to maximize the demands being served.

Cell size – the communication range of the BS. Large cell size increases the network reachability, but reduces the cell capacity and vice versa.

Packet delay - the time required for a packet sent from the source node to reach the BS. Low packet delay represents the effectiveness of the channel assignment scheme.

C. Simulation Results

Considering Figures 5, 6, and 7, we observe that when the number of relaying nodes (*RNs*) is zero, the OCS and SCS cases are reduced to a single-hop case. For the SCS case, many source nodes cannot reach the BS to use the available cell capacity because the cell size is small (low network reachability). Therefore, the cell (or BS) throughput and the call acceptance ratio (*AR*) are low. For the large cell size single-hop case, although the cell size is large (high network reachability), the cell capacity is too small to meet the demand. Thus, the throughput and the *AR* are also low. For the OCS case, the cell sizes are adjusted to 780m to maximize the demands that can be

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served. The single-hop case has higher throughput and *AR* than that of SCS because it has a better combination of coverage and capacity than that of SCS.

As the number of *RN*s increases, more source nodes can reach the BS through multi-hop relaying. Thus, the throughput and *AR* of both OCS and SCS increases. Note that when the number of *RNs* approaches 40, the throughput of OCS only slightly increases. This is due to the combined effect of the high increase in packet delay and modest increase in *AR* as compared to the case of zero *RN* in which a considerable number of calls are already accepted. Thus, increasing the number of *RN*s to 40 does not have significant effect on *AR*.

When the number of *RN*s reaches 80, the network is medium dense. More nodes can reach the BSs which increase the reachable demand. Thus, in the OCS case, the cell sizes are adjusted to a smaller value to achieve a higher cell capacity to meet the increased reachable demand.

When the number of *RN*s reaches 120 and beyond, the network reachability is no longer an issue, but the capacity is because most source nodes can reach the BSs through relaying. OCS uses the same (small) cell size as that of SCS to achieve maximum capacity to serve the demands. Thus, both OCS and SCS achieve their highest throughput.

In Fig. 8, although the packet delay of both OCS and SCS cases is higher than that of the single-hop case because multi-hopping is involved, the delay is still considered to be low in a multi-hop environment. This is due to the effectiveness of the channel assignment scheme. Fig. 9 shows the delay-throughput characteristic of OCS and SCS which follows a general trend in multi-hopping situation.

We observe that OCS always achieves the highest throughput and *AR* because OCS always gives the optimal cell sizes for different nodal densities and traffic patterns and assigns the source nodes (points) optimally among the three BSs. Such characteristic makes OCS a useful planning aid in network planning process. In general, OCS has on average 167% throughput higher than that of SCS when the network density is sparse to medium (see Fig. 5).

V. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a scheme called Optimal Cell Size (OCS) to compute optimal cell sizes in a TDD W-CDMA MCN. OCS provides an optimal balance between cellular capacity and coverage that maximizes the system throughput. OCS can cope with dynamic network conditions and can also be considered as a network planning aid for cellular systems and MCN. Simulation results show that OCS has on average 167% throughput higher than that of the fixed small cell size (SCS) multi-hop case when the network is sparse and medium dense.

Investigating an effective power control mechanism to maintain the cell size and the cell capacity could be the future work. Another direction is devising heuristic techniques for finding cell size, especially in large systems where OCS could be computationally expensive.

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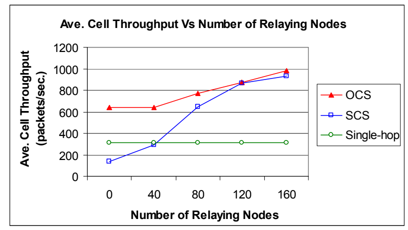

Figure 5. Average Cell Throughput

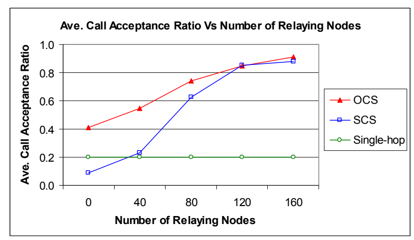

Figure 6. Average Call Acceptance Ratio

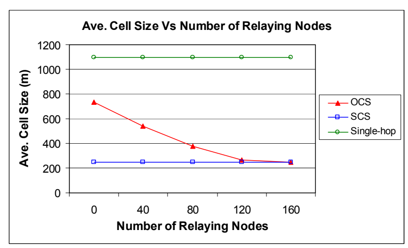

Figure 7. Average Cell Size

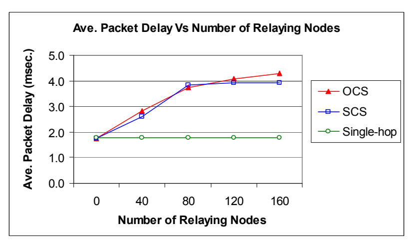

Figure 8. Average Packet Delay

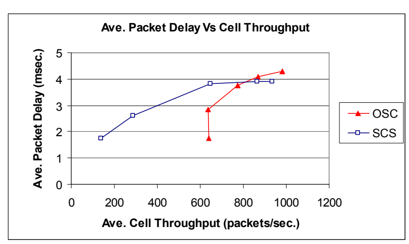

Figure 9. Packet Delay Versus Cell Throughput

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