CHAPTER 1: INTRODUCTION

Growing number of wireless users and high data rate multimedia applications with varying QoS requirements for 3G and beyond wireless systems, are demanding novel communication techniques and network architectures. Researchers are investigating various aspects of wireless systems to achieve this. This includes, but is not limited to signal processing, interference mitigation techniques, smart antennas, medium access control, wireless architectures, radio resource management, etc. The idea of exploring new wireless architectures other than the traditional cellular network is quite interesting. However, these new architectures will be appealing if they are flexible enough to integrate with the existing universally deployed cellular networks.

Multi-hop (MH) network is one such architecture in which relays are used to forward the traffic of the users having poor coverage to the base stations. The concept of multi-hopping or relaying is not new [1,2,5], and it is the basis of ad-hoc networks having an infrastructure-less architecture, i.e. no base stations or access points . However, the consideration of multi-hopping in infrastructure-based architectures like cellular networks has recently gained significant interest [1,5,17]. Traditionally, in cellular networks, coverage enhancement can be achieved in the following two ways.

- Installing more base stations in the network. Although this resolves the coverage problem to a great extent but still cannot guarantee connectivity to nodes under deep shadowing or in small coverage gaps. Moreover, this solution is expensive and may not be viable in low user density areas.

- Installing repeaters in low coverage regions in the network such as subways, tunnels, covered parking lots, etc [20,21]. Repeaters are inexpensive, but they simply boost all the received signals without intelligence, resulting in unnecessary high interference. In 2G wireless networks, built for voice communication only, such repeaters work fine. However, for 3G systems and beyond with voice, data and multimedia services with varying QoS requirements, such simple repeaters are not adequate.

Conversely, relays are intelligent units, which forward the signals of only those nodes that are in need of assistance (experiencing certain QoS degradation, such as inadequate SINR). The relaying can be performed by either separate fixed entities deployed at carefully selected locations in the network or by the user terminals themselves. The later is also termed as peer-to-peer relaying. In case of separate network entities, a relay's functional complexity is less than that of BS but more than that of ordinary node terminals. In peer-to-peer relaying, sometime also referred to as user cooperative relaying, users with viable SINR links to the base stations, apart from their own communication, support other users. The more the user density, the higher is the probability of finding good relays. Hence, enhanced coverage comes from the user nodes and not necessarily from the base stations as in traditional single-hop (SH) cellular network.

Another advantage of relaying is that it requires lower transmit power than that of direct node-BS links in traditional cellular networks for the same SINR. This is because multihop routes have short intermediate links to the destination, which leads to low path loss and as a result smaller transmit power is required to achieve the desired signal strength [10,11]. This results in reduced co-channel interference leading to increased system capacity and enhanced battery life. However, there are some concerns and issues associated with multi-hop communication such as complex routing and channel assignment schemes, large control signaling overhead, high latency, increased battery power consumption, sophisticated and thus costly user terminals, etc.

1.1 Thesis Motivation

Multihopping in traditional cellular network seems to be an interesting idea, especially if peer-to-peer relaying is employed. Peer-to-peer relaying means that no additional infrastructure is needed, and seamless integration with existing single-hop networks can be easily implemented, although it implies some added complexity on user terminals. It is attractive not only in terms of cost, but also for fast deployment time (software modification) especially in areas where infrastructure expansion is difficult to realize. Multihopping in peer-to-peer mobile cellular networks has shown significant improvement in coverage by providing connectivity to nodes in deep shadowing, near the edge or beyond the regular boundaries of a cell [4,12]. However, not enough research literature is available to establish concrete understanding of multi-hopping system performance. Moreover, some issues associated with mobility like handoff, Doppler's effect, fast channel estimation, adaptive routing, battery drain, etc., have raised concerns and debates on the viability of peer-to-peer relaying in mobile networks.

To address these concerns, it would be natural to study multi-hopping in fixed wireless network first, before considering it for mobile communication. Fixed wireless multi-hop networks are also referred to as Wireless Mesh Networks, where every node is connected to other node via a LOS or NLOS link and the network looks like a mesh. Mesh connectivity leads to a network with high coverage, route diversity, adaptability to changing environment, tolerance to link failures, and interference avoidance capability. Effective utilization of resources and network load balancing is easy to realize. Some investigation on mesh network in the LMDS band has shown high node throughput and spectral efficiency [3]. However, restriction of line of sight (LOS) is a prime implementation barrier. To assure this, extra relay units have to be installed, which in turn increases both upfront infrastructure and running cost. Based on the high potential of multi-hopping, mesh network provisioning is recommended by IEEE 802.16 committee on fixed broadband wireless access in 2-11 GHz band, in which LOS requirement is not a concern [8].

This thesis investigates and analyzes the performance of cellular mesh network in the framework of IEEE 802.16, but its analysis and findings are not necessarily limited to it. A cellular network in a start-up phase with low user density and poor coverage is considered. Peer-to-peer relaying is used whenever necessary to achieve connectivity. Multihop performance is evaluated in a high frequency reuse environment with no additional relaying channels. The performance of multihop network is compared with that of traditional single-hop cellular network using similar parameters for fair comparison.

1.2 Thesis Objectives

The main objectives of this research are:

1) To investigate the performance gains achieved by enabling peer-to-peer multihopping in TDMA based fixed cellular wireless network with poor single-hop coverage. Performance measures considered are outage probability, node throughput and spectral efficiency coverage.
2) To investigate the sensitivity of network performance measures outlined above to the number of frequency channels available in the network.
3) To analyze the reasons of performance improvement and constraints in single and multihop fixed cellular network.
4) To investigate the performance gains achieved by enabling peer-to-peer multihopping in a hostile environment with high frequency reuse and no separate relays and relaying channels.
5) To investigate and analyze the impact of increasing node offered load on the performance of single and multihop fixed cellular networks.
6) To investigate and analyze the impact of using multihop only when necessary on various performance measures of fixed cellular networks.
7) To investigate whether the multihop offered performance gain is bounded by relay density or channel resources.

8) To investigate the number of hops required to provide multihop connectivity when using the reserved policy of using *minimum number of hops route first*.

9) To investigate the impact of "free matching time slots" requirement in a TDMA based multihop network.

1.3 Relevant Literature

The potential of relaying to give performance improvements in ad-hoc network has created a lot of interest to explore its performance in cellular networks. A good overview of relaying in fixed and mobile cellular networks is available in [17], which identifies interesting research areas. A mathematical characterization of multihop wireless channel is presented in [13]. Analog and digital relaying is discussed. Analog relaying means that the signal received by the relay is amplified without processing to the intended destination. Hence both the signal and noise are amplified. Digital relaying refers to the decoding and re-encoding of the signal at the relay.

Multihop channels without and with diversity, and their mathematical characterization are discussed in [13, 14]. It was found that multihop with diversity always outperforms the multihop without diversity. Another work on multihop diversity is presented in [23]. Peer to peer relaying in HiperLAN/2 is considered to measure throughput using multihop and multihop chase diversity. Improved throughputs were achieved on both schemes, however, at the cost of increased energy requirements due to relaying.

An interesting study to measure coverage enhancement in mobile cellular network through peer-to-peer relaying is discussed in [4,18]. Adjacent cell channels were used for relaying, with and without power control. Relaying is found to give significant improvement in coverage in both cases. However if the cell size is big, power control may not help much. For small cell size, power control minimizes the co-channel interference and further contributes to coverage enhancement.

Impact of relay selection policy on the capacity enhancement of mobile cellular network is found in [19]. Random, semi-smart and smart relay selection schemes are discussed. It was found that there does not exist much difference in performance gains from each. Therefore the overheads and complex processing associated with semi-smart and smart selection schemes do not justify, and a simple relay selection scheme can give the similar gains.

The capability of relaying to aid in load balancing of a network is discussed in [15]. It was found that relaying effectively diverts the traffic of a highly loaded cell to the adjacent cells with less traffic. This not only improves the systems performance in general but also ensures effective utilization of resources.

Spatial diversity using neighbour user terminals in mobile cellular networks, also termed as user cooperative diversity is presented in [11,24]. The results show a significant improvement in node throughput due to reduced outage. Such user cooperative spatial diversity in mobile environment can cause battery drain and undesirable situation for the user, but the user mobility gives high spatial diversity advantages, especially under deep shadowing.

1.4 Thesis Organization

Chapter 2 describes the system model of the network considered in this study. Network architecture describes the cell type, frequency reuse and user nodes distribution. Source node, relay and relayee are defined. Then, resource management policies are discussed, and local and global resource allocation policies are defined. Antenna type and large scale path loss model considered are shown. Routing search algorithm is presented with an illustrating example. Slot assignment policy and issue of free matching slot is then explained with example. Finally, probabilistic characterization of network traffic is explained under the traffic model.

Chapter 3 presents a tabulation of various system parameters, their type and simulation values considered in this study. Simulation procedure is then briefly discussed followed by flow charts of the main simulation and call admission procedure.

Chapter 4 discusses the simulation results. Simulation results are categorized into three main sections: outage probability, node throughput and spectral efficiency coverage. Graphical results are presented along with detailed analysis of both single-hop and multihop results with respect to the number of frequency channels for each performance measure.

Chapter 5 provides a brief summary of the thesis and concluding remarks. The contributions of the thesis are highlighted. Later, a series of interesting future research topics are identified.

CHAPTER 2: SYSTEM MODEL

This chapter describes the system model used in the study. The entire system model is broadly classified into network architecture, propagation, routing, and traffic models. The network architecture model describes the network type, entities and resource management policy. The propagation model explains the path loss model, link types and related assumptions. The routing model describes the procedure used to develop the routing table, route selection policy, followed by the channel assignment procedure. The traffic model explains network traffic considered, and how burst arrival and size are probabilistically modeled.

2.1 Network Architecture

The network scenario considered in this study is shown in Figure 2.1. A cellular network is partitioned into four, square shaped cells with base station (BS) in the center of the cell and user nodes uniformly distributed throughout the network. Square shaped cells are considered for the purpose of simulation simplicity. A low node density, noise limited network representing a start up phase is considered. The network has poor single-hop coverage, mostly experienced by nodes at the edge of the cells or under deep shadowing. Most of the studies on multihop (MH) networks consider more than two network entities [3,5] such as base station, user node, access point, seed node, mesh insertion point, wireless router, etc. However, this study considers only two main entities typical of any cellular network, i.e. base station and user node. A normal user terminal acts as relay for other nodes, i.e. there are no separate relay entities in the network; hence no additional infrastructure is needed. This is also termed as peer-to-peer relaying. This leads to easy implementation and integration of multi-hopping feature through software algorithms and routing protocols. It will also ensure a fair comparison with a single-hop network (traditional cellular). The terminologies for network entities that will be used hereafter are defined as follows:

- ***Source Node***: The user node at which the data transmission is initiated.
- ***Relayee Node***: The user node in need of relaying assistance. It could be a source node or an intermediate relay node.
- ***Relay Node***: The user node, which apart from its own communication, is assisting other node(s) to forward traffic to the base station (as in 2-hop link), or to another relay node in the network (as in 3-hop link).
- ***Base Station***: The base station is primarily responsible for connecting nodes to the backbone, along with managing most control activities such as call admission, route and channel assignment, radio resource management, scheduling, power control, etc.

Single carrier channels are considered, while the employed multiple access technique is synchronous TDMA. Synchronous means that all node transmissions on the uplink are concurrent and slot synchronized. These transmissions could be from a node to another node or from a node to a base station. A node requesting service is assigned a unique frequency and time slot pair, and full channel bandwidth during the entire duration of the slot.

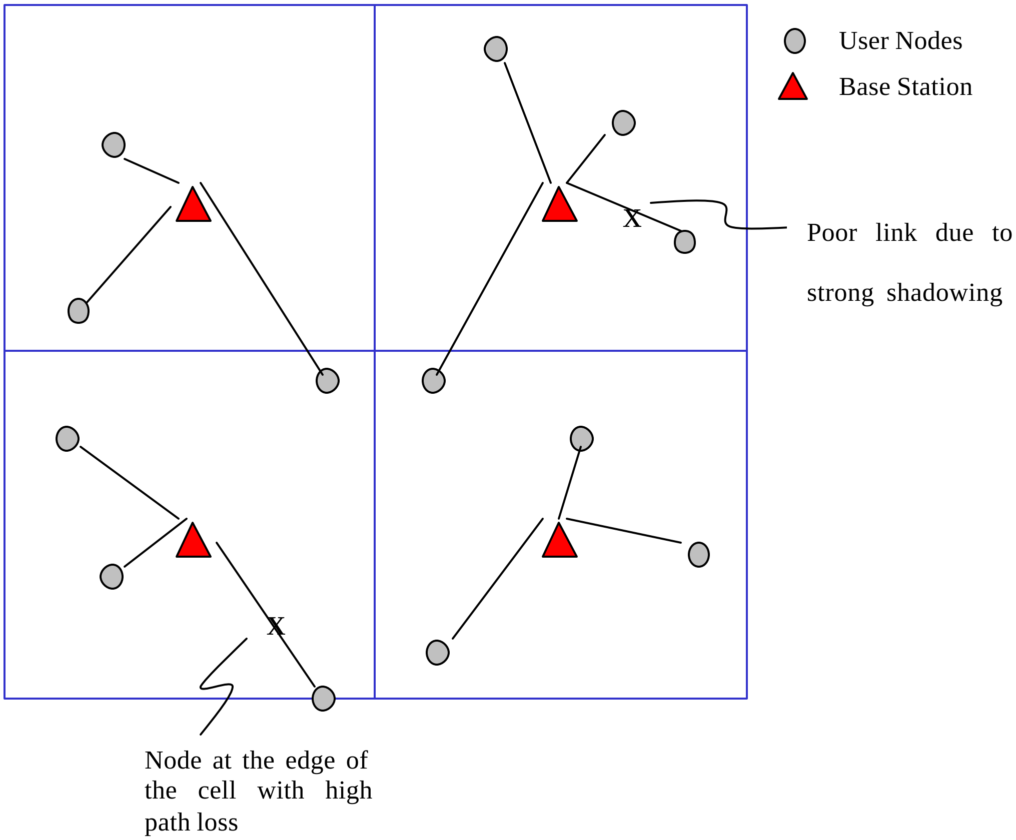

Figure 2.1. Cellular network under consideration, with user nodes uniformly distributed

Aggressive frequency reuse is considered, with all carriers used in all cells. This means no cell planning required and worst-case co-channel interference scenario considered. No separate relaying channels are used, i.e. same frequency channels are used for relaying as for regular single-hop communication with orthogonal time slots on two consecutive hops of a particular link. This will ensure a fair spectral comparison of cellular mesh network with traditional single-hop cellular network.

Network performance on the uplink or reverse link is analyzed. This is because, with expected broadband applications such as video conferencing, telemedicine and interactive remote training sessions, the uplink transmission will also require high data rates like downlinks and will meet quality of services (QoS) requirements. Moreover uplink performance analysis is considered relatively more complex than downlink, because of the distributed nature of traffic generation, multiple concurrent transmission and highly variable interference levels. Hence a proper study of the uplink will give deeper understanding of the impact of enabling multi-hopping on network performance, and will be equally applicable to the downlink.

2.2 Resource Management Scheme

The resource management scheme is used to manage and assign the spectral resources (channels or time slots), the transmitted power , the admission of new calls and access to the base stations. Since fixed transmit power is considered in this study, resource management here refers only to how the channel (time slots) are managed and allocated.

2.2.1 Local Resource Management

Local resource management means that a user node in a particular cell can only be serviced through its own (local) base station resources, and can only take relaying assistance from nodes in that cell only. This approach is simple to implement, process and manage, but may lead to non-optimum utilization of spectral resources (frequency channels). This is especially true in case of non-uniform distribution of nodes or unbalanced traffic in different regions of the network. Also, nodes at the edge of the cell may experience high outage due to poor link quality and unavailability of relay nodes in the same cell. Figure 2.2 illustrates a cellular mesh network with local resource management scenario. The solid line represents a viable direct link from node to the base station and the dotted line shows a viable node-to-node link. A link is considered viable based on certain criterion. This criterion could be a threshold value of path loss or signal to interference plus noise ratio, beyond which signal quality is unacceptable.

2.2.2 Global Resource Management

It means that a user node in a particular cell can be serviced through any base station in the network, and can take relaying assistance from any node in any cell. This approach is complex in terms of control information processing, implementation and management, but may lead to optimum utilization of spectral resources (frequency channels). This is also termed as resource pooling. With this type of resource allocation policy, nodes with coverage problem have much more opportunities to get a good single-hop or multihop link to one of the base stations, as shown in Figure 2.3.

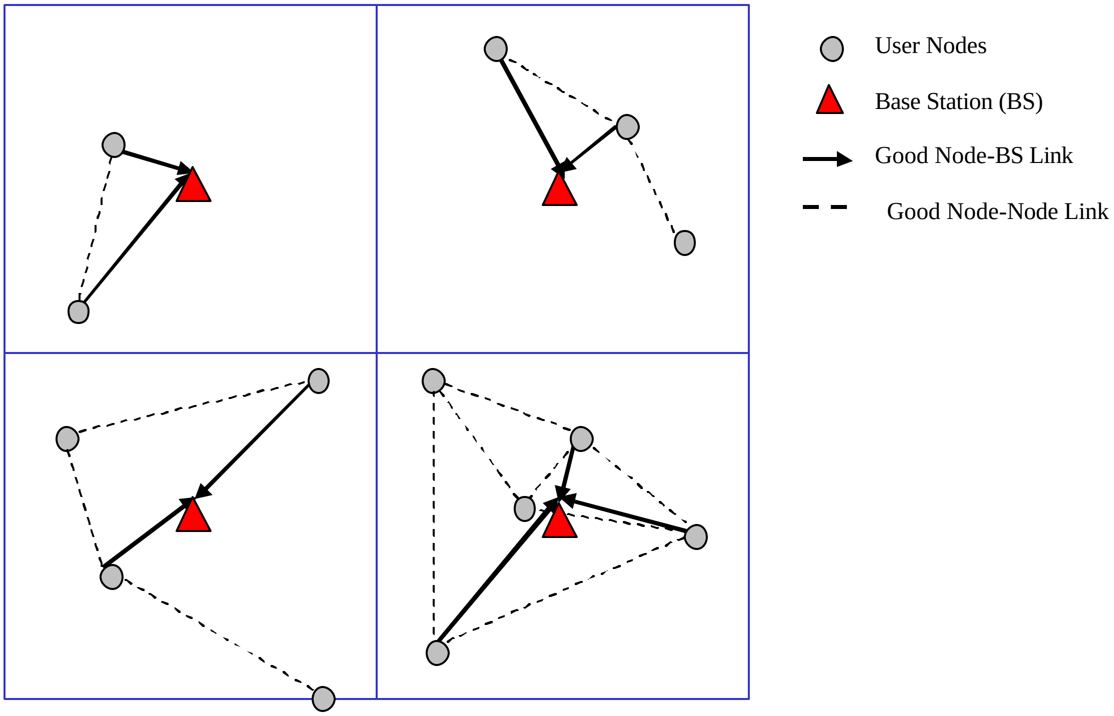

Figure 2.2. Connectivity in cellular mesh network with local resource allocation policy

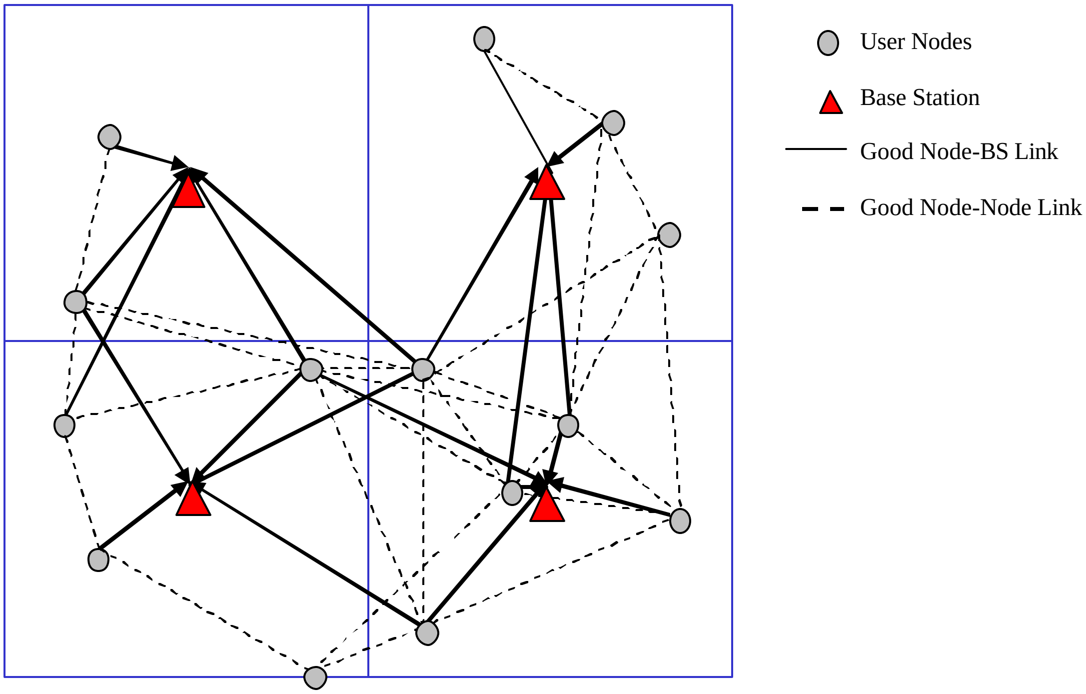

Figure 2.3 Connectivity in cellular mesh network with global resource allocation policy

In this study, global resource management policy is used, because we are considering a low node density network (hence low relay density) with poor single-hop coverage. Therefore, it is expected that many nodes will need relaying assistance. Multihopping will increase as traffic grows, not only because of more demand of resources (channels or time slots) from nodes not having initial single-hop coverage but also from nodes initially having good single-hop coverage but their SINR had degraded due to high frequency reuse in the network.

2.3 Antennas

Transmit and receive antennas at the user nodes and base stations are directional, switched beam type. The user end antennas are roof mounted. Since the user nodes are fixed, the location of each user is exactly known; hence with the use of switched beam, a node can exactly point its antenna beam towards the intended receiver or transmitter. In modeling, the main lobe gain is fixed throughout the antenna beam width. Similarly, the side and back lobes have identical gain.

2.4 Propagation Model

This study considers a suburban environment like a moderately dense residential area. The average signal power received at the base station or relay node can be represented by the following formula [6]

$$P_r = \frac{P_t G_t G_r}{PL} \qquad (2.1)$$

where

P_t = Transmit power

G_t = Transmit antenna gain

G_r = Receive antenna gain

PL = Path loss

If the transmit power, antenna gains and path loss are given in dB scale, then the average received power in dB can be represented as follows

$$P_r(dB) = P_t(dB)+G_t(dB)+G_r(dB)-PL(dB) \tag{2.2}$$

The large scale path loss (PL) considered in this study is based on the following log distance path loss model [6]

$$PL(dB) = 20\log\left(\frac{4pd_o}{l}\right) + 10n\log\left(\frac{d}{d_o}\right) + X_s \tag{2.3}$$

where

PL = Path loss

d_o = Reference distance

n = Propagation exponent for path loss

l = Wave length of frequency carrier

d = Distance between two nodes or node and base station

X_σ = Log normal shadowing with standard deviation of σ

The communication links are divided into two categories, a) node to node link and b) node to base station links. Since on node to node links, both transmitter and receiver antenna heights are low (although rooftop mounted), relatively higher path loss exponent is considered, compared to node to base station link. Independent and fixed lognormal shadowing is considered on each link with zero mean and different values of standard deviation for node-to-node links and node to BS links (relatively larger values for node to node link, for the same reason mentioned above).

Multipath fading is not considered in this study assuming that it is taken care of by micro diversity or some other means. It is expected, however, that due to the fixed position of the user nodes, the fading would be slow and temporally correlated [22]. Since the frequency channels are considered around 2.5 GHz., therefore communication is possible through both line of sight (LOS) and non line of sight (NLOS) links.

2.5 Noise Power

Additive white gaussian noise is considered. The noise power is calculated at the receiver using the following relationship [9]

$$P_n = kT_oB_cF_n \qquad (2.4)$$

where,

k = Boltzman's constant $1.38\text{x}10^{-23}$ Joules/Kelvin.

T_o = System temperature, 300^oK

B_c = Channel bandwidth

F_n = Thermal noise figure, 5 dB

2.6 Routing

For a source node to reach a base station using multi-hopping, it needs some specific route. Usually, there is more than one acceptable multi-hop route for any node base station pair. The criterion for link acceptance could be a certain path loss or SINR threshold value on all hops and/or a certain constraint on the maximum number of hops. Once the criterion is chosen then an iterative search using some appropriate routing algorithm can be applied to find the optimum route for transmission.

In this study, path loss is chosen as the cost function, rather than SINR since all user nodes are fixed and as a result the large scale path loss (log distance path loss + shadowing) is fixed on all links. Thus, we can develop a static multi-hop routing table for each node-BS pair. Routing tables need not to be updated frequently, and are modified only when new nodes join the network. In contrast to path loss, SINR is highly dynamic and varies from slot to slot, thus we will have to resort to on-the-spot iterative search if we use it as the cost for route selection. Pre-built routing tables can save lot of processing time required for on-the-spot iterative search for optimum available route. Moreover, we are doing burst level simulation, i.e. every new burst arrival at a certain source node may be assigned a different route based on the availability; therefore at high traffic loads, such on-the-spot iterative route search may not be an efficient solution and may lead to undesirable delays and large buffering.

Furthermore, with routing table, “route diversity” is always available at hand. Usually route diversity means that multiple routes are used to transmit copy of the same message, and combine them at the final destination using maximal ratio combining or some other method. In this study we did not use route diversity in this sense, but from the perspective that a routing table at hand itself gives readily available route diversity to choose from. In other words a survivable network is present, where failure of one route does not break the communication, and many alternates routes are available to keep the communication active.

A question arises at this point: why opt for an exhaustive search algorithm rather than any widely used fast converging algorithms such as Dijkastra's or Bellman-Ford to construct routing tables?. Actually during the course of our investigation, before choosing the exhaustive search procedure, we did try to modify the classical Bellman Ford algorithm to provide multiple 2-hop and 3-hop routes based on our criterion of *min{max(PLi)}*. It was found that, although these algorithms are efficient in providing the best route, they turned out to be not less complex than the exhaustive search when used to calculate multiple m-hop routes. However, more investigation can be done in this area, and if some solution already exists in the literature, it can be tested to compare the efficiency.

2.6.1 Algorithm for Route Table Construction

A simple search algorithm is used to develop the routing tables. Only 2 hop and 3 hop routing tables are developed for each node base station pair. The algorithm uses iterative sorting technique to arrange the routes, hence simple but exhaustive. The maximum path loss value beyond which a link is not considered for communication is termed as "path loss threshold" (PL_{th}). The criterion used in this study, for setting up (ordering) the multiple MH routes for any node-BS pair is:

$$R_s = \underset{\text{for } \forall\, a \in A}{min \arg} \{max\,(PL_i)\} \qquad (2.5)$$

where,

R_s = m-hop routing table (sorted)

PL_i = Path loss on the i^{th} hop, *i= 1,2 for 2-hop route, i=1,2,3 for 3-hop route*

A = Set of all possible *m-hop* routes

The routing table algorithm is summarized as below:

Step 1: Reject all node to node and node to base station links with $PL>PL_{th}$

Step 2: List all 2-hop and 3-hop routes between source node and base stations.

Step 3: Arrange in ascending order, the routes found in Step 2 using the criterion $min\{max(PL_i)\}$, where *i*=1,2 for 2-hop routes, and *i*=1,2,3 for 3-hop routes.

Step 4: If there is tie in $max(PL_i)$ value on multiple routes, then arrange those routes in ascending order of $min\{\Sigma PL_i\}$.

2.6.2 Example of Routes Search Algorithm

To clarify exactly how the routing algorithm works, consider the mesh network illustrated in Figure 2.4. Consider the threshold path loss value (PL_{th}) to be 120 dB. Let's say we are interested in finding the multiple routes from node#1 to the base station. As shown, the direct link from the node#1 to the base station is unusable because of high path loss. Next, the four steps algorithm is used to find all possible 2-hop and 3-hop routes from node#1 to the base station. According to Step 1, all links having path loss greater than 120 dB are discarded. Now, for 2-hop routes search, the step#2 is to list all possible two hop routes from node#1 to the base station, and identify the highest path loss link on each of those routes, as shown next.

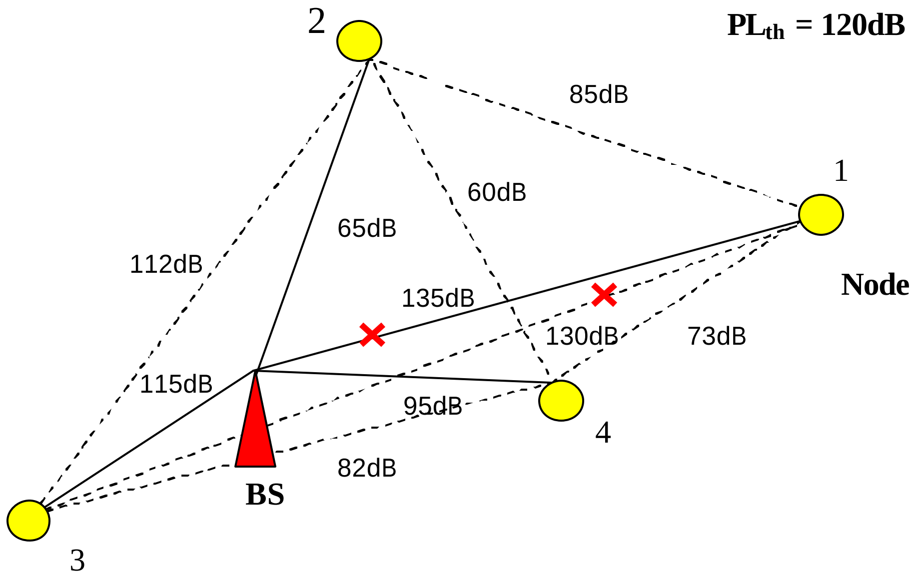

Figure 2.4 Example of mesh network considered for calculating the route tables

2-Hop Route	Link Path loss (dB)	
1 - 2 - BS	85	65
1 - 4 - BS	73	95

In step#3, the 2-hop routes are arranged in the order of $min\{max(PL_i)\}$, followed by step#4, which is not applicable in this case. The final 2-hop route table for node#1 is:

2-Hop Route	Link Path loss (dB)	
1 - 2 - BS	85	65
1 - 4 - BS	73	95

Similarly, the outcomes of step#2 to step#4 for 3-hop routes are shown below

Step #2:

3-Hops Routes	Link Path loss (dB)		
1 - 2 - 3 -BS	85	112	115
1 - 2 - 4 -BS	85	60	95
1 - 4 - 2 -BS	73	60	65
1 - 4 - 3 -BS	73	82	115

Step #3:

3-Hops Routes	Link Path loss (dB)		
1 - 4 - 2 -BS	73	60	65
1 - 2 - 4 -BS	85	60	95
1 - 2 - 3 -BS	85	112	115
1 - 4 - 3 -BS	73	82	115

Step #4:

3-Hops Routes	Link Path loss (dB)		
1 - 4 - 2 - BS	73	60	65
1 - 2 - 4 - BS	85	60	95
1 - 4 - 3 - BS	73	82	115
1 - 2 - 3 - BS	85	112	115

2.7 Route Selection Policy

Since high frequency reuse and fixed transmit power is considered; enabling aggressive multihopping in this scenario might lead to high co-channel interference. Based on this understanding, the used route selection policy is “minimum number of hops route first”. This means, first the source node looks for a single-hop connection to a base station with “matching” free slot and the achieved signal to interference plus noise ratio ($SINR_{ach}$) greater than or equal to the $SINR_{th}$ value. If a good single-hop connection is found, multihop routes are not evaluated, otherwise the source node explores all 2-hop routes in the routing table, followed by 3-hop routes; if even a 3-hop route is not found, the burst is denied service and outage occurs. If matching free slots are found on a particular route, these free slots are checked for the required $SINR_{th}$, if the received signal to interference plus noise ratio $SINR_r < SINR_{th}$ on any one link, this route is rejected and the next best route in the table is explored. Figure 2.5 shows an example of route selection using this policy. The $SINR_{th}$ considered is 4.5 dB. As illustrated, node 1 found two good SINR matching free slots on the base stations. Hence the node is assigned the best SINR route of 8.4 dB, although the source node has significantly higher SINR on the

2-hop and 3-hop routes. Some of the salient features of the minimum number of hops route first assignment policy are as follow:

- Less time slots used, meaning low hard blocking and outage.
- Links with at-least $SINR_{th}$ used. This simply means that the primary objective of this route selection scheme is to minimize the outage not to maximize the throughput.
- Algorithm simplicity.

2.8 Slot Assignment Policy

Whenever a node generates a data burst, it requests a time slot allocation from the base station(s). The base station(s) measures the received signal to interference and noise ratio ($SINR_r$) on its free time slots of all channels with respect to the source node. Consider a node *i* transmitting towards base station *j* on channel *f* during time slot *s*, then the signal to interference plus noise ratio achieved by node *i* at BS *j* represented by $SINR_{i,j}^{f,s}$ would be,

$$SINR_{i,j}^{f,s} = \frac{G_{ij} P_i^{f,s}}{P_n + \sum_{\substack{k=1 \\ k \neq i}}^{K^{f,s}} G_{kj} P_k^{f,s}} \tag{2.6}$$

where

G_{ij} = Path gain on the link between node *i* and base station *j*, this path gain includes the effect of transmit and receive antenna gains also.

$P_i^{f,s}$ = Transmit power of node *i* on slot *s* of channel *f*.

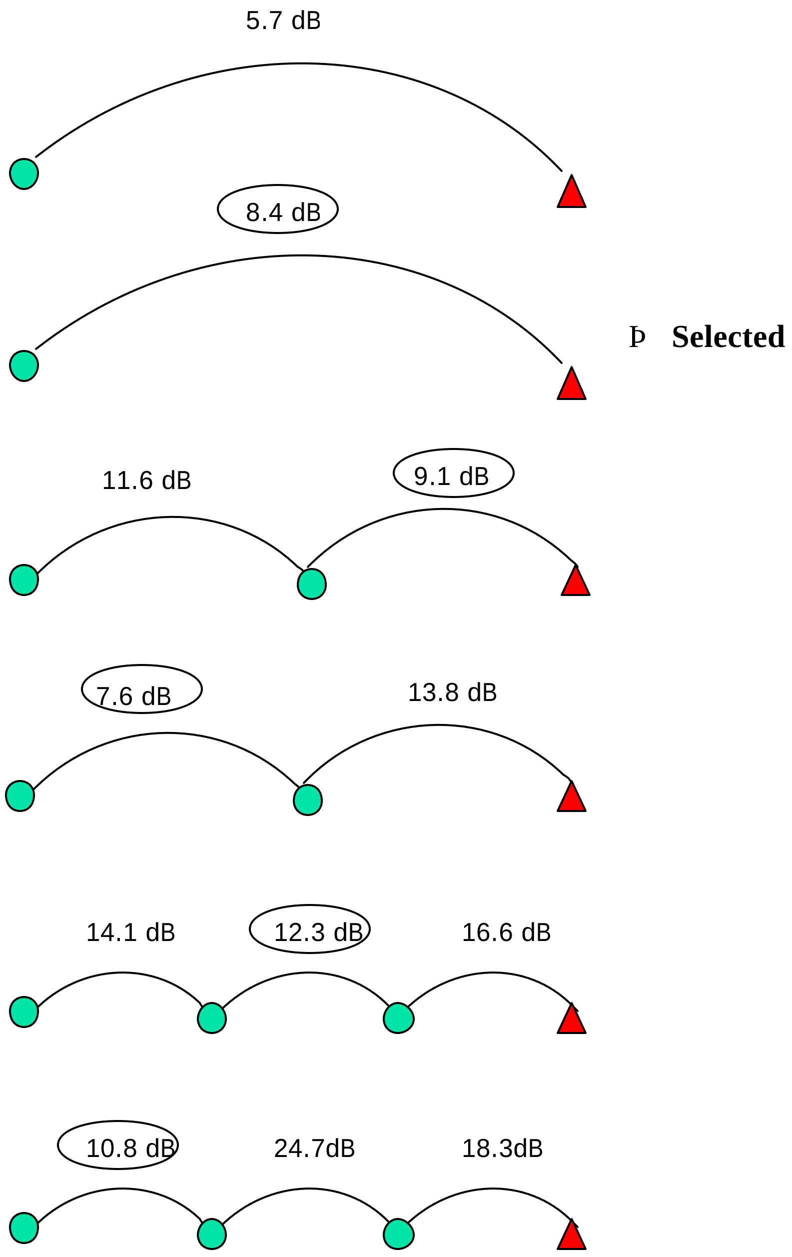

Figure 2.5 Example of minimum number of hops route first policy

P_n = Noise power

$K^{f,s}$ = Total number of other nodes transmitting on channel f during time slot s

$P_k^{f,s}$ = Transmit power of node k on slot s of channel f

If $SINR_r$ on free slot(s) is greater than $SINR_{th}$, then a suitable route (SH or MH) is assigned to the source node for that particular burst session. Once a route is chosen, the free slot with best SINR is allocated on each hop.

2.8.1 Issue of Free Matching Time slots

An associated constraint introduced by multi-hopping in TDMA based system found during modeling is the need of "matching" free time slots rather than just free time slots for any connection. In traditional single-hop TDMA, a node gets connected to the base station on any free time slot, provided it has the required *SINR*, while in multi-hopping, this constraint is due to the reservation of time slots on relay node by a relayee node. It is even worse when frequency channels are few and/or there are few good relays to the base station, and all nodes with poor coverage are trying to access the base station through one of those few relays. This might lead to the rejection of many good possible connections and can even lead to burst blockage.

The issue of matching free slot is illustrated through an example shown in Figure 2.6. As can be ascertained, node 4 has a good link to the base station(s), hence most of its slots are already occupied by other nodes to forward their traffic. The occupied and free slots shown in Figure 2.6 represent the current status on of the frequency channel. Now at

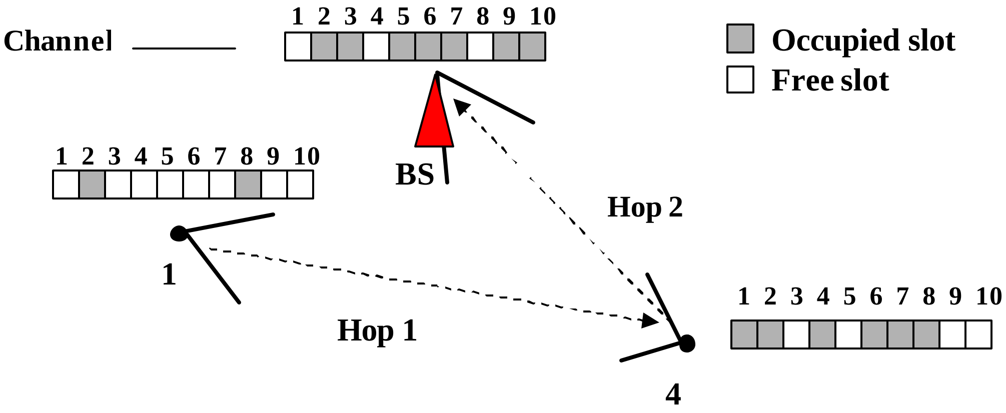

Figure 2.6 Example of free matching time slot issue

this point node 1 wants the support of node 4 to relay its traffic. As illustrated in Figure 2.6 and Table 2.1, there are free matching slots available on first hop between node 1 and node 4. However, on the second hop although the base station has free slots available, no matching free slots found between node 4 and base station. Hence node 1 request cannot be served and the call is blocked. A good resource management and scheduling scheme can overcome this problem to a large extent (although there are associated overheads), but its not accounted for in the system model for the sake of simplicity. Moreover, this is only a concern found during the system modeling phase, but its seriousness is not yet clear and need to be evaluated from the simulation results. Therefore in the simulation modeling, statistics regarding this issue is collected to see its impact on outage.

	1st Hop		**2nd Hop**	
	Node1	**Node4**	**Node4**	**BS**
Free Time slots	1,3,4,5,6,7,9,10	3,5,9,10	3,5,9,10	1,4,8
Matching free slots	3,5,9,10		Nil	
Rearrange slots in SINR descending order	9,5,3,10		Nil	
Select the first slot (best SINR slot) for this hop	9		Not Possible	

Table 2.1 Results of example on free matching time slot issue

2.9 Transmit Power and Modulation

The model considers fixed transmit power on all active links. This includes both node to node and node to base station links. Although this lead to higher co-channel interference levels, we exploited high P_t and good $SINR$ links using adaptive modulation and coding to achieve high node throughput. Different combinations of coded QPSK and M-QAM are used. If any link on a route has $SINR_{ach} < SINR_{th}$, then that frame will be dropped. Adaptive coding and modulation (ACM) is selected independently on each hop of the route based on the $SINR$ level. Mapping of adaptive coding and modulation with respect to $SINR$ is shown in Table 2.2*, and is based on Bit Interleaved Coded Modulation (BICM) [7], for BER=10^{-6}.

SINR(dB)	bps/Hz	Adaptive coding and modulation
> 26.0	6	1 - 64 QAM
21.94-26.0	5.25	7/8 - 64 QAM
19.0-21.94	4.5	¾ - 64 QAM
17.7-19.0	4	2/3 - 64 QAM
15.0-17.7	3.5	7/8 - 16 QAM
14.02-15.0	3	¾ - 16 QAM
12.0-14.02	2.67	2/3 - 16 QAM
10.93-12.0	2	½ - 16 QAM
7.45-10.93	1.5	¾ - QPSK
4.65-7.45	1	½ - QPSK
< 4.65	0	-

Table 2.2 Mapping of adaptive coding and modulation to SINR

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* This mapping is derived from the data provided by Dr. Sirikiat Ariyavisitakul by private communication.

2.10 Buffered Data Transmission

Buffered transmission on each link is considered. It is assumed that every node has enough buffer memory to accommodate its own data and that of its relayees. Although buffered data transmission has some associated issues of introducing more delay and hardware cost, it offers more benefit such as:

- Flexibility of independently choosing adaptive coding and modulation levels on each hop based on its SINR.
- Simple call admission control policy.
- Support of regenerative relaying.
- Effective utilization of available resources: time slots are released as the data transfer completes on a link, and are not occupied until the data is transferred from the source to destination as in the case of no buffered data transmission.

Each source node generates a data burst of certain size (kbits) based on the traffic model discussed in the next section. Once a route (SH or MH) is selected to serve this burst, each transmitter (source node and relays) on this route will transfer data by independently choosing a modulation and coding level based on the *SINR* on that particular hop. Transmission on each hop l continues until the whole data burst is transferred from the source to destination. Adaptive coding and modulation on each hop can differ from frame to frame due to change in interference levels. Track of all active burst sessions along with the size of data transmission in each hop are updated at the end of every frame. A fair allocation of time slot resources is done, by assigning one slot per frame to each hop of a route for a particular active burst session. This way more concurrent active sessions can be set up, which will be required at high traffic levels.

Buffered transmission allows simple call admission policy. Any new call, satisfying minimum of $SINR_{th}$ on all hops of a particular route is admitted. Contrary to this, no-buffered data transmission requires connection oriented service, therefore same SINR on all hops of a particular route has to be maintained to ensure smooth data transfer. The same is true about all currently active sessions. This can be done in two ways

- Implement a strict call admission policy, such that all those calls (or queued) whose admission may lead to degradation of SINR on any hop of all active routes are denied service.
- Use power control to maintain same SINR on the entire route, and this has to be ensured for all active sessions.

Furthermore, the use of digital relaying as considered in this study, requires buffering anyway, because received data has to be decoded, demodulated and re-encoded before transmission on the next hop. Hence, the use of buffered transmission naturally supports digital relaying.

Figure 2.7 illustrates an example of buffered data transferring on a 2-hop route. The time scale T1, T2, T3,… represents the start time of each frame. Adaptive modulation and coding on each hop is shown in the form of corresponding spectral

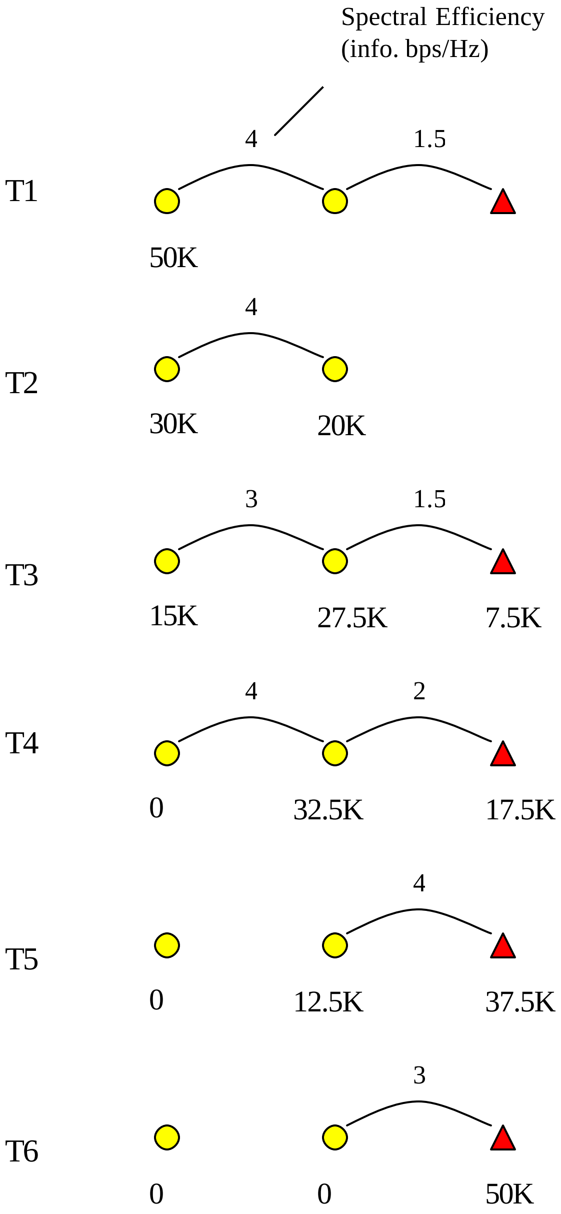


Figure 2.7 Example of buffered data transmission considered in the system model.

efficiency (information bits per second per hertz). Each hop is assigned one slot for transmission and it can accommodate 5000 symbols. A data burst of size 50 kbits is initiated from a node at time T1, and data is transferred on each hop frame by frame based on the spectral efficiency during the corresponding frame. As shown in Figure 2.7, the minimum SINR (in terms of spectral efficiency) on the route is the bottleneck in data throughput.

However, as each node complete its data transfer, it releases the resource (time slot) so that it can help other nodes needing relaying assistant. This is particularly important when good relays are few. The data transfer activity continues until the whole burst reached the base station.

2.11 Traffic Model

The user nodes are considered to be generating bursty traffic sessions, typical of http, ftp and some audio and video download applications. Single quality of service (non delay sensitive, same $SINR_{th}$) is considered for all bursts. The overall network traffic arrival follows a Poisson distribution with a mean arrival rate of λ burst per second. Burst size is exponentially distributed with a mean of μ kbits. Figure 2.8 illustrates how the burst arrivals are served. T_1, T_2, … represent the time units in multiple of frame duration (T_f). Burst requests B_1, B_2 and B_3 arrived during frame time T_1 get serviced at the start of next frame time T_2 if, successfully admitted. The service duration of a burst depends upon the size and SINR on the route.

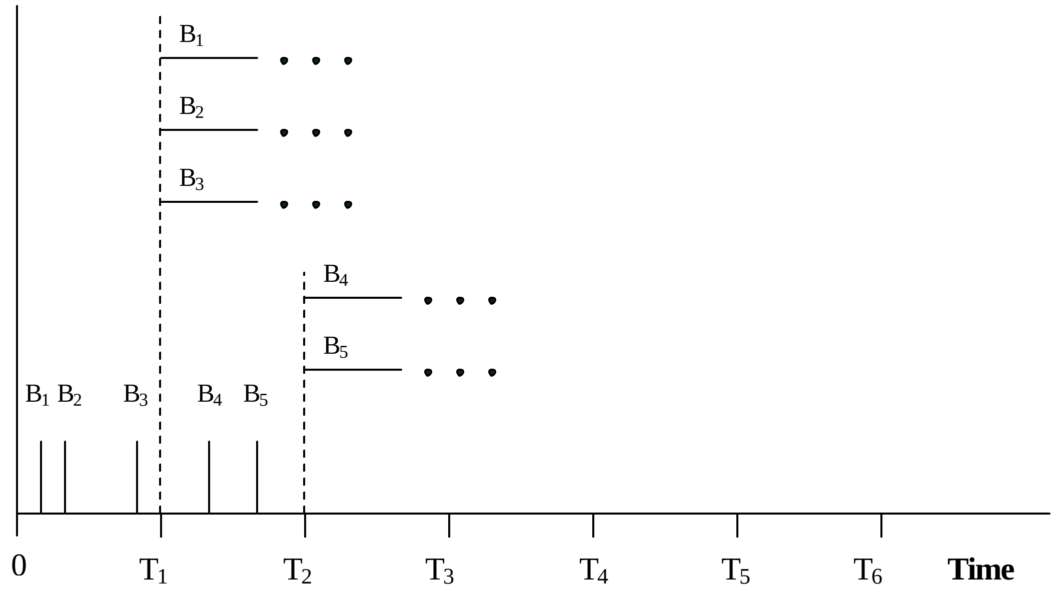


Figure 2.8 Illustration of burst arrival and start of service

CHAPTER 3: SIMULATION DESCRIPTION

This chapter describes the system simulation developed to analyze the performance of the mesh network discussed in the previous chapter. Section 3.1 includes a list of all system parameters, their types and chosen values used in this simulation. Section 3.2 highlights the major assumptions made in this simulation along with the reasoning and limitations of each. Finally, Section 3.3 briefly describes the simulation process and algorithms.

3.1 Simulation Parameters

System Parameter	Type	Simulation Value
Network Architecture	Cellular	- 4 square shaped cell, each 3x3 km^2. - 200 nodes uniformly distributed in the network.
Network Entities	Node & Base Station	
Carrier Frequency		Around 2.5 GHz.
Channels		No. of Channels = 2-6, with 5 MHz. each
Frequency reuse factor	No frequency planning	1
Noise Power	AWGN	Noise Power = -130 dBW (based on noise figure = 5 dB, & transmission bandwidth of 5 MHz)
Multiple Access	Synchronous TDMA	All node transmissions are slot synchronized
Link Analysis	Uplink or Reverse Link	
Transmit Power	Fixed	P_t = 2 watts
Path loss	- Exponential path loss	Node-BS links

	plus independent and fixed shadowing.	- Reference distance d_o = 10m - Propagation exponent n = 3.8 - Zero mean lognormal shadowing with σ = 4 dB <u>Node-Node links</u> - Reference distance d_o = 10m - Propagation Exponent n = 4 - Zero mean lognormal shadowing with σ = 6 dB
Antenna Type	- Roof top mounted -Directional switched beam at both BSs and nodes	- 30^o beam width - Main lobe gain = 7 dB - Side & back lobe gain = 0 dB
Relaying Channel	No separate relaying channels.	Zero
Maximum Permissible hops		3
Call Admission Policy	$SINR_{ach} \geq SINR_{th}$ on all hops.	$SINR_{th}$ = 4.65 dB
Max. Acceptable Path loss for Multihopping.	Propagation path loss + shadowing	PL_{max} = 126 dB
Node Buffer Size		Unlimited
Traffic Model	Bursty	- Burst arrival rate: Poisson distributed with mean λ=400-8400 burst/sec - Burst Size: Exponentially distributed with mean μ=15kbits.
Connection Type	Semi Connection Oriented	1 slot per frame on each hop is assigned on the complete connection.
Frame Specs	Fixed time slot duration	Frame duration=10ms No. of slots per frame=10
Service Types	One	- No of slot needed = 1 - $SINR_{th}$ = 4.65 dB - No delay constraint
Adaptive coding and modulation	Code rate & Modulation level mapped to SINR	Refer to Table 2.1 (Chapter 2)
Frame Error	$SINR_{ach} < SINR_{th}$ on any hop.	$SINR_{th}$ = 4.65 dB
Automatic Repeat Request (ARQ)	Continuous ARQ	- Upper limit on consecutive frame dropping before ARQ = 2 - Retransmit entire burst

3.2 Simulation Assumptions

- Snap shot processing at frame level: This means that call admission and release procedures, resource allocation decisions, SINR calculation, and statistics collection are carried out at the start of each frame only. Nothing is changing in between the frames.

- Frame transmissions are slot synchronized: This is applicable to frame transmissions from nodes (source node or relays(s)) to nodes as well as from nodes (or relay) to base stations. This assumption is necessary to make sure that co-channel interference and SINR are calculated properly. This is important for slot assignment decision and for right selection of the coding rate and modulation level.

- Independent & fixed shadowing on all links : Since node density is low, it is reasonable to assume that there is no spatial correlation between shadowing values at different nodes, on both node-node and node-BS links. Also, fixed shadowing is assumed based on the stationary nodes assumption.

- Negligible Doppler's shift: This assumption is valid due to stationary nodes.

- Micro-diversity is tackling multipath fading: Temporally correlated multipath fading is expected on each link, due to stationary nodes. However, multipath fading is not considered in the simulation. It is assumed to be taken care of by micro diversity or some other means, both on the nodes and base stations.

- Unlimited buffer capacity on each node: This is assumed for modeling and simulation simplicity. In addition, memory chips are pretty cheap to support this assumption.

- All nodes are active: This means that each node is generating the average node traffic under consideration. Moreover, the nodes have to be in always on condition irrespective of whether they are sending the data or not. This is to make sure that a node is available to serve as relay whenever needed. No power constraint is involved because of the fixed position of the node.

- Separate control channels are available: This is necessary to share information among nodes and between nodes & base stations (like ARQ acknowledgement, slot assignment/release information, adaptive coding and modulation level to be selected for the next transmission, start and end of the data transmission, etc.).

- Continuous ARQ: It means that a receiver (node or BS) sends the acknowledgement to the transmitter for every frame. This acknowledgment shows whether the frame was received in error or not.

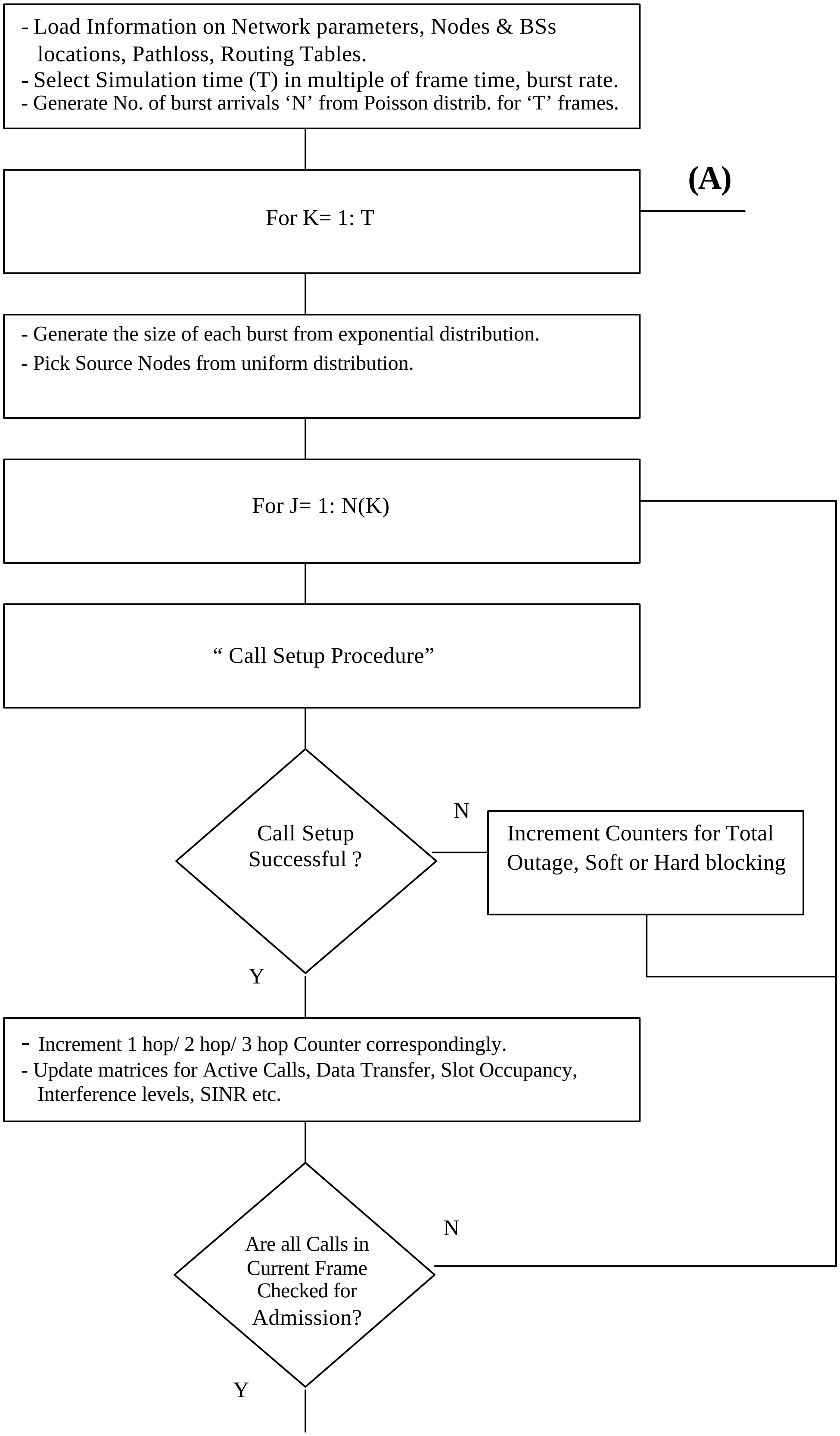
3.3 Simulation Algorithm and Flowcharts

A network level simulation was carried out to measure the performance of both single-hop and multihop fixed cellular network. This is a hybrid, time and event driven simulation. It is time driven in the sense that the simulation itself runs for a specified time in terms of multiple of frame duration. It is event driven in the sense that changes in the system (interference level, slot availability, etc.) and statistics collection depend upon the burst arrival & departure events. The burst arrival events are generated before the start of the simulation and are known a priori on the time scale. The burst departure event time is, however, unknown a priori, because it depends on various random variables such as burst size, node selection, node locations, SINR values, coding rate and modulation level, etc.

Routing tables from each node-BS(s) pair are developed before the start of the main simulation, and are called as needed. Due to the use of switched beam directional antennas, the interference experienced by nodes and base stations will depend on the directivity of each transmitter (source node or relay). Since nodes are stationary, it is possible to calculate accurately the receive antenna gains that each node and BS will experience, with respect to a specific transmitter receiver pair. Therefore, receive interference gain matrices are calculated prior to the start of the main simulation.

The entire simulation is conducted in the form of frame transmissions. Therefore, the simulation time scale is in multiples of frame time. All call arrivals in the network during the current frame transmission are processed and inducted at the start of the next frame. On the other hand, all call departures during the current frame are processed and resources released at the end of the current frame, before admitting new arrivals. Existing calls requiring re-routing due to high frame outage are processed before admitting new calls to ensure the connectivity of existing active calls. New call arrivals are assigned to source nodes using uniform distribution, while burst sizes corresponding to those calls are generated using exponential distribution. All these calls go through call admission procedure where their $\mathrm{SINR}_{\mathrm{ach}}$ are calculated. Those calls fulfilling the requirements of having $SINR_{ach}$ greater than $SINR_{th}$, and subject to the availability of channel resources (time slots) are assigned minimum number of hop route. Otherwise, the call will be blocked and will contribute to outage.

The data transfer on each established call continues on a frame to frame basis until the whole burst is transmitted. All frame transmissions are individually mapped to certain code rate and modulation level based on the predicted received SINR. This predicted SINR is based on some feedback from the base stations, as they have the knowledge of all accepted & released calls, call routes and link path loss. A frame received with $SINR_{ach}$ less than $SINR_{th}$,, is dropped by the receiver, and error acknowledgement is sent to either the transmitter or base station. Based on the count of these acknowledgements, a decision to re-route a call might be made in order to avoid further degradation of throughput. Samples of various spectral efficiency coverage and node throughput for each node are collected at the end of each frame time. The first 10% of the collected statistics are rejected to minimize the initial bias, and to make sure that steady state results are obtained.


- Load Information on Network parameters, Nodes & BSs locations, Pathloss, Routing Tables.
- Select Simulation time (T) in multiple of frame time, burst rate.
- Generate No. of burst arrivals 'N' from Poisson distrib. for 'T' frames.
For K= 1: T
(A)
- Generate the size of each burst from exponential distribution.
- Pick Source Nodes from uniform distribution.
For J= 1: N(K)
" Call Setup Procedure"
Call Setup Successful ?
N
Increment Counters for Total Outage, Soft or Hard blocking
Y
- Increment 1 hop/ 2 hop/ 3 hop Counter correspondingly.
- Update matrices for Active Calls, Data Transfer, Slot Occupancy, Interference levels, SINR etc.
Are all Calls in Current Frame Checked for Admission?
N
Y

Cont…

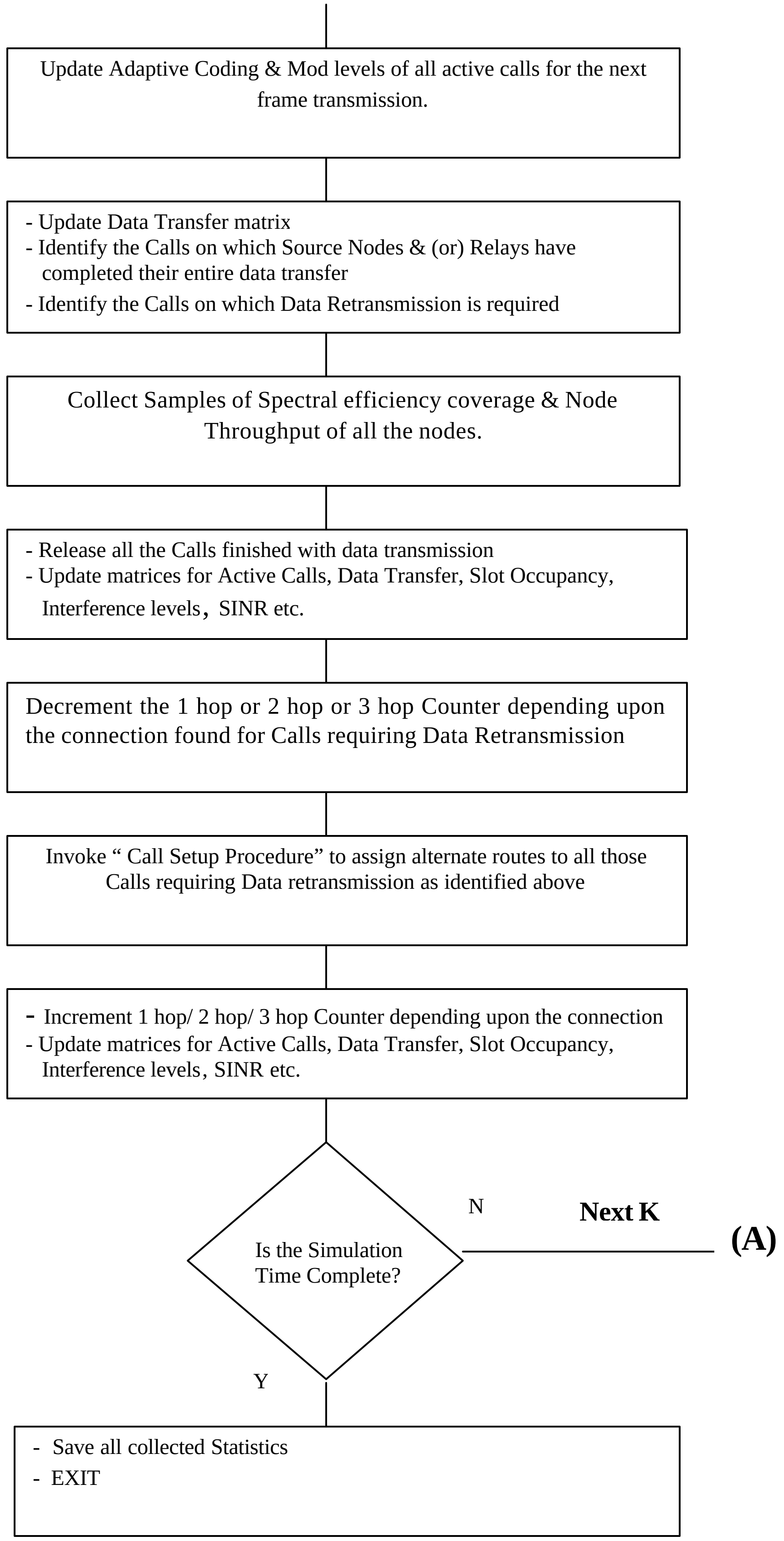


Figure 3.1 Flow chart for main simulation program

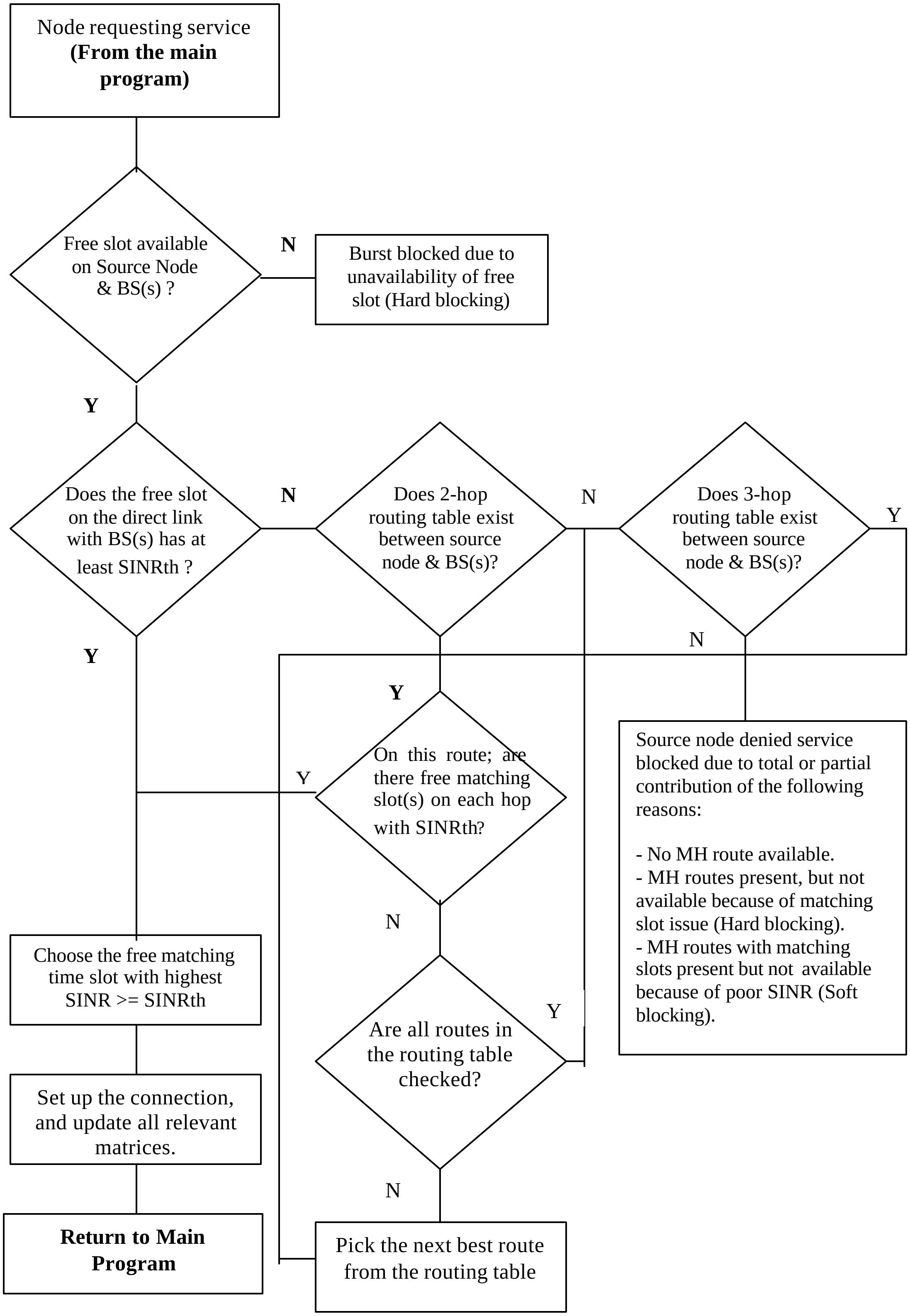


Figure 3.2 Flow chart for call admission procedure

CHAPTER 4: SIMULATION RESULTS AND ANALYSIS

In this chapter, the simulation results for the system model discussed in the previous chapter are presented and analyzed. Network performance results of both multihop and traditional single-hop network in a TDMA-based fixed cellular architecture are presented. These results are evaluated as a function of average generated node traffic or offered node load. Network performance measures of interest considered are: outage, net node throughput and spectral efficiency coverage. Sensitivity of these performance measures to the number of available frequency channels in the system is evaluated, which is one of the primary goals of this thesis.

The chapter is divided into three main sections based on the network performance measure analyzed. Section 1 contains the results and detail analysis of outage in single-hop and multihop network considered. The contribution of 2-hop and 3-hop connections in reducing outage in multihop network are also presented. Section 2 contains results and analysis of net node throughput, and how adaptive coding and modulation contributed to it. These are elaborated using results of mean node spectral efficiencies and burst readmission curves. Section 3 discusses the results of spectral efficiency coverage potential offered by multihop network compared to a similar traditional single-hop network. In each of these sections, first an overall performance comparison result of single-hop and multihop network as a function of available frequency channel is presented. Then detail analytical results are presented which shows the causes and constraints behind each one of them.

It is important to remember that all these results and discussion are limited to two main considerations. First, the single-hop network is pre-dominantly noise limited with poor coverage. Second, multihopping is used only when necessary, based on the route selection policy of minimum number of hops route first. Hence, the primary purpose of introducing multihopping here is to minimize the outage not to maximize the node throughput. High frequency reuse, and no separate relaying channels means high co-channel interference as multi-hopping increases. Moreover, since the cell size is large (with relatively large inter-node distances, noise and interference will dictate the SINR and not the desired signal power. Therefore, if some higher average node throughput is achieved, it will be an additional benefit.

Before starting discussion on the results, it will be appropriate to clarify the terminology "Generated Traffic Per Node" used as the independent variable to evaluate the results. It is assumed in the simulation that all the nodes are active and constantly generating traffic. Generated traffic can also be referred to as "offered load", and should be treated as synonyms, wherever they appear in this document. As discussed in Chapter 3, the nature of this generated traffic is bursty. The rate of generation of these bursts is directly proportional to the generated traffic per node. If one is interested in knowing the aggregate generated network traffic or offered network load at a certain instant, he needs to simply multiply the generated traffic per node by the number of nodes in the network. The use of generated traffic per node informs the service provider of the user nodes' performance as a function of the average offered load.

4.1 Outage Probability

In this study, outage is defined as the phenomenon that occurs when a requesting node is denied service from the base station(s). Thus outage is an aggregate effect of two major causes: poor coverage (inadequate SINR), and lack of frequency channel resources (time slots).

Poor coverage means node(s) has inadequate SINR to establish a communication link with the base station or other nodes. This type of outage is also referred to as "*soft blocking*". Inadequate SINR can be a combined effect of two or more factors such as, large distance path loss (for nodes at the edge of the cell), deep shadowing, upper constraint on transmit power, co-channel interference and noise power.

Lack of frequency channel resources (time slots) occurs, when a node requesting service has adequate SINR to establish a link, but is denied services because of the unavailability of time slots on the base station. This type of outage is also called "*hard blocking*".

4.1.1 Comparative Analysis of Outage in Single-hop and Multihop Network

Figure 4.1 shows a comparative analysis of outage in single-hop and multihop networks with respect to number of available frequency channels. Single-hop network due to the considered poor coverage, has consistently high outage (~38-40%) irrespective of generated node traffic and the number of available frequency channels. This means that if

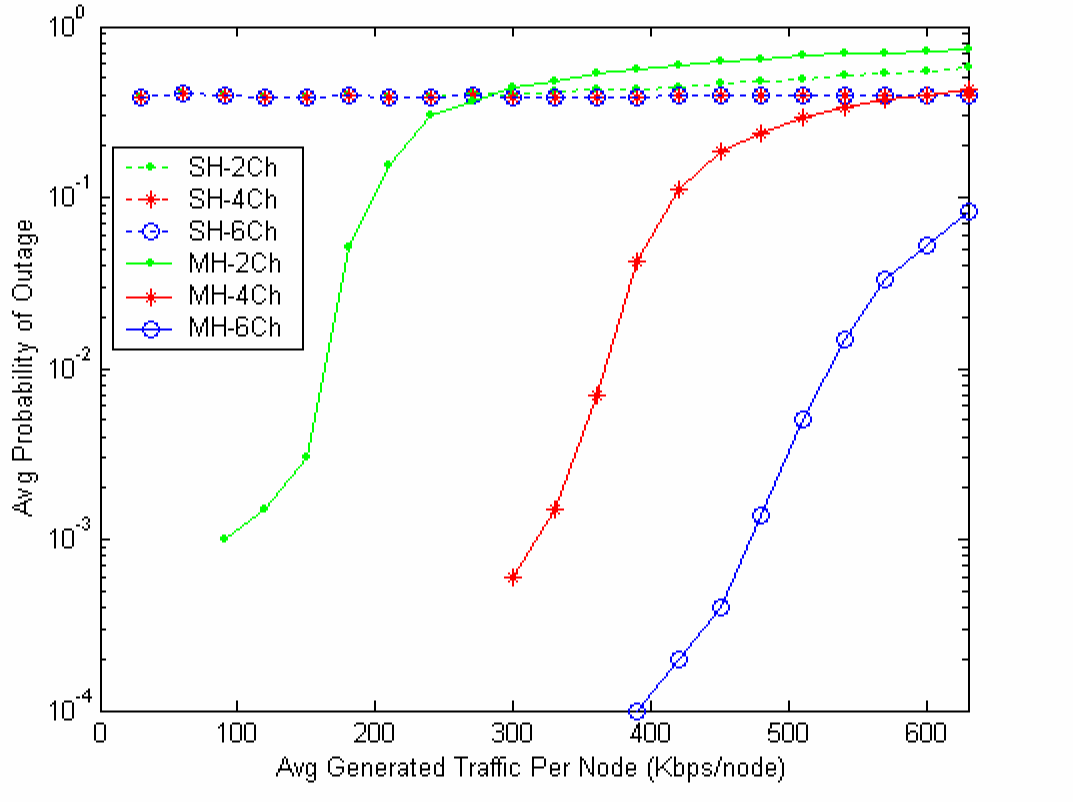


Figure 4.1 Average probability of outage in single-hop and multihop networks with 2, 4 and 6 frequency channels

some nodes do not have single-hop coverage to the base station(s), then no matter how much spectral resources (channels) are provided, they just cannot be served because of the poor coverage. This poor coverage is the cost of low upfront infrastructure (limited number of base stations). If frequency channels are few like in the case of 2 channels, then at high node traffic levels, the impact of limited channels (time slots) exhaustion or hard blocking also adds up, resulting in increased outage probability.

The strength of MH to provide high coverage is obvious from Figure 4.1. Even in the absence of separate relaying channels, no frequency planning and fixed transmit power; two to four orders of magnitude improvement (reduction) in outage probability is achieved, depending upon the number of available frequency channel and average generated traffic per node. As can be ascertained, if number of channels is increased to 4, low outage probability can be obtained for higher node traffic levels. Increasing the channels to 6, guarantees three to four order of magnitude improvement for light to medium node traffic levels, and almost 60-70% reduced outage at high traffic levels.

This simply shows that, the more the number of frequency channels available, the more profound are the improvement in outage from the use of multihopping. This is because, when more channels are available, the source node and relay(s) have more choices available to avoid high interference channels (time slots). Furthermore, using switched beam directional antennas, nodes can choose viable relays to find a MH route to the destination, thus ensuring high coverage and low outage probability.

4.1.2 Breakdown Analysis of Outage in Single-hop Network

The detailed outage analysis of single-hop network with respect to different number of frequency channels is shown in Figure 4.2 to Figure 4.4. The total outage phenomenon is broken into three major contributing factors:

- ***Poor coverage*** ($SINR_{ach} < SINR_{th}$) on all channels (and their time slots) of the base stations, irrespective of time slots are free or not – (Soft blocking).
- ***Unavailability of free time slots on the base stations*** **–** (Hard blocking).
- ***Poor $SINR_{ach}$ on the free time slots of the base stations*** **–** (Soft blocking).

Figure 4.2 shows the outage breakdown results for 2-channel single-hop network. Consistent 38-40% outage due to initial poor coverage exists throughout, irrespective of generated node traffic. Few channel resources (time slots) leads to hard blocking and starts contributing to total outage at medium node traffic levels. This hard blocking keeps growing as node traffic increases. This means an additional 2-15% outage over the range of this traffic level. The total outage is further increased by inter-cell co-channel interference due to frequency reuse of unity. Use of directional antennas minimizes this effect to a great extent, but still another 2-5% outage result from it, at medium to high traffic levels.

Figure 4.3 shows the outage breakdown analysis of single-hop network with 4 channels. With more frequency channels available, the impact of both unavailability of time slot resources (hard blocking) and inter-cell interference (due to more choice of interference avoidance) on outage probability almost vanishes over the entire range of generated traffic except slightly at high traffic level.

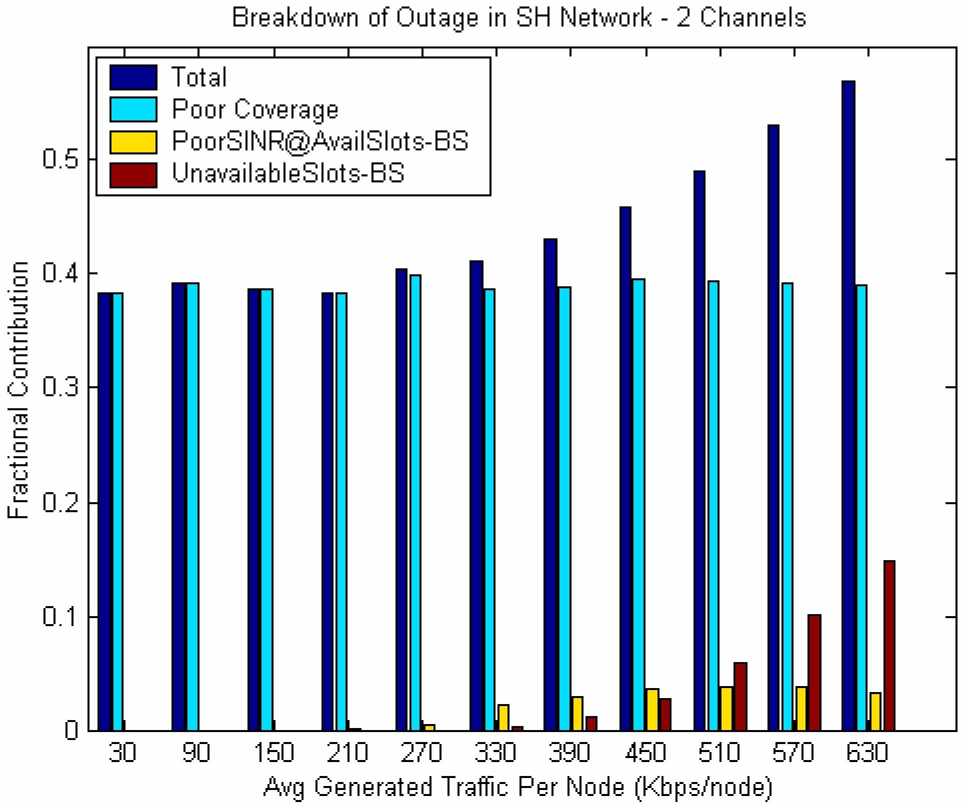


Figure 4.2 Contribution of different factors in outage probability of single-hop network with 2 channels

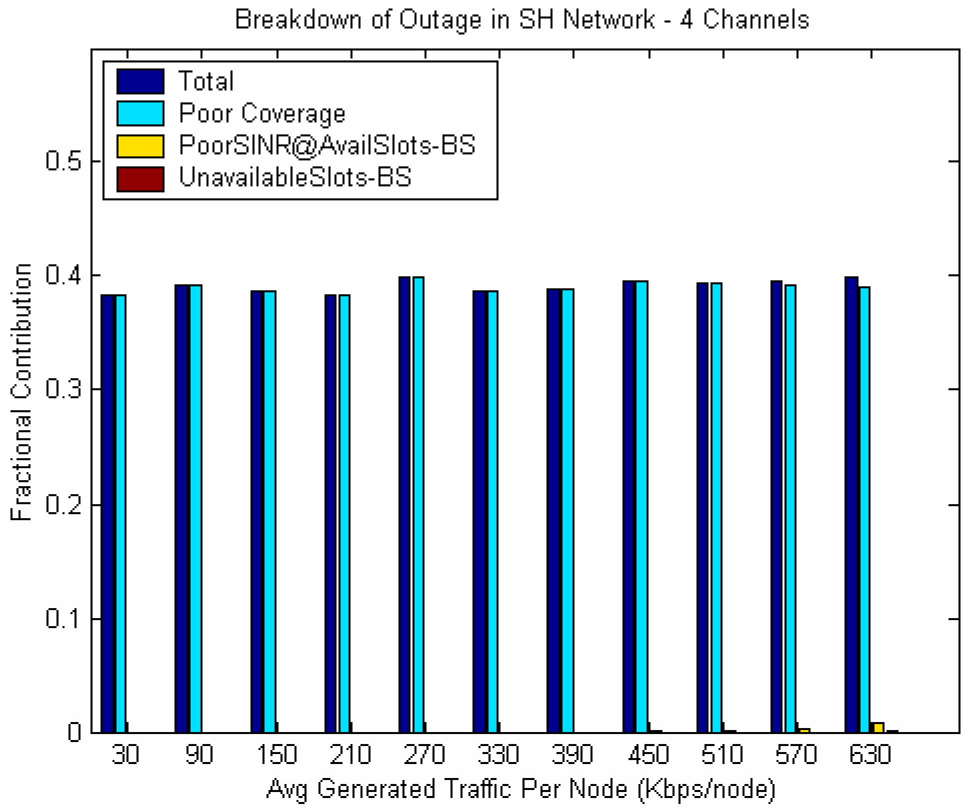


Figure 4.3 Contribution of different factors in outage probability of single-hop network with 4 channels

Figure 4.4 shows the breakdown analysis of outage in single-hop network with 6 channels, where now the network has enough spectral resources (channels, time slots) to accommodate the entire offered load from the nodes under the coverage region, and to avoid any significant co-channel interference. Thus the outage is now entirely due to nodes with initial poor coverage, and this is true over the entire range of offered load or node traffic.

4.1.3 Breakdown Analysis of Outage in Multihop Network

For detailed outage analysis in multihop network, statistics are collected to show contribution of the following three major factors in total outage.

- ***Unavailability of free time slots on base stations*** – (Hard blocking).
- ***Poor SINR on matching free slots*** on one or more hops of all available MH routes between a source node and base stations –(Soft blocking).
- ***Unavailability of matching free slots*** on one or more hops of all available MH routes between a source node and base stations – (Hard blocking).

Since semi-connection oriented connection with digital relaying is considered here, multihop connection requires larger service times (in terms of time slots occupancy) than single-hop connection, provided the minimum SINR on any hop of the MH route is equal to SINR on single-hop connection. This is because, if we can transfer some data using single-hop in one time slot, then a 2-hop transmission will require the base station time slot to be occupied for two frame times, one for the transmission of data from source node

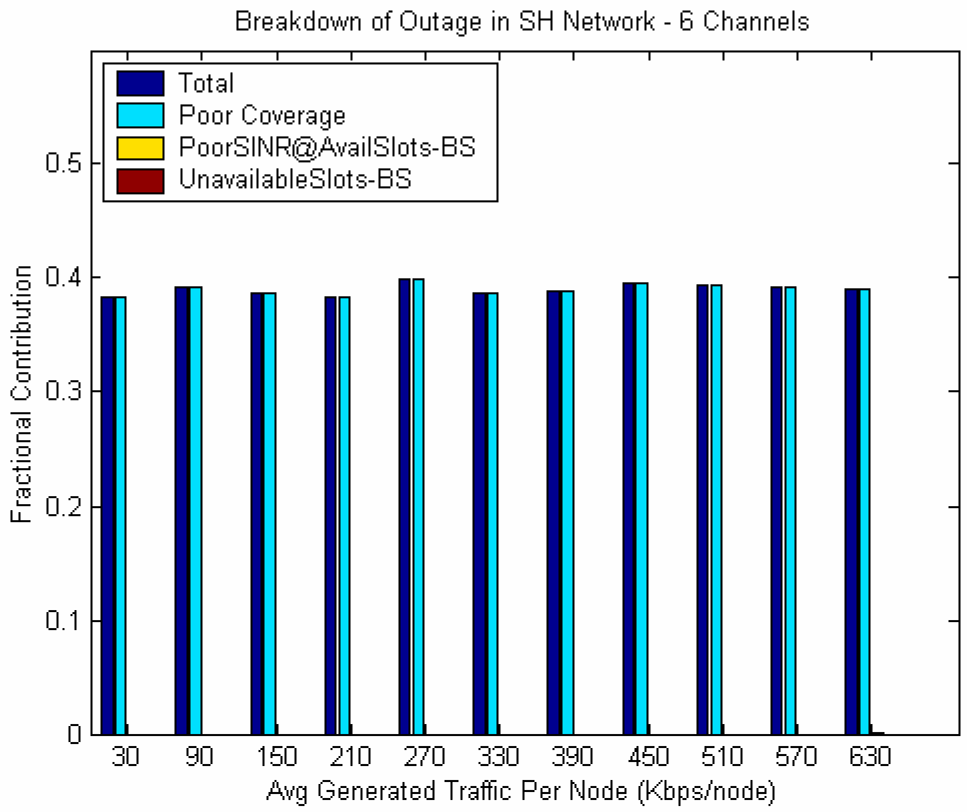


Figure 4.4 Contribution of different factors in outage probability of single-hop network with 6-channels

to relay (when BS slot is occupied but idle), and second for transmission from relay to BS (when BS slot is occupied and active). Initially the slots on both hops have to be reserved, until the data to be transmitted does not finishes on each transmitter on the route. As each transmitter has finished sending all its data, it will release its resources (time slots). Similarly a 3-hop connection will require a base station slot to be occupied for three frame times compared to corresponding single-hop connection, and an m-hop connection will require ‘m’ frame times.

At low traffic loads, this characteristic of multi-hopping does not matter much and coverage enhancement of multi-hopping overrides this and gives reduced outage. But at higher traffic loads, this issue becomes prominent, supplemented by higher co-channel interference levels (both inter-cell and intra-cell), and consequently lower SINR levels on the links (both because of frequency reuse and fixed P_t). This poor SINR further elongates the duration of time slot occupancy as data transfer takes more time. All these factors lead to higher outage.

This trend in MH network continues with the increase in network traffic load and if frequency channels are few like in the case of 2 channels, even cross over occurs, where single-hop and multi-hop outage converge. Further increase in node traffic leads to more outage in MH networks, making single-hop networks a better choice, as shown in Figure 4.1. However as more frequency channels are provided, the outage reduction obtained from multihopping is extended to higher traffic levels as clear from the curves of 4 channels and 6 channels in Figure 4.1.

The analysis of MH network presented in Figure 4.5 to Figure 4.7 verifies this explanation. The major factor behind outage in MH network is the lack of channel resources (time slots), and not poor SINR, irrespective of node traffic density. If frequency channels are few like 2-channels, then as shown in Figure 4.5, this will start showing up at lower traffic levels, and keep on growing as traffic load increases. The contribution of poor SINR on outage is relatively much smaller throughout because of the fact that every node has enough relays around it to choose from, such that high co-channel interference can be avoided to achieve at least the SINR required for communication.

As can be ascertained in Figure 4.5, the constraint of free matching time slots on a MH route (discussed in chapter 3), is negligible. This means that even in the adverse condition when only 2 channels are available, and a very low relay density is around, the issue of matching free time slots does not matter. Of course, as more channels (time slots) are available, and (or) relay density grows, chances are that this issue will become insignificant.

Figure 4.6 shows the outage breakdown for MH network with 4 channels. It is clear that as number of channel increases, the outage does not exist any more for light to medium offered loads. The outage is shifted towards higher traffic levels, and again the major contributing factor is resource limitation, for reasons already discussed. As expected from the discussion in the previous paragraph, the issue of matching time slots availability does not offer any impact on total outages.

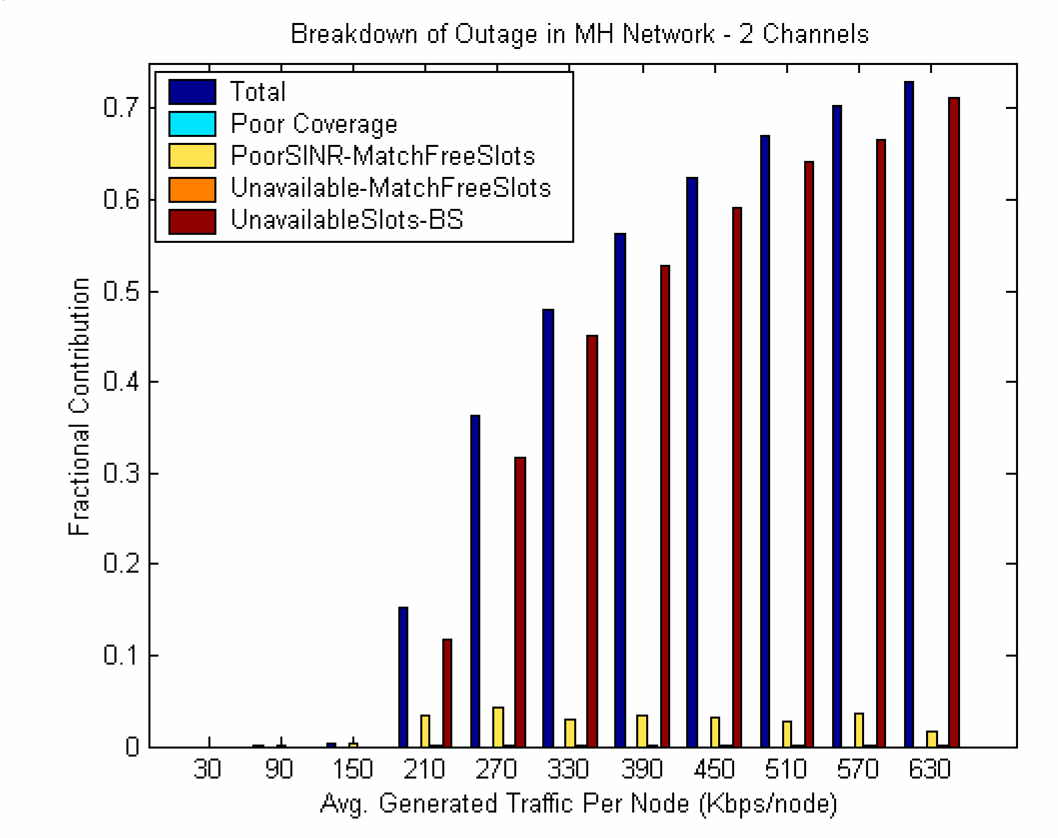


Figure 4.5 Contribution of different factors in outage probability of multihop network with 2 channels

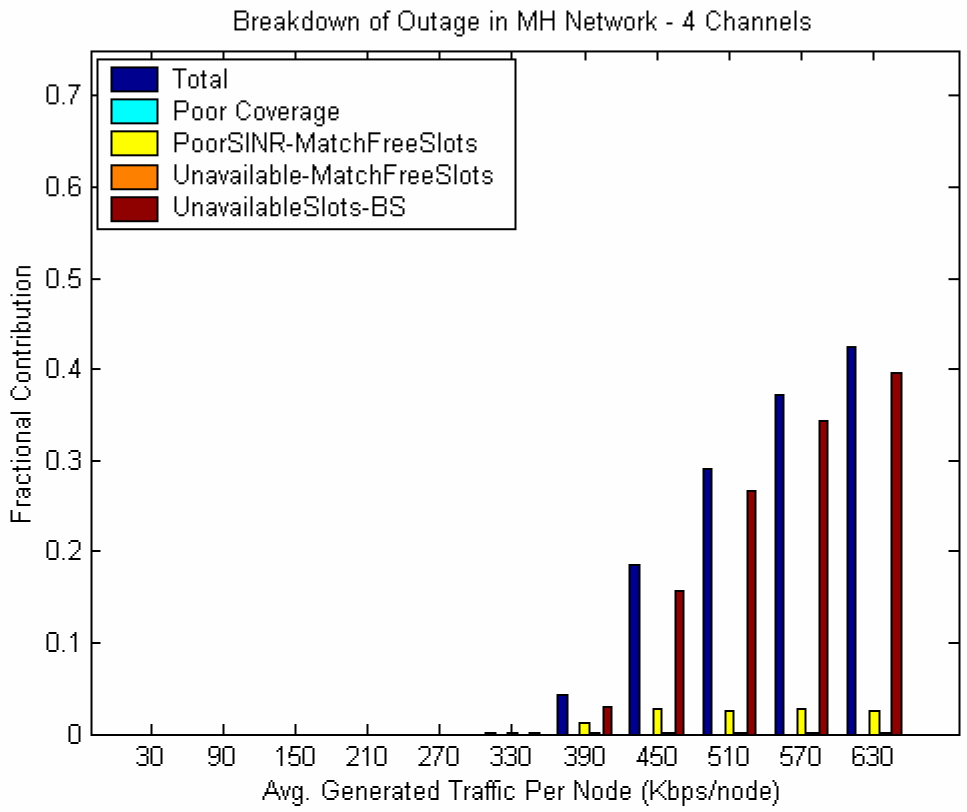


Figure 4.6 Contribution of different factors in outage probability of multihop network with 4 channels

As shown in Figure 4.7, further increasing the number of channels to 6 in MH network, eliminated the outage over the extended range of generated node traffic levels, except some at high traffic levels only, and that also primarily because of unavailability of time slots.

The above multihop outage analysis reveals an interesting finding. Even with a very low node density considered in this study (5.5 nodes/km^2), the outage due to unavailability of matching time slots on one or more hops of MH route is almost negligible irrespective of the number of frequency channels and generated node traffic load (ascertained in Figure 4.5 through Figure 4.7).

This simply means that there are enough relay nodes around every node, such that a node with poor coverage can always find a viable relay to forward its traffic. Thus the issue of matching time slots availability discussed in chapter 3 (System Model) does not ascertain to be a constraining issue, at least with the minimum number of hops route first assignment policy. This again is a proof of the immense potential present in multihopping to provide high coverage.

The contribution of single-hop, 2 hop and 3 hop routes in enhancing the connectivity is presented in this section. Figure 4.8 shows this contribution in multihop network for 2-channel case. At low traffic levels, the nodes with no single-hop connectivity are fully supported by 2-hop connections with sufficient SINR required for connection setup, and 3-hop connections are never needed.

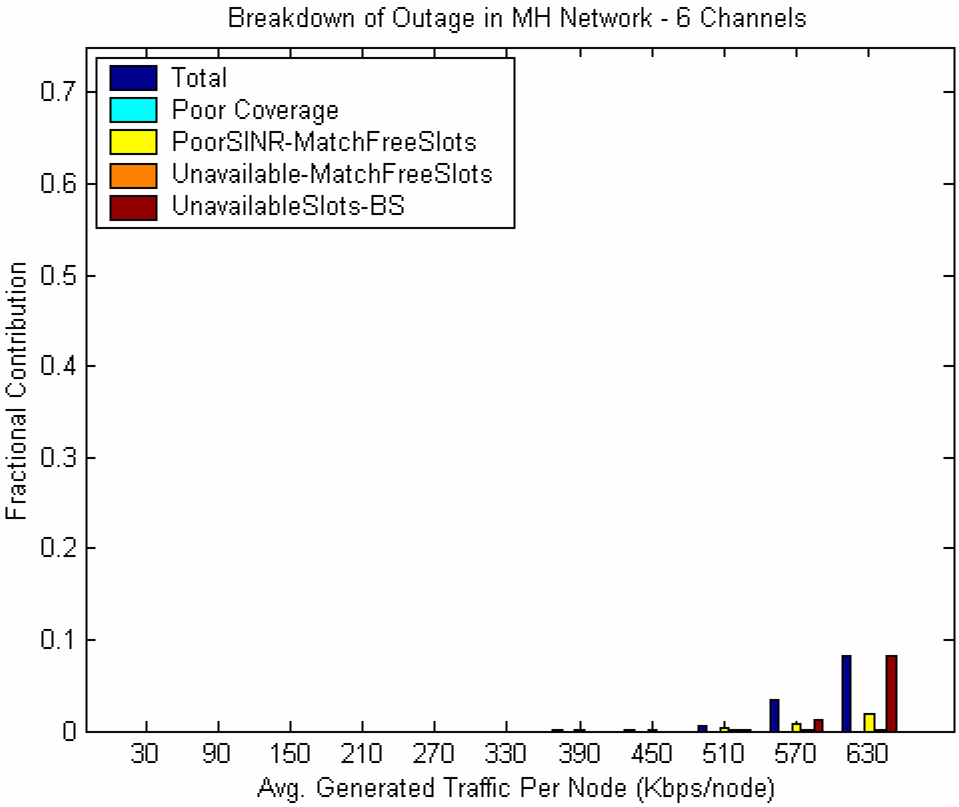


Figure 4.7 Contribution of different factors in outage probability of multihop network with 6 channels

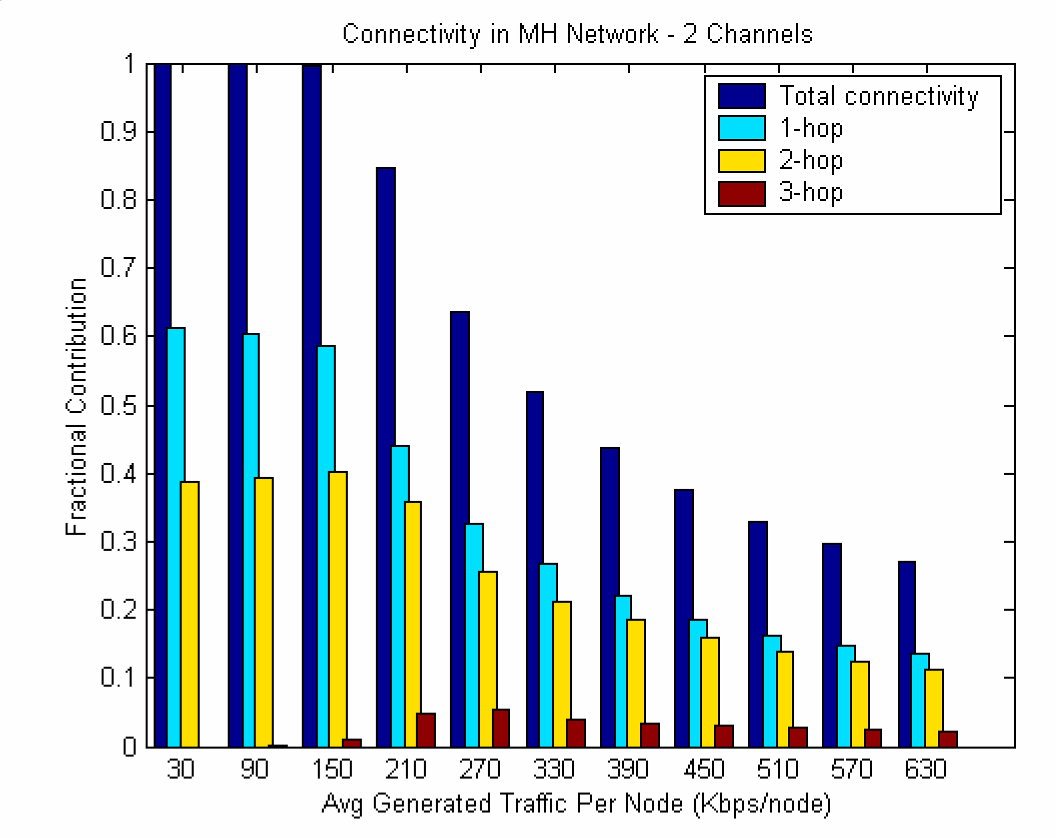


Figure 4.8 Contribution of m-hop connectivity in multihop network with 2 channels

As the traffic load increases, more concurrent 2-hop connections are active. Since no separate relaying channels are considered, this leads to higher inter-cell and intra-cell co-channel interference. This means new connection requesting for service will find it hard to get a 2-hop route with good SINR channels (time slots) on both hops, and they will start using 3-hop connection with shorter links and hence higher SINR.

Conversely, more 3-hop routes mean more co-channel interference and for longer durations (due to inherently longer service times associated with multihop connection discussed before). This leads to a chain reaction of higher co-channel interference to the extent that connectivity of MH network degrades beyond the similar single-hop network.

As the number of channels are increased to 4, chances of finding a 2-hop route with viable SINR channels (time slots) on both hops is extended to medium traffic levels, hence the need to switch to 3-hop connection is limited to high traffic levels, as shown in Figure 4.9.

As shown in Figure 4.10, increasing the number of channels to 6, almost eliminates the need for a 3-hop connection throughout the range of traffic levels considered. This simply means that a 2-hop route with viable SINR channels is almost always available.

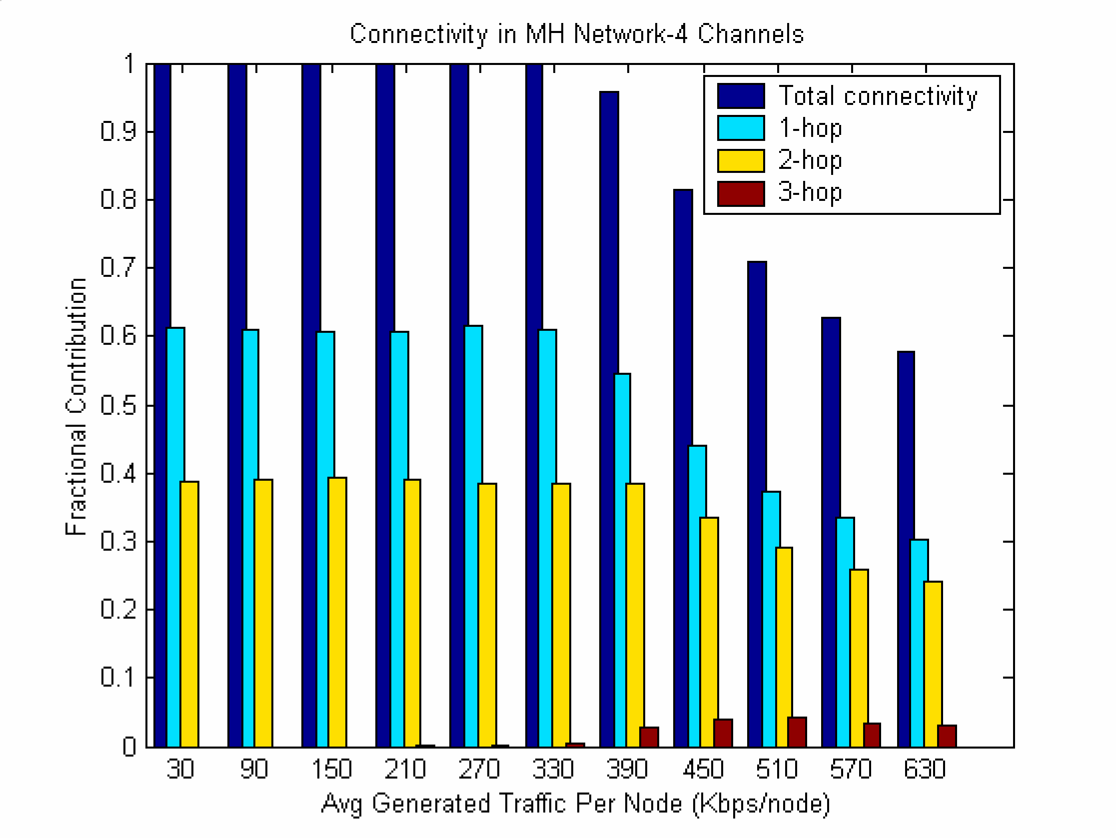


Figure 4.9 Contribution of m-hop connectivity in multihop network with 4 channels

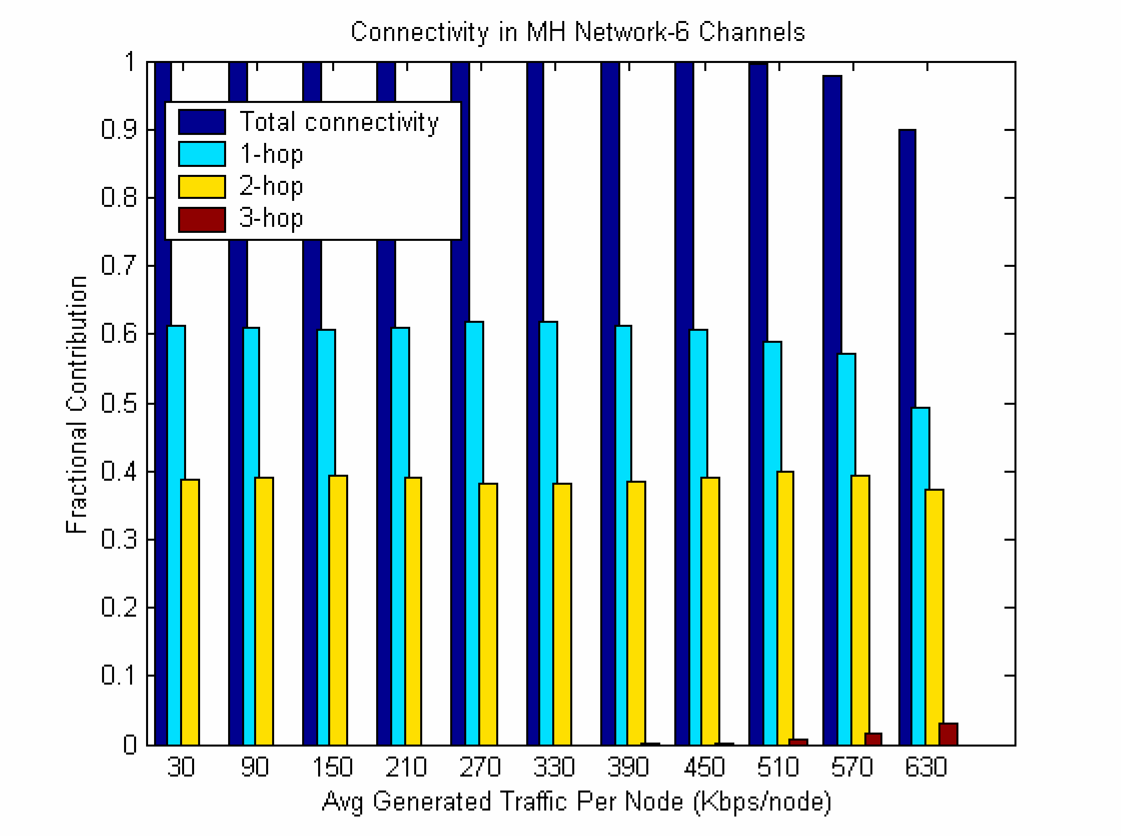


Figure 4.10 Contribution of m-hop connectivity in multihop network with 6 channels

4.2 Node Throughput

4.2.1 Comparative Analysis of Node Throughput in Single-hop and Multihop Networks

Figure 4.11 shows the comparative analysis of average net node throughput of single-hop and multihop networks with respect to an ideal network. In the ideal network, there are no constraints such as frequency channels, SINR, transmit power etc. Hence all the generated node traffic is supported and delivered to the destination. This means a linear relationship of unity slope exist between average generated node traffic and average net node throughput, as shown in Figure 4.11.

In SH network any traffic generated from poorly covered nodes is just not supported, irrespective of the number of available frequency channels. Hence a slope of approximately 0.62 (corresponding to SH coverage of 62% in this study) exists between average generated node traffic and average net node throughput, for light to medium traffic levels. The good SINR links are exploited using adaptive coding and modulation based on the Table 1, specified in Chapter 3 (System Model). As traffic grows, the impact of limited frequency channels and inter-cell co-channel interference comes into play resulting in degradation of mean spectral efficiency (bps/Hz) of the nodes as shown in Figure 4.12, and lower net node throughput shown in Figure 4.11. The use of directional antennas on both the user nodes and base stations minimizes the interference to a great extent, as observed from the results of outage in the previous section. Therefore, the impact of limited frequency channels in throughput degradation is more prominent than inter-cell interference.

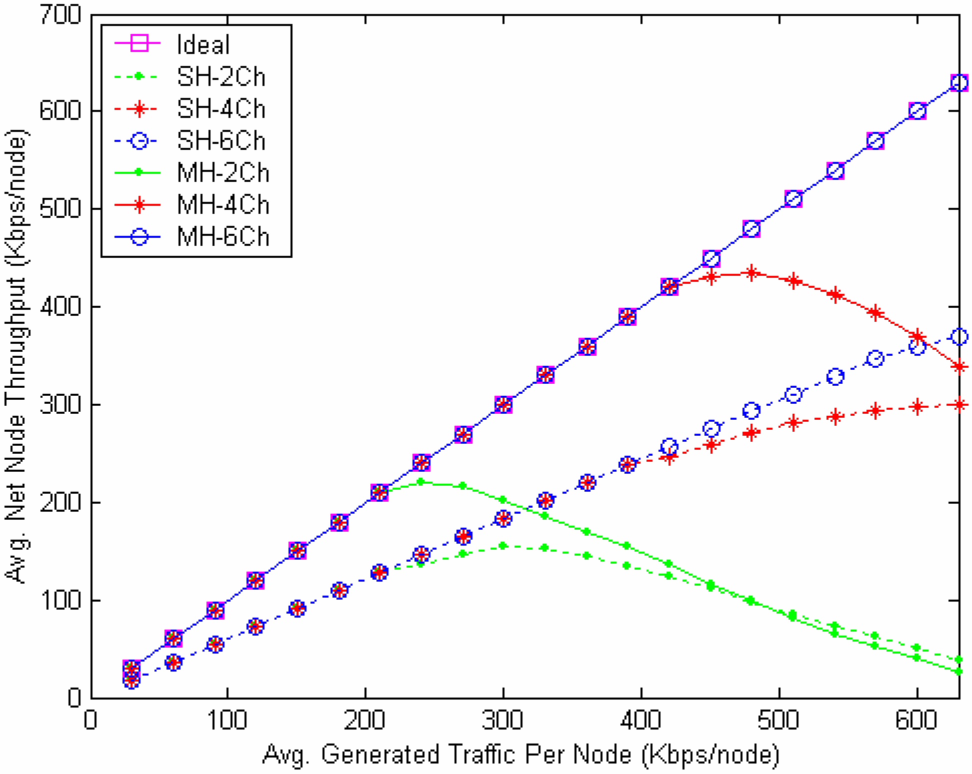


Figure 4.11 Average net node throughput of single-hop and multihop networks with 2, 4 and 6 frequency channels

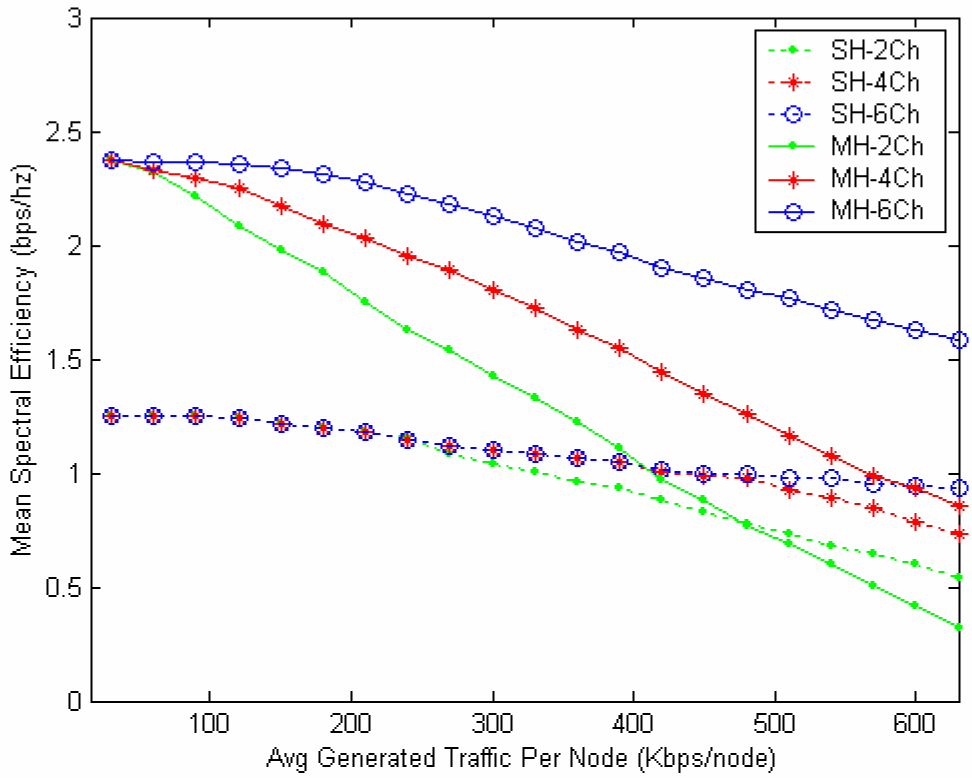


Figure 4.12 Mean spectral efficiency of single-hop and multihop networks with 2, 4 and 6 frequency channels

As the number of available frequency channels is increased to 4 in single-hop network, not only is the degradation in node throughput shifted farther on the traffic scale, but also it became less steep than the degradation in 2 channel case, as shown in Figure 4.11. Similar less steep trend can be observed for the mean node spectral efficiency for 4 channels single-hop network shown in Figure 4.12. A further increase in the number of frequency channels to 6, ensures full throughput for all nodes under the coverage, even at the highest offered load considered.

In MH network, full coverage and high SINR due to shorter links and fixed transmit power lead to 100% node throughput for light to medium offered traffic levels as shown in Figure 4.11. Higher SINR leads to higher adaptive coding and modulation levels, resulting in much higher mean spectral efficiencies compared to the corresponding single-hop counterpart, as can be ascertained in Figure 4.12. However, as generated traffic level increase, more concurrent multihop routes exist in the network. This leads to more frequency channel reuse (as no separate relaying channels are considered), and longer channel occupancy. As a result, this introduces higher co-channel interference levels (both inter-cell and intra-cell) and degradation in spectral efficiency as obvious from Figure 4.12. If frequency channels are few like in the 2 channels multihop case, this effect is more prominent; hence the resulting drop in spectral efficiency is quite steep, with respect to increasing traffic. At low to medium traffic levels however, this drop in spectral efficiency does not affect linearly the node throughput, because even after the degradation in spectral efficiency, it is large enough to support the generated traffic, as shown in Figure 4.11 and is still much superior to the corresponding SH network.

However, this superior performance is not realizable without a suitable re-transmission and re-routing scheme. This is because; the high co-channel interference in MH network can degrade some active connections to the extent of high frame outage probability.

A suitable ARQ scheme is needed to identify such high frame outage probability, so that data can be retransmitted. But simply re-transmitting the data on the same route will not solve the problem, because it will go through the same high frame outage due to high co-channel interference on that route. This might lead to poor node throughput and long transmission delays, which is not acceptable in real time applications and delay sensitive services such as voice and video conferencing. Hence, the entire burst is retransmitted from the source node after choosing a viable alternate route to the base station. Figure 4.13 shows the probability of such re-transmission (and re-routing) for SH and MH as the function of available frequency channels.

As can be ascertained, SH network rarely needs retransmission because of noise limited nature of the system, irrespective of the number of available frequency channels. Retransmission in MH network is a strong direct function of frequency channels. For MH network with 2 channels, the probability of retransmission (and re-routing) grows steeply with the increase in the offered node traffic, for obvious reason of high co-channel interference. As the number of channels is increased to 4 in MH network, a significant reduction in the retransmission can be ascertained, and full node throughput is extended to medium-high traffic levels.

Further increase in traffic results in the degradation of node throughput for reasons discussed above. With 6 channels, 100% node throughput is achieved over the entire range of generate node traffic (and retransmission is rarely needed even at high traffic levels as shown in Figure 4.11).

4.2.2 Contribution of Adaptive Coding and Modulation in Node Throughput of Single-hop Network

The contribution of different adaptive coding and modulation schemes in the node throughput of single-hop network with 2 channels is illustrated in Figure 4.14. Since the SH network has only 62% coverage, 38% of the total data transmission (in terms of frames) is just not supported due to poor SINR. Moreover at high loading levels, some data traffic will be unsupported due to the unavailability of spectral resources (time slots). This is because, both type of outages ultimately degrades the average node throughput.

Approximately 25% of the data transmission is based on minimum acceptable ACM scheme of r:½-QPSK or 1 bps/Hz at light traffic, which simply means a considerable percentage of nodes with single-hop coverage, can barely achieve the minimum SINR level to support their transmissions. This is mainly because the SH network considered is noise limited, and partly because of fixed (but independent) shadowing. Therefore nodes experiencing deep shadowing will always experience weak signal strength. This is to some extent been taken care of by using the policy of assigning the best SINR channel (time slot) available.

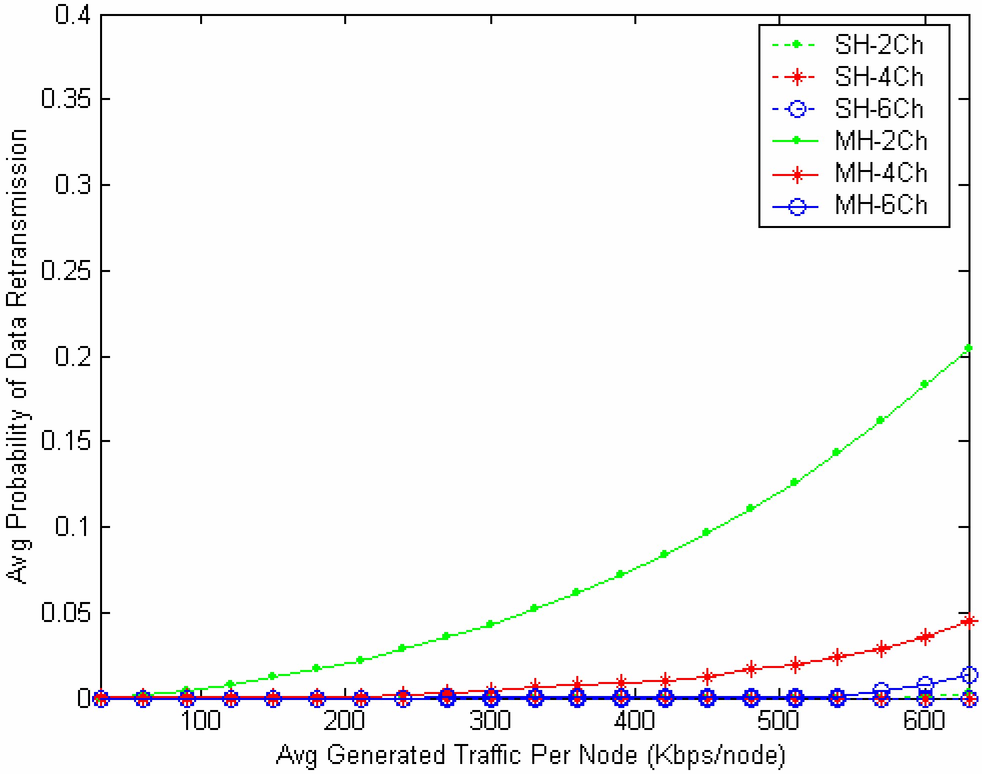


Figure 4.13 Average probability of data retransmission in single-hop and multihop networks with 2, 4 and 6 frequency channels

With the increase in average node traffic, intra-cell co-channel interference (although weak) starts to degrade SINR on some of these r:½-QPSK links to the extent that they cannot support the data transmission anymore, resulting in an increase in unsupported transmissions and corresponding decrease in r:½-QPSK transmissions. Furthermore, the unavailability of channels (time slots) at high traffic levels also contributes to the unsupported transmission. A similar, but less steep trend can be ascertained for r:¾-QPSK transmissions. Concerning, higher level modulation transmissions, the degradation is not prominent because the SINR values are high enough to be degraded appreciable by even the worst co-channel interference values arising from the adjacent cells.

Figure 4.15 shows the contribution of adaptive coding and modulation in data throughput of SH network with 4 channels. Only at high generated traffic levels, is a slight increase in unsupported frames observed and a corresponding drop in r:½-QPSK transmissions, while for all higher modulation level transmissions, the impact of increasing network traffic is almost negligible.

Further increase in number of channels to 6 gives almost consistent performance over the entire range of traffic level considered, as shown in Figure 4.16. This means that enough channels (time slots) exist in the network so that nodes with coverage can always avoid interference to achieve their desired throughput.

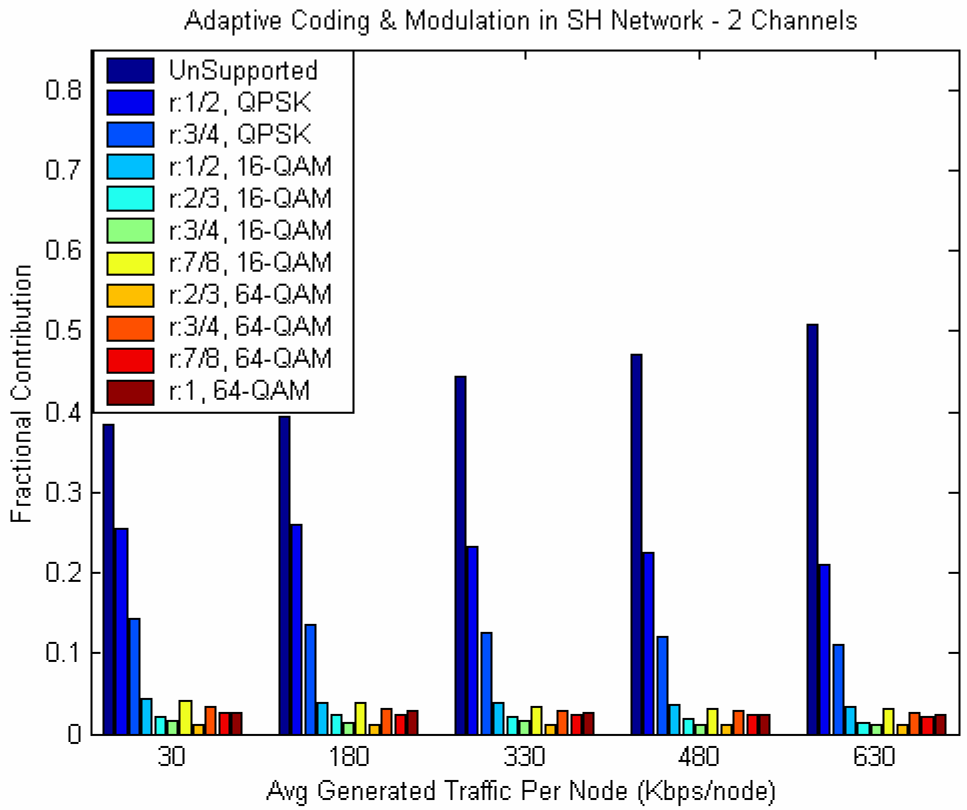


Figure 4.14 Contribution of different adaptive coding and modulation schemes in node throughput of single-hop network with 2-channels

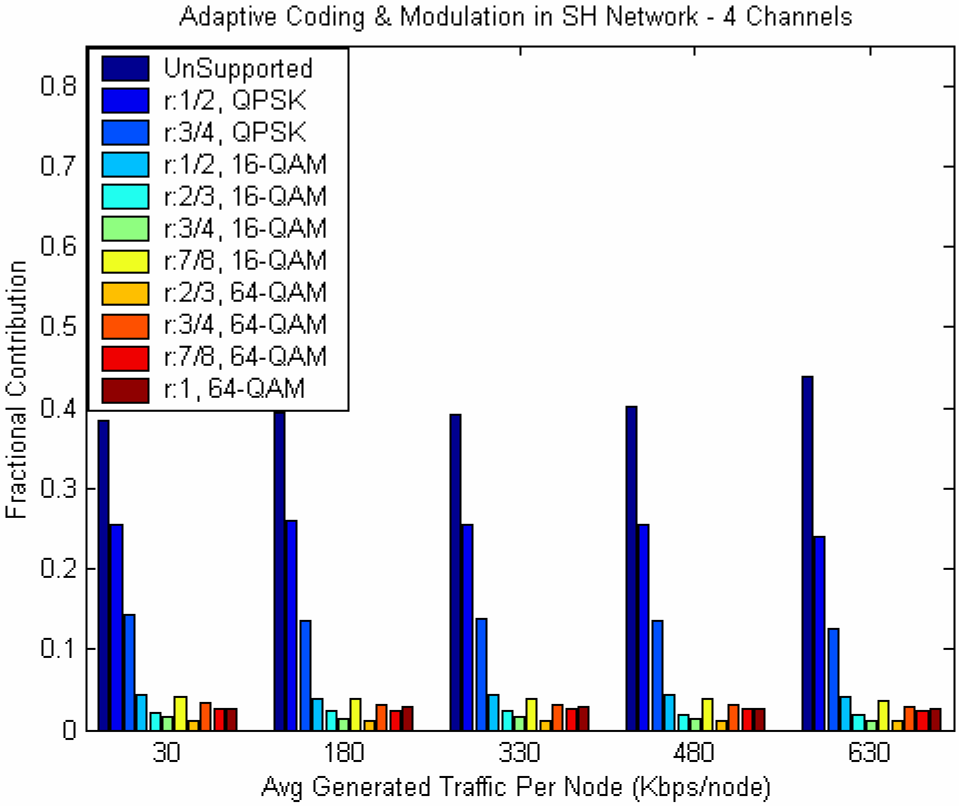


Figure 4.15 Contribution of different adaptive coding and modulation schemes in node throughput of single-hop network with 4-channels

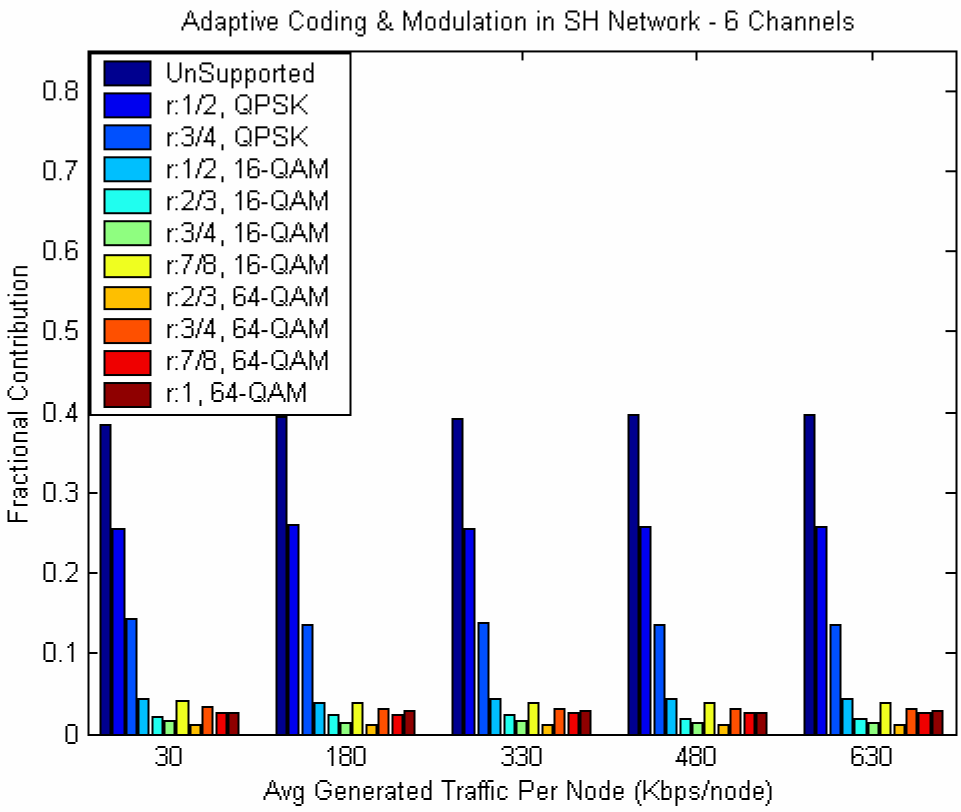


Figure 4.16 Contribution of different adaptive coding and modulation schemes in node throughput of single-hop network with 6-channels

4.2.3 Contribution of Adaptive Coding and Modulation in Node Throughput of Multihop Network

As can be ascertained from the results presented in Figure 4.17 for MH network with 2 channels, not only are all data transmissions supported, but also significantly large number of transmissions use high modulation levels. This is primarily because the multihop routing tables are developed on the criterion (*min{max(PLi)}*), such that when a MH route is chosen, it is the best among all available alternates. On top of that, the best SINR free channels (time slots) are assigned. As the network traffic increases, more and more MH concurrent transmissions result in large intra-cell and inter-cell co-channel interference (because of no separate relaying channels), leading to a significant rise in unsupported transmissions (frames).

This trend grows rapidly with increasing traffic, mainly because of the limited number of channels to the point that it rises beyond that of a corresponding single-hop network shown in Figure 4.14. This high number of unsupported transmission is not only because of those transmissions which were barely supported previously at low coding and modulation levels such as r:½-QPSK or r:¾-QPSK, but also from high modulation as can be ascertained in Figure 4.17. This impact is much more pronounced at high traffic levels, when transmissions on different code rates of 16-QAM and 64-QAM are almost negligible.

Figure 4.18 shows the results for MH network with 4 channels. Here, since more time slots are available, large interference time slots can be avoided to achieve higher

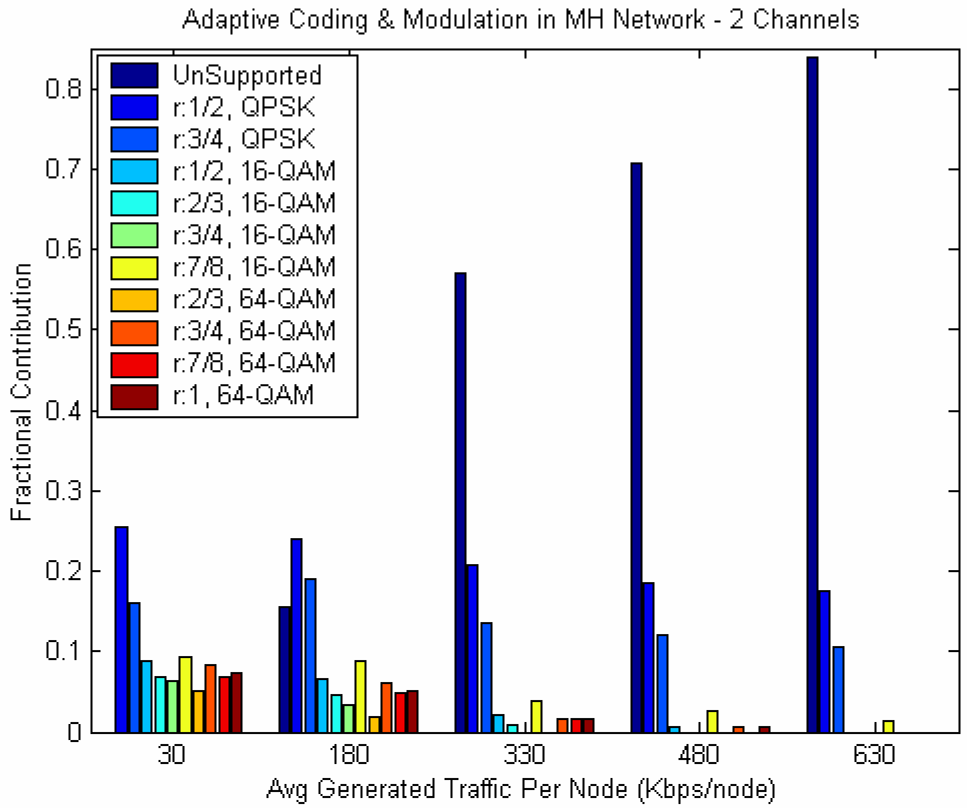


Figure 4.17 Contribution of different adaptive coding and modulation schemes in node throughput of multihop network with 2-channels

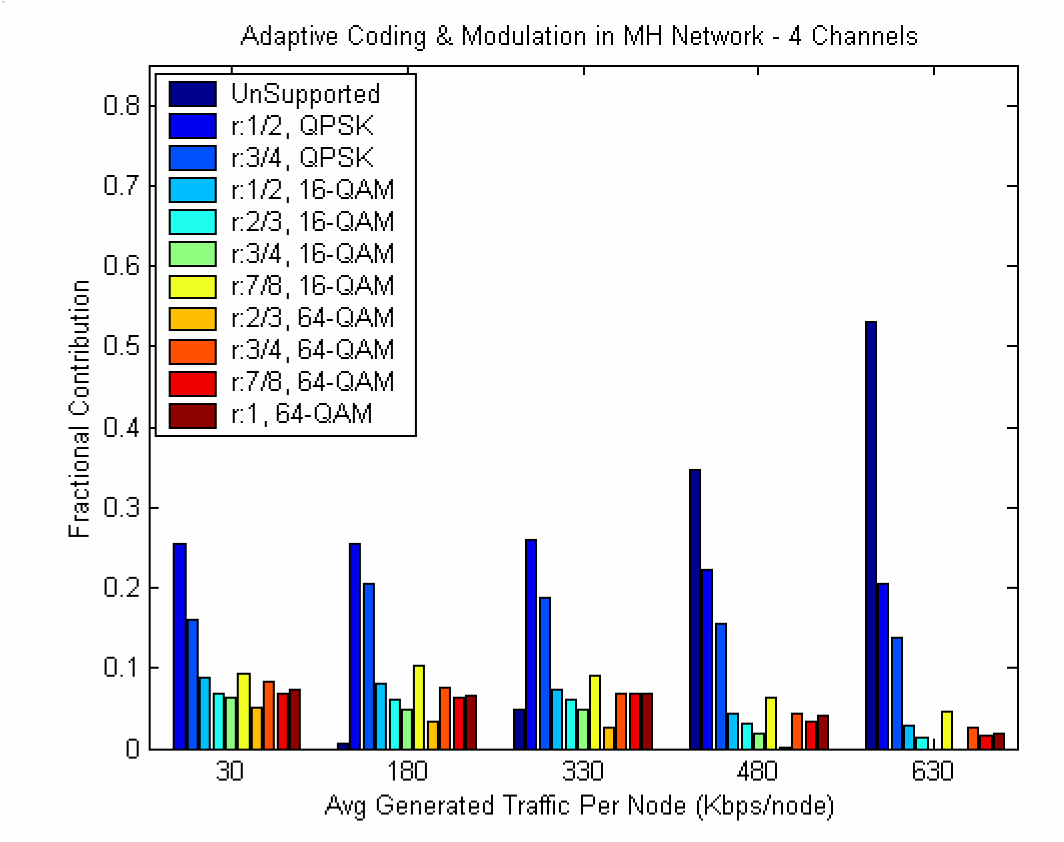


Figure 4.18 Contribution of different adaptive coding and modulation schemes in node throughput of multihop network with 4-channels

SINR. This leads to more frequent use of higher modulation levels of 16-QAM and 64-QAM, and up to medium-high traffic levels. With further increase in traffic level, co-channel interference becomes large enough to cause a substantial increase in unsupported transmissions.

As shown in Figure 4.19, the increase in the number of channels to 6 enables data transmissions to be carried out at different code rates of higher modulation levels. Moreover, the use of high modulation levels are maintained over the entire range of generated traffic load considered, as if co-channel interference has no impact. This reflects the immense interference avoiding capability of MH network in general, and in specific when directional antennas are used.

4.3 Spectral Efficiency Coverage

Before discussing spectral efficiency coverage, it would be appropriate to define node coverage itself. In this study, node coverage is defined for single-hop and multihop network as follows.

Single-hop Node Coverage: “Percentage of total number of nodes with 95% probability of achieved signal to interference plus noise ratio ($SINR_{ach}$) greater than or equal to targeted signal to interference plus noise ratio ($SINR_t$) on any time slot (free or occupied) of the base station(s)”.

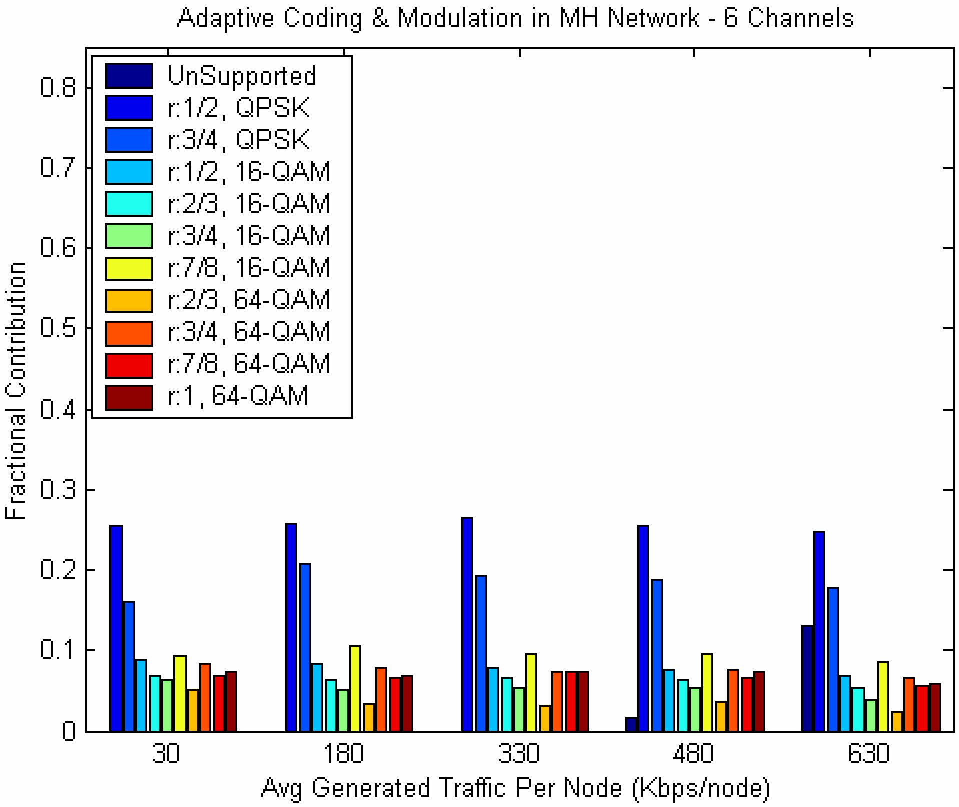


Figure 4.19 Contribution of different adaptive coding and modulation schemes in node throughput of multihop network with 6-channels

Multihop Node Coverage: "Percentage of total number of nodes with 95% probability of $SINR_{ach}$ greater than or equal to $SINR_t$, on any time slot (free or occupied) of relay(s) and base station".

Spectral Efficiency Coverage: "Percentage of total number of nodes with coverage of $SINR_t$ corresponding to a certain spectral efficiency".

In this study we are mapping $SINR_{ach}$ to adaptive coding and modulation, therefore if a node has $SINR_{ach}$ of 4.65-7.45 dB for 95% of the time, then based on mapping in Table 1 (Chapter 3, System Model), this node has spectral efficiency coverage of r:½-QPSK or 1 bps/hz. Similarly for $SINR_{ach}$ of 14.02-15.0 dB for 95% of the time, a node has spectral efficiency coverage of r:¾-16QAM or 3 bps/Hz, and so on.

$SINR_t$ can vary depending upon the service type and required quality of service. By calculating SINR on both free and occupied slots, what we mean to do is to present the *potential* in SH and MH networks to achieve certain SINR coverage. In other word, if more frequency channel resources are provided, such coverage can be practically guaranteed.

4.3.1 Spectral Efficiency Coverage in Single-hop Network

Figure 4.20 shows the potential of single-hop network to achieve a series of node spectral efficiency coverage for 2-channel case. Approximately 62% have r:½-QPSK or 1 bps/Hz coverage. This spectral efficiency coverage is consistently available over the entire coverage of the traffic level considered in this study. Similarly 44% of the nodes have r:¾-QPSK or 1.5bps/Hz coverage, and 32% have r:½-16QAM or 2 bps/Hz coverage and so on.

It is worth noting that increasing generated traffic level is not affecting the potential coverage except in the case of highest considered 64QAM or 6 bps/Hz coverage. The reason is that the SH network considered is noise limited and directional antennas are used, therefore even the highest co-channel interference arising from the adjacent cells (frequency reuse=1) is not significant, and nodes can always find a time slot (free or occupied) to achieve the desired SINR. Only in the case of 64QAM coverage, which only 5% of the nodes have initially, this inter-cell co-channel interference is large enough to slightly degrade the coverage to 2%.

If the number of channels are increased to 4, it can be ascertained that in Figure 4.21 that even the slight degradation in 64QAM coverage at high traffic levels does not exist any more, simply because nodes not having the desired coverage previously, have more time slots to choose from to achieve the required SINR.

Increasing the channel to 6 gives similar results (Figure 4.22), and no further coverage improvement is achieved simply because, nodes outside the coverage region just cannot attain it, irrespective of the number of frequency channels (or time slots) provided.

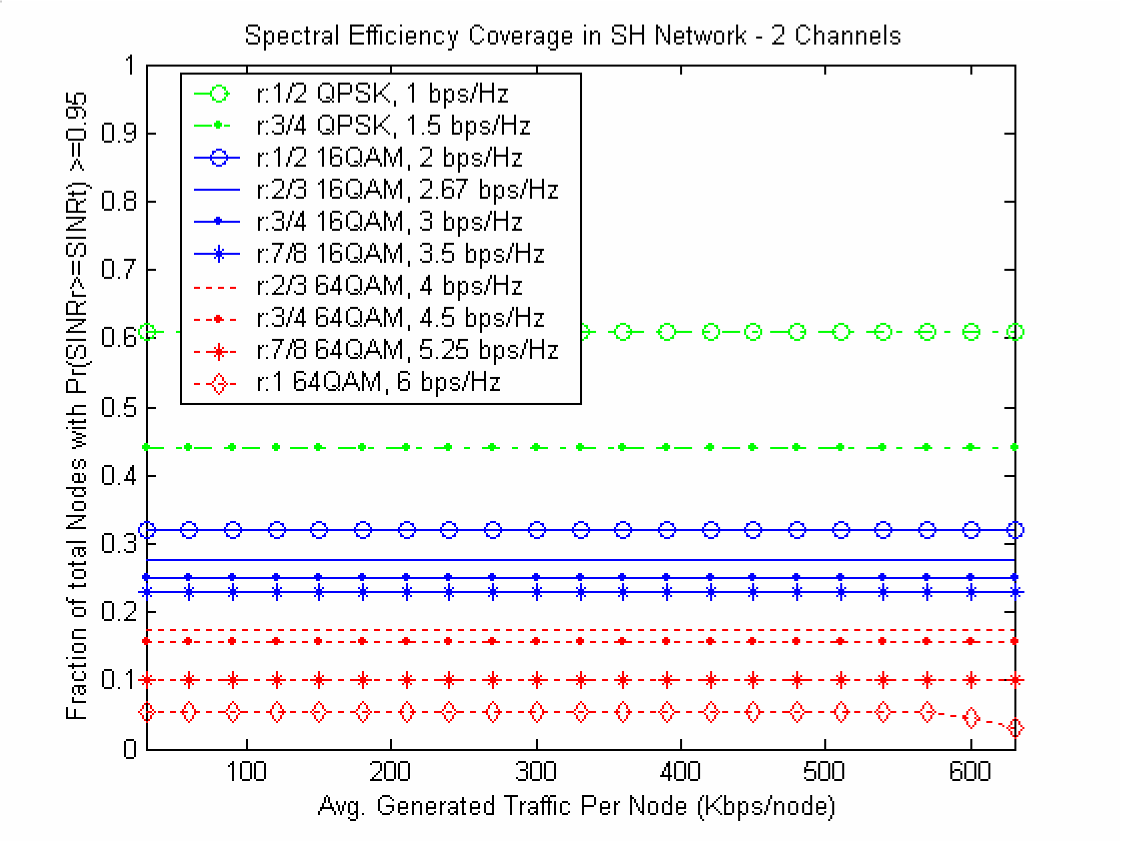


Figure 4.20 Spectral efficiency coverage available in single-hop network with 2-channels

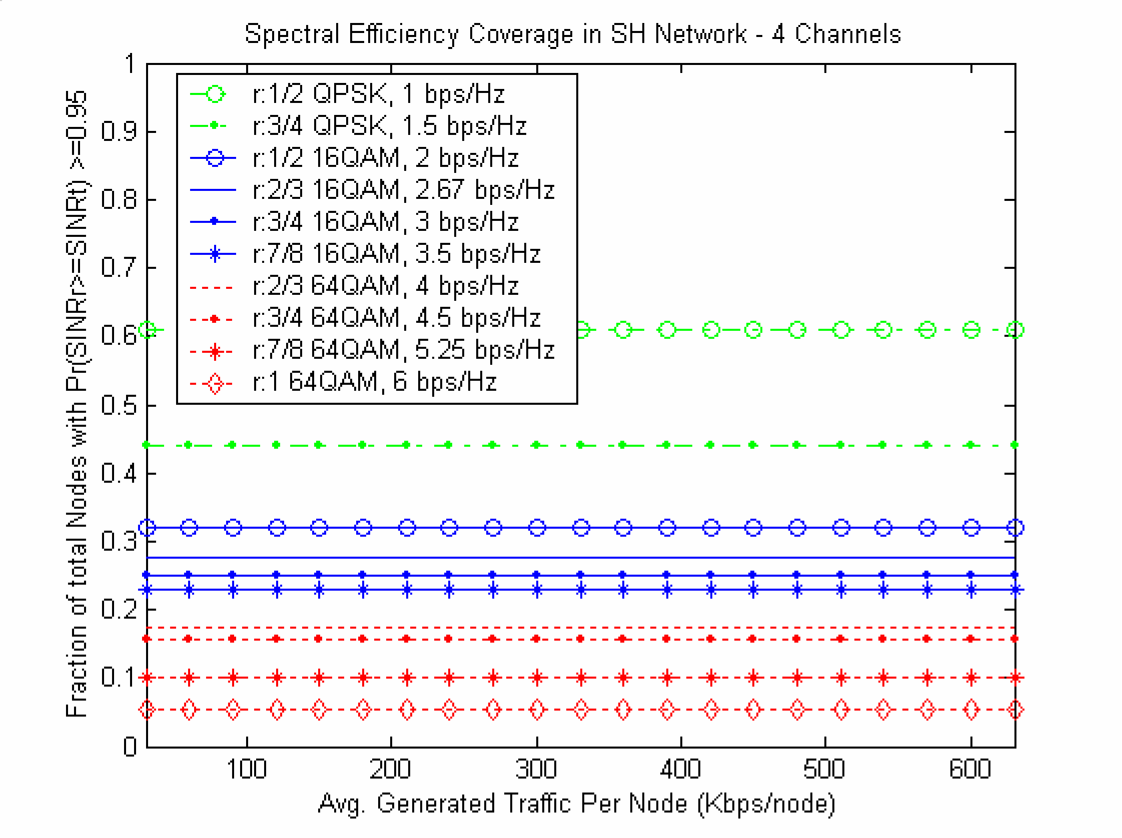


Figure 4.21 Spectral efficiency coverage available in single-hop network with 4-channels

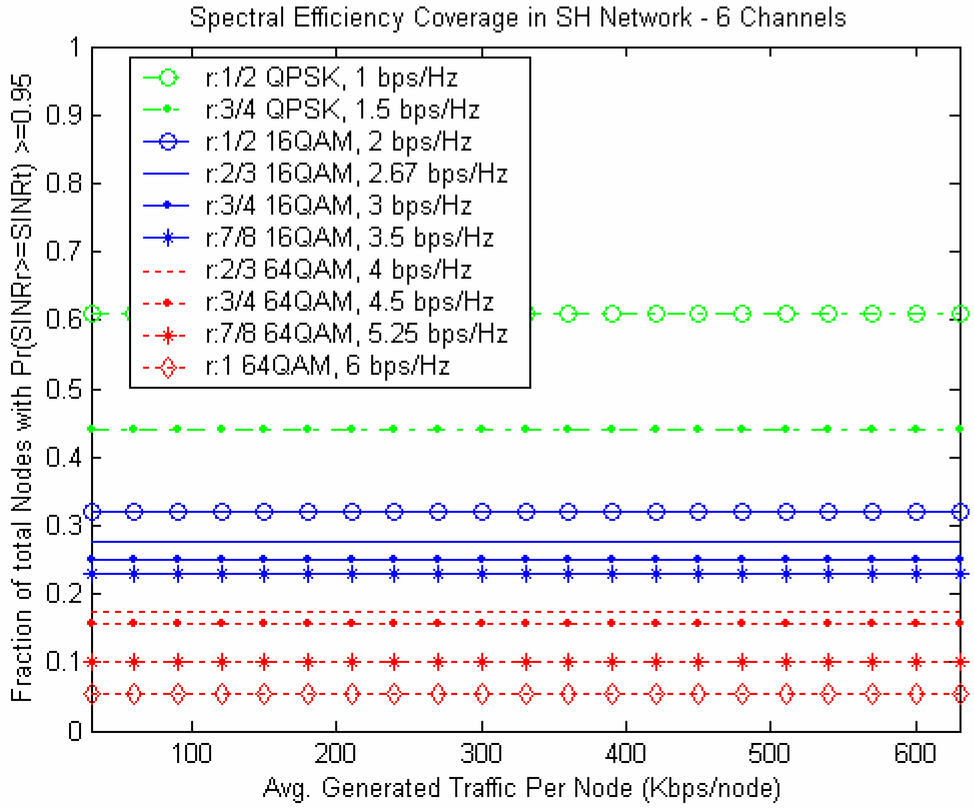


Figure 4.22 Spectral efficiency coverage available in single-hop network with 6-channels

4.3.2 Spectral Efficiency Coverage in Multihop Network

The strength of MH to improve coverage is reflected in the results below. Even in the presence of high frequency reuse and no separate relaying channels to minimize interference, MH offered substantial improvement in node coverage for all data rates. Figure 4.23 shows the results for the 2-channel case. As can be ascertained, multihopping leads to 100% node coverage of r:½-QPSK or 1bps/Hz over the entire range of traffic level, as compared to only 62% in corresponding single-hop case (Figure 4.20).

In addition, the 100% node coverage is extended up to r:2/3-16QAM or 2.67 bps/Hz. This is followed by 98% node coverage of r:¾-16QAM or 3bps/Hz, and 95% node coverage for r:7/8-16QAM or 3.5 bps/Hz, compared to only 25% and 23% corresponding node coverage in similar single-hop network (Figure 4.20). This improved coverage trend continues for higher spectral efficiency coverage too. However as traffic grows, more and more concurrent MH routes exist in the network. This means aggressive reuse of frequencies (time slots) as no separate relaying channels are considered. This leads to both high inter-cell and intra-cell co-channel interference. On top of that, multihopping has an inherent feature of occupying resources (channels or time slots) for longer duration especially in case of digital relaying. This feature is a direct function of the number of hops. Both these issues in MH links result in deterioration of SINR, and therefore node coverage for high data rates starts degrading at medium to high traffic levels. In case of r:7/8-64QAM, node coverage drops from 37% to 30%, while in 64QAM, it drops from 17% to 3%, almost the same as that of a similar SH network (Figure 4.20).

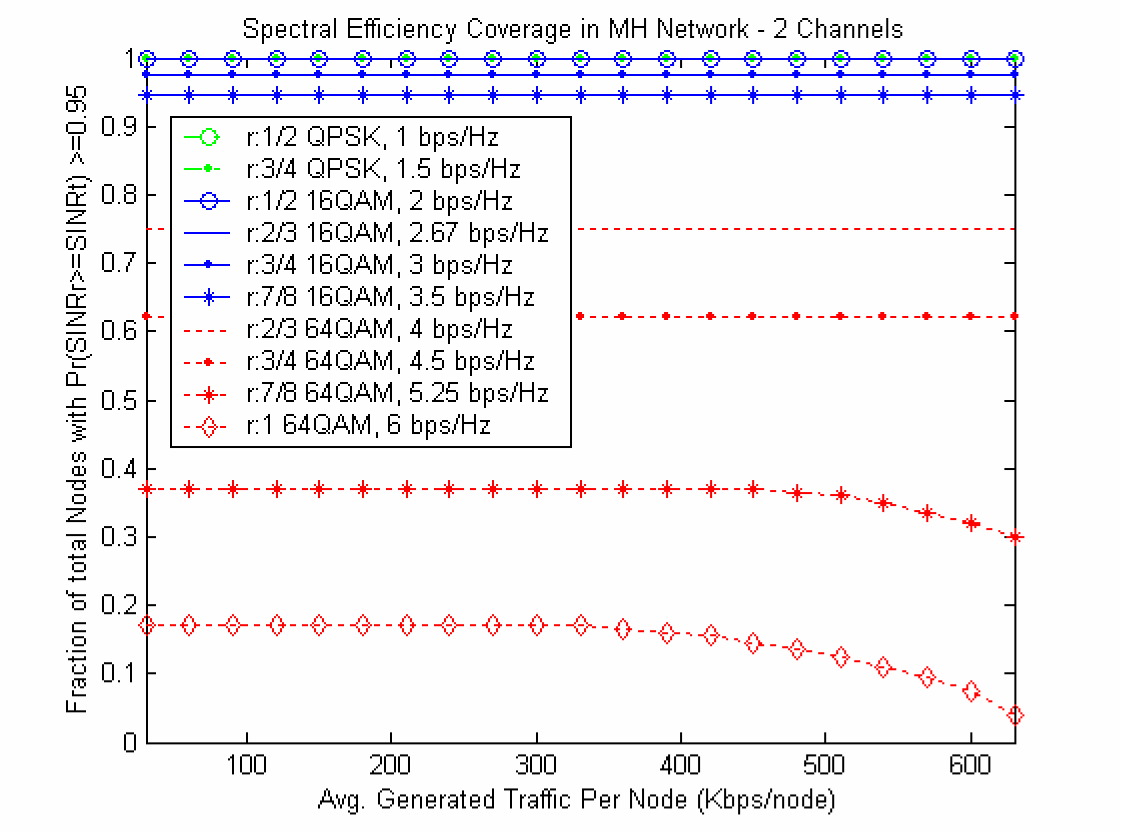


Figure 4.23 Spectral efficiency coverage available in multihop network with 2-channels

When the number of frequency channel is increased to 4, the node coverage of r:7/8-64QAM improves to 36% and 64QAM to 12% at highest traffic level considered as shown in Figure 4.24. This happens simply because now relays have more time slots available and high interference can be avoided to ensure desired SINR on all hops.

Figure 4.25 shows that further increase in the number of frequency channels to 6, leads to consistent node coverage over the entire range of traffic levels, for all considered data rates.

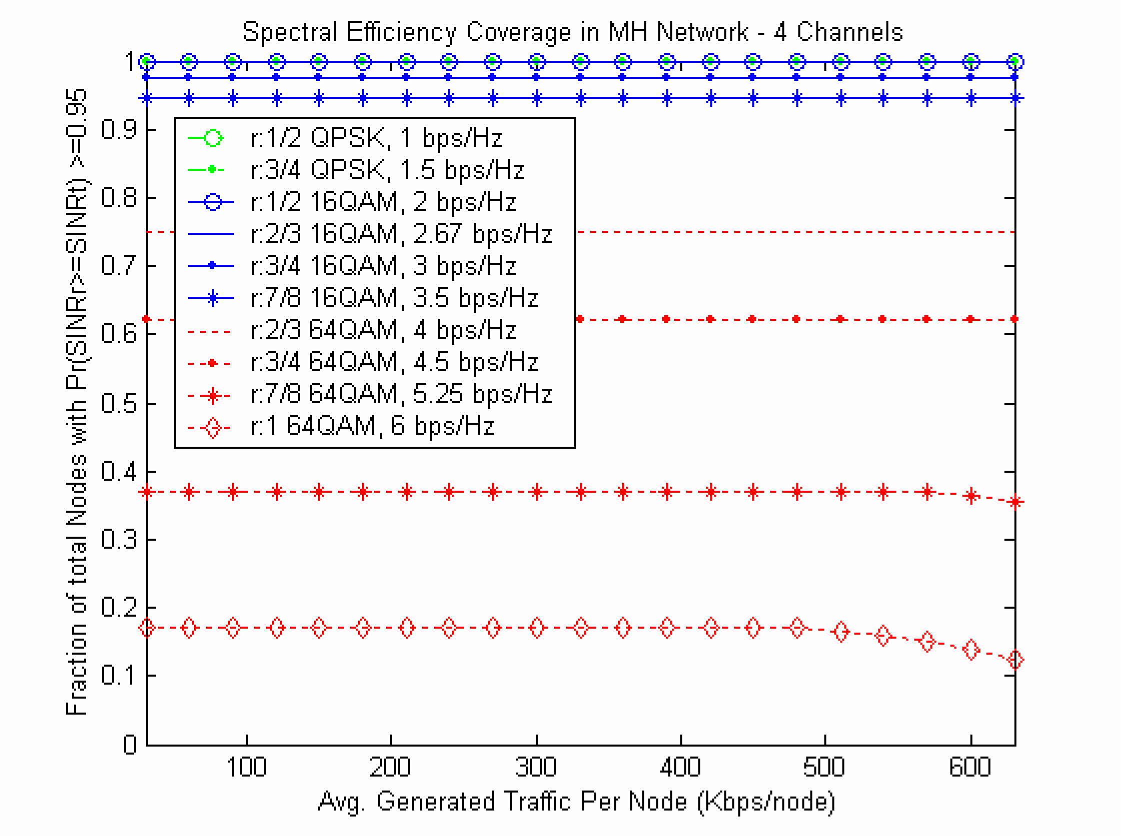


Figure 4.24 Spectral efficiency coverage available in multihop network with 4-channels

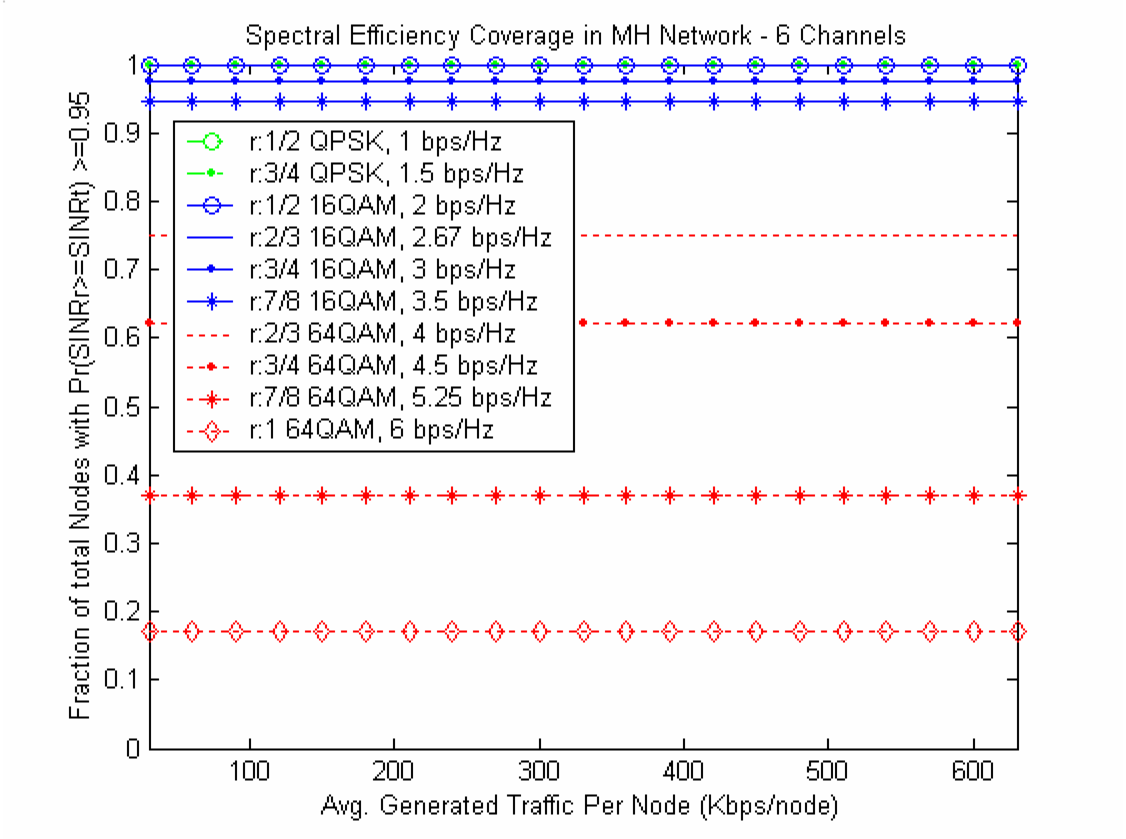


Figure 4.25 Spectral efficiency coverage available in multihop network with 6-channels

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Thesis Summary

This research investigated and analyzed the performance gains, complexities and constraints associated with multi-hopping in a TDMA based broadband fixed cellular network, compared to a traditional cellular or single-hop network. The performance metrics studied here are the outage probability, node throughout and spectral efficiency coverage. Sensitivity of these performance metrics on the number of available frequency channels is analyzed and discussed. A low user density network with few base stations is considered, and both user terminal and base stations are equipped with directional, switched beam antennas. Multi-hopping was implemented using the user node terminals, hence no separate relaying entities or additional infrastructure were considered. Multi-hopping capabilities were analyzed in a very hostile environment with around 60% single-hop coverage no separate relaying channels aggressive frequency reuse and low relay node density. This was chosen to ensure a fair comparison with traditional cellular network on one hand, and to study the performance impacts of seamless extension of multi-hopping feature to the existing widely deployed cellular network without incurring any serious additional infrastructure cost.

Minimum number of hops selection policy is used with upper constraint of three hops. Fixed power transmission is considered on all hops, with SINR mapping to different adaptive coding and modulation schemes. Computer simulations were developed for both single-hop and multihop networks to collect detailed statistics for in-depth cause and effect analysis of all performance measures mentioned above, with respect to increasing offered node traffic. Graphical results were presented with discussion on each to gain deeper insight into the mechanisms controlling the system performance of multi-hopping networks.

Even in the presence of such hostile channel conditions, promising results are obtained to emphasize the high potential of multihopping in fixed cellular networks. Results show that multihopping provide not only significant improvement (reduction) in the outage probability, but also simultaneously yields high node throughput and spectral efficiency coverage, compared with corresponding traditional single-hop cellular networks. However, these performance gains are found to be strongly dependent on the number of frequency channels in the system. In case of few channels, multihopping can give initial performance benefits at very low node traffic, but as the offered load increases, the performance degrades due to high co-channel interference, leading to a significant drop in node throughput and large transmission delays. With increased number of channels, superior multihop performance is guaranteed over the extensive range offered node traffic. On the contrary, the single-hop network cannot benefit from these increased channels, because nodes outside the coverage region will always contribute to the outage and low average throughput irrespective of the number of channels. The contributions of this study are summarized in the next section.

The results in general are very appealing for service providers looking to provide affordable high data rate service to all users even in a low node density network. Although user terminals might be a little more expensive, yet this additional cost can be offset by multihopping capability of network scaling and low infrastructure cost. Proper selection of cell sizes, based on node densities to ensure reasonable number of alternate multihop routes, can be an important initial decision in a successfully feasible deployment. Implementation of multihopping involves the complexity of routing and overheads of control information exchange between nodes and BSs, but this is not a critical issue here due to the fixed nature of user nodes. Although this study is performed for the uplink, most of the findings are also applicable to downlink analysis. In fact, downlink communication via multihopping will be more coordinated and well managed since base stations can control network access more easily.

5.2 Thesis Contributions

This thesis has provided a series of interesting findings about multihop implementation with no separate relaying channels, in TDMA based fixed cellular networks with poor single-hop coverage. The thesis contributions are as follows.

1) Multihop performance benefits like low outage probability and high node throughput are strongly dependent on the amount of available spectral resources (number of available frequency channels or time slots) in the network.

2) A low relay density with good links in peer-to-peer relaying is enough to provide high coverage enhancement expected from multihopping. In other words, relay density is not a critical constraint (unless it is below realistic values) in providing coverage

3) In noise limited single-hop networks, poor coverage is the primary performance constraint, while in multihop networks, the main constraint is the spectral resources (number of frequency channels).

4) If switched beam directional antennas are deployed at both user terminals and base stations, then even in the absence of separate relaying channels, and in the presence of high frequency reuse, multihopping can improve outage probability, node throughput and high spectral efficiency coverage.

5) “Matching free time slots” bottleneck in low relay density TDMA based multihop network, as discussed in chapter 2 is not found to be a critical issue, irrespective of the number of available frequency channels.

6) It is found that, if switched beam directional antennas are used, multihopping has the potential of converting an interference limited system into an almost noise limited system, by avoiding high interference channels (time slots) and bad relay links.

7) In the absence of separate relaying channels and power control, the defensive approach of using multihopping only when necessary, not only provides outage gains but also automatically yields high node throughput.

8) If “minimum number of hop routes first” route selection policy is used, then 2 hop routes are sufficient if high number of frequency channels are available, even if relay density is low.

9) High spectral efficiency coverage in multihop network is a direct function of the relay node density.

10) Fixed transmit power is acceptable in multihopping at low traffic densities, but leads to high co-channel interference and serious performance degradation at medium-high offered traffic levels.

11) A good transmission scheduling and load balancing algorithm is needed to extract high node throughput and low transmission delays from multihopping in a highly aggressive frequency reuse environment with few channels.

5.3 Receiver Complexity Issues:

Some receiver issues associated with the system model are discussed below:

- Since we are using switched beam directional antennas on the nodes as well as the base stations, during a particular time slot, a node would be communicating with another node or base station using a specific channel. If more than one channel is available, then a corresponding number of switched beams will be required. If TDD is used, then slot reservation has to be done for uplink and downlink communication. TDD implementation is cost effective, as no extra hardware is required, however there are associated delay and scheduling overheads. FDD can be implemented by using a duplex switch for each beam, moreover sufficient spacing between the carriers should be considered to avoid high adjacent channel interference.

- Multiple frequency channels require additional receiver hardware, with one RF chain for each channel.

- Buffered transmission with independent ACM selection on each hop requires a large buffer space on each node. Receiver should be smart enough to manage the data arriving from various users on different channels, process them, and transmit them to the desired locations. Therefore the buffer size and hence cost will the increase with increase in the offered load, and number of channels.

- Instantaneous transmit power of each relayer node will increase as the relayer load and number of channels increases. This is so because, at high relaying load, a relayer will be simultaneously transmitting power on multiple channels, hence high rating power amplifiers will be needed. Although energy availability is not the constraint due to stationary positioning of the nodes, the receiver will be complex and expensive.

5.4 Proposed Future Research

Based on the findings and issues derived from this thesis, there seems to be great room for further investigations in this area. Some of possible relevant studies that can further enhance the understanding of fixed multihop cellular networks could be:

- Sensitivity analysis of the MH network performance on the number of available frequency channels with power control.

- Performance evaluation of MH network with different route selection schemes like $max\{min(SINR_i)\}$, QoS based, etc, as a function of available frequency channels, with and without power control.

- Sensitivity analysis of the MH network performance on the number of available frequency channels without intermediate relay buffering.

- Generally multihop implementation requires large control information exchange among nodes and base stations (which is an overhead); therefore investigation should be done to evaluate performance of MH Networks with local and global spectral resource utilization policies. Performance sensitivity against relay density and number of frequency channels can be analyzed.

- Performance evaluation of the fixed MH Network, using indoor user terminals with omni-directional antennas (no relaying capability), and fixed relay units with directional antennas pointed to the base stations. Performance sensitivity on the relay node density and different frequency reuse factor can be investigated.

- Evaluation of different scheduling algorithms for time slots allocation to analyze their impact on SINR and transmission delays in fixed MH networks.

- Impact of diversity (space and macro) on the performance of fixed MH Networks.

- Performance evaluation of fixed MH networks with CDMA /OFDMA.

- Performance evaluation of multihopping in fixed cellular packet switched networks.

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