Two-Hop Relaying in CDMA Networks Using the Unlicensed Bands

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By

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the degree of

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In partial fulfillment of the requirements for the Degree of Master of Applied Science

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Abstract

Recently there has been significant interest in augmenting the conventional cellular networks with the multihop capability to obtain better high data rate performance in the context of enhanced-3G and beyond-3G networks.

This thesis deals with the power allocation strategies in the reverse-link of two-hop multimedia CDMA networks. In this envisioned network, the WTs (Wireless Terminals – portable devices used to transmit and/or receive electronic information via an air interface(s)) which cannot establish a direct link with the BS (at the required rates) seek the assistance of those WTs which can; in other words, whenever needed, some WTs are used as relayers for some other WTs (relayees) if this is possible. In a two-hop link, the first hop (relayee to relayer) uses the unlicensed band and the second hop (relayer to BS) uses the cellular band. This arrangement not only guarantees that no additional expensive cellular spectrum will be used to facilitate a two-hop link, but it also guarantees that if anything goes wrong in the first hop, this will not affect the performance of the WTs which directly communicate with the BS in the cellular band.

The performance of any CDMA network depends on the implementation of a good power allocation and control scheme. The optimum power allocation and control in the reverse link of the conventional single-hop CDMA networks is well known. The main contribution of this thesis is the development of a good power allocation scheme (which is tied to the proper selection of relayers) in the first hop. It is worth emphasizing that the nature of the reverse-link power allocation problem is very different in the many one-to-one links (or possibly numerous several-to-one links) which collectively constitute the first hop of the two-hop CDMA network under

consideration, in comparison to that in the single many-to-one link in the reverse link of a conventional single-hop CDMA network.

The simulation results show that the two-hop relaying, facilitated with the developed novel power allocation scheme, yields considerable enhancements in the CDMA cell capacity, coverage, and throughput.

Acknowledgements

I give thanks and praise to God, my Creator, Sustainer and Redeemer for giving me the strength to pursue this project to its completion.

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I am also grateful to the technical support staff in the Systems and Computer Engineering Department for installing the hardware and software needed as tools during the course of this project. I would also like to thank them for maintaining these tools; for being available to rectify software or hardware problems when they occurred. My gratitude is also extended to CITO for their financial support, without which this project would not have been possible.

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List of Acronyms

BS	Base Station
CDMA	Code Division Multiple Access
FR	Fixed Relayer
PSD	Power Spectral Density
QoS	Quality of Service
WT	Wireless Terminal

List of Symbols

f	Fractional consumption of WT
G	Link gain
$G_{\min(i,k)}^{hop1}$	Minimum acceptable hop 1 link gain between WT i and relayer k
$G_{\min(i,k\to BS)}^{hop2}$	Minimum acceptable link gain on hop 2 for relayee i between relayer k and the BS
K	Number of WTs in the system
K_R	Number of relayees in the system
N	Spreading Gain
$P_{\max}$	Maximum transmit power
P_N	Noise power
P_R	Receive power
$P_{R,\min(i,BS)}^{hop2}$	Minimum acceptable receive power for WT i at the BS
$P_{R,\min(i,k)}^{hop1}$	Minimum receive power for relayee i at relayer k on hop1
P_T	Transmit power
$P_{T,avail(i,k\to BS)}^{hop2}$	Transmit power available at relayer k to transmit the signal for WT i to the BS
$P_{T,\max(i)}$	Maximum transmit power for WT i
R	Cell radius
R_{bit}	Bit rate
$SINR$	Signal to Interference and Noise Ratio

SIR	Signal to Interference Ratio
T	Bit duration
W	System bandwidth
γ	SIR
$\gamma_{\min(i,k)}$	Minimum acceptable *SINR* of WT i at relayer k
τ	Chip duration

Chapter 1 Introduction

Some of the objectives of future generation wireless networks are to reliably provide various types of services such as e-mail, file transfer, internet surfing etc. at reasonable costs (i.e. to both the service provider and the subscribers) to a large subscriber base [36, 37]. Thus, increases in capacity, coverage and throughput will be demanded in these future systems. With current technologies the objectives of these future generation wireless networks cannot be met, primarily because of the substantial costs involved in building new base stations in order to meet the increased performance demands. However, networks utilizing the relaying scheme (includes the power allocation algorithm and the relayer selection scheme) proposed in this thesis are expected to perform significantly better than current systems that do not use relaying. In addition, the proposed relaying scheme can be quickly deployed at significantly lower costs than are possible with current networks.

1.1 Thesis Motivation

Relaying is proposed for future wireless networks because it can significantly increase the performance [5, 14, 15]. CDMA networks are not exempt from the observations noted above in [5, 14, 15], in fact, [8] showed that a two hop cellular CDMA system experienced significant throughput increases when relaying was employed. However, the performance of CDMA networks is interference limited [32, 33]. In addition, outage in CDMA systems occurs when the interference level reaches a certain value, which is above the background noise level [29]. Therefore, effective power allocation is mandatory if significant performance improvements are to be realized in CDMA networks that employ relaying.

It is the development of an effective power allocation algorithm which distinguishes this thesis from the many recent publications, such as [8, 9], on CDMA relaying networks. Power allocation in conventional single hop CDMA networks, where there exists a single many-to-one link in the reverse link, is already known [1]. However, the first hop of two hop CDMA networks has many one-to-one links (or possibly numerous several-to-one links) and consequently, is a difficult problem to solve. We have developed a novel power allocation algorithm which accepts WTs with different QoS specifications and supports them by allocating an appropriate power level to each WT (Wireless Terminal – a portable device used to transmit and/or receive electronic information via an air interface(s)). This power allocation algorithm is effective in the first hop of two hop CDMA networks and is the key distinguishing feature of this thesis. In addition to this novel power allocation algorithm, a relayer selection method which incorporates fair resource allotment and avoids bottlenecks was also developed during this project.

Also of interest is the concept of path loss reduction using relaying, in which longer paths are broken into shorter ones, potentially resulting in reduced transmit powers by exploiting the nonlinear relationship between distance and path loss [10-12, 17, 20]. Relaying can also be used in load balancing, in which relayers are used to move traffic from a congested to a non-congested cell [13]. In [16] the use of directional antennas to reduce interference in a TDD W-CDMA network is explored, promising further performance enhancements to relaying systems. Relaying can also be done through fixed relayers which have stable locations. Fixed relayers may have higher power caps than WTs and therefore can yield additional performance enhancements to relaying systems.

Relaying also has its problems. These problems include increased WT complexity and the utilization of a WT's power to support the transmissions of other WTs [18]; however, MeshNetworks has successfully used WTs to transmit signals for other WTs, demonstrating that this type of transmission is feasible [38]. In addition, the propagation environment in which WT-to-WT relaying occurs is poor due to the antenna locations, which are closer to the ground and may be in pockets, drawers or bags; therefore, extra signal attenuation is expected to occur [19]. On the other hand, there are many WTs which have the potential to be relayers because they have adequate links to the BS and sufficient power to transmit the signal of another WT.

The aforementioned interference limited performance of CDMA networks can become evident when WTs try to get connected to the BS. Some WTs may not be able to connect to the BS due to inadequate *SINR*; however, the WTs that are connected to the BS may be used to relay the signals of the unconnected WTs to the BS. The relaying scheme devised for this project works by having WTs with connections to the BS (candidate relayers) receive signals from WTs that cannot get connected (relayees); the relayers then transmit these received signals to the BS. It should be noted that candidate relayers become relayers when they transmit signals received from relayees to the BS. All transmissions in this project are in the reverse link (i.e. from the WTs to the BS).

In this project relaying is done in the unlicensed bands (5 GHz) and the connection to the BS occurs in the licensed bands (2 GHz). In other words, the first hop takes place in the unlicensed bands while the second hop takes place in the licensed bands; therefore, each WT will need two air interfaces, one at 2 GHz and another at 5 GHz. Shadow fading is used in both hops (standard deviation = 8 dB); however, multipath fading is excluded. Multipath fading is excluded because of its fast changing nature (in both time and distance). These rapid changes are likely to result in relayer selection oscillation, in which a relayee switches between relayers due to the fast changing links. However, fixed relayers, unlike WTs, can be feasibly built with RAKE receivers, which may help mitigate the effects of multipath fading. The use of fixed relayers is explored in this thesis; however, including multipath fading would have compromised direct comparisons between fixed and WT relaying since the WTs do not include multipath fading. CDMA is used in both the licensed and unlicensed bands and the WTs are placed in a hexagonal cell with a centrally located BS; the CDMA schemes used will be described later.

The unlicensed bands are used for relaying because they are free, so the performance of the network can be enhanced without the cost of additional spectra license fees. In addition, by using the unlicensed bands, power control errors during relaying will not affect the WTs in the licensed bands. Also, the problem of "inter-hop interference", as described in [9], and which caused significant capacity degradation when multi-hop relaying was employed in [9], is not an issue since the first and second hops are decoupled. On the downside, the devices utilizing the unlicensed bands may interfere with each other resulting in performance degradation. Also, these devices may differ widely in their average transmission durations and technologies used, so it may be difficult to enforce efficient spectrum utilization. Furthermore, since the spectrum is free, there is no incentive to use these bands efficiently; therefore, some devices may waste spectrum in order to improve their own performance at the expense of others [34]. However, since CDMA is highly resistant to interference, it is more robust in this unlicensed environment.

The term "fractional consumption" (f) is used throughout this thesis. This term is not well known in the wireless field's literature; therefore, it will be briefly explained. Fractional consumption is a counting mechanism to keep track of a system's capacity consumption; different users may have different fractional consumption figures. For example, a system having WTs, each with f = 0.3, can only accommodate 3 WTs; now the sum of the fractional consumptions is 0.9. Another system having class A (fa=0.15) and class B (fb=0.2) WTs, has a total fractional consumption of 0.95 when 6 WTs (5 class A and 1 class B) are present. This fractional consumption concept was developed at Carleton University in Ottawa; more details concerning it can be found in [6].

The system used in this paper consists of a single hexagonal cell with no mobility. However, the system can be extended to include a multi-cell environment. The system configuration is shown in Figure 1.1, below, where the dots represent WTs, the dashed lines represent the first hop and the solid lines represent hop 2.

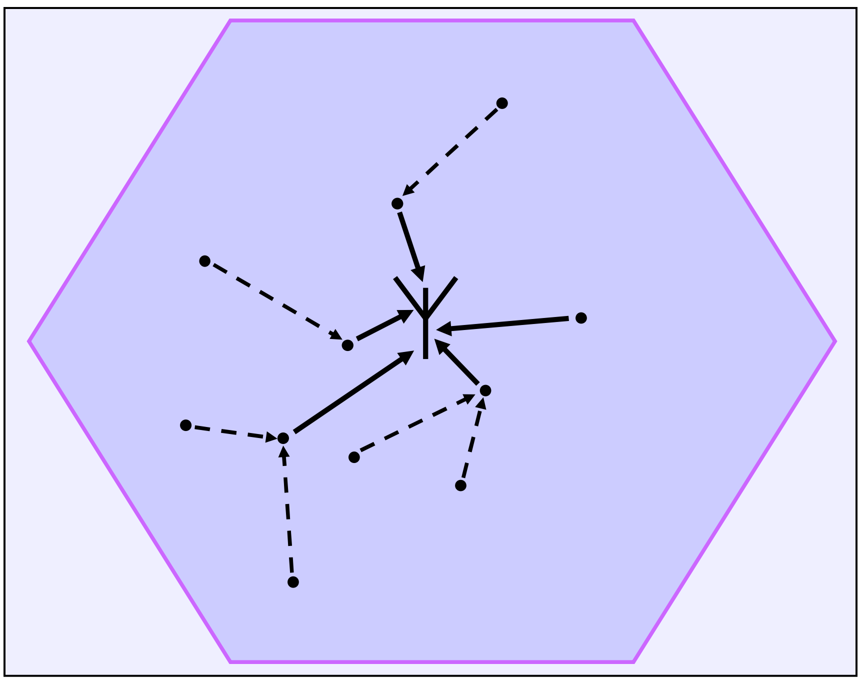

Figure 1.1: System configuration

1.2 Thesis Objectives

The objectives of this thesis are as follows:

- Develop a novel power allocation scheme to facilitate relaying in two hop CDMA networks.

- To determine the performance improvements to be had with WT relayers only, under diverse conditions such as various cell radii and power caps (i.e. maximum transmit power).
- To ascertain the performance gains to be had with fixed relayers only, under various conditions such as different cell radii and maximum transmit power levels.
- To determine the performance enhancements to be obtained with combined fixed and WT relayers under different conditions such as various cell radii and power caps.
- Based on the three preceding observations determine the conditions under which relaying is most feasible and the relayer type(s) which has the best cost/performance ratio.

1.3 Thesis Organization

The thesis will be organized as follows:

- The derivation of the basic CDMA SIR equation
- Power allocations in two hop CDMA networks
- The relayer selection scheme
- A detailed example showing how the system works
- Additional system operation details
- Algorithm extensions to multi-class scenarios
- Simulation results and their explanations
- Conclusions and future work
- References.

Chapter 2 Algorithm Developments

2.1 Derivation of Basic CDMA SIR Equation

The derivation in this section is taken from [6] and the following assumptions are made in it:

- There is no AWGN (Added White Gaussian Noise)
- There is only one cell
- There is chip level synchronization
- The spreading code is a random (Bernoulli) code (i.e. each chip has a 50:50 chance of being either +1 or -1)
- Uplink transmission.

The ensuing figures (i.e. Figures 2.1 to 2.5) give a graphic portrayal of the derivation. In addition, a brief explanation of each figure is given below:

- Figure 2.1 shows the basic CDMA uplink scenario in which the spreading of the data signal, followed by its amplification and transmission is displayed. Then the summation of each WT's wideband signal at the BS is shown.
- Figure 2.2 shows the PSDs (describes how a signal's power varies with frequency and is the square of the absolute value of the Fourier transform of the signal) of the data, chip and transmitted signals (from top to bottom).
- Figure 2.3 shows the PSDs of all the WTs wideband signals as seen by the BS.
- Figure 2.4 shows how the data signal of a single WT (the desired signal) is derived from the sum of the wideband signals of all the WTs.

- Figure 2.5 shows the result of passing the signals in Figure 2.4 through a low pass filter; the power of the desired signal versus the powers of the interfering signals can be clearly seen.

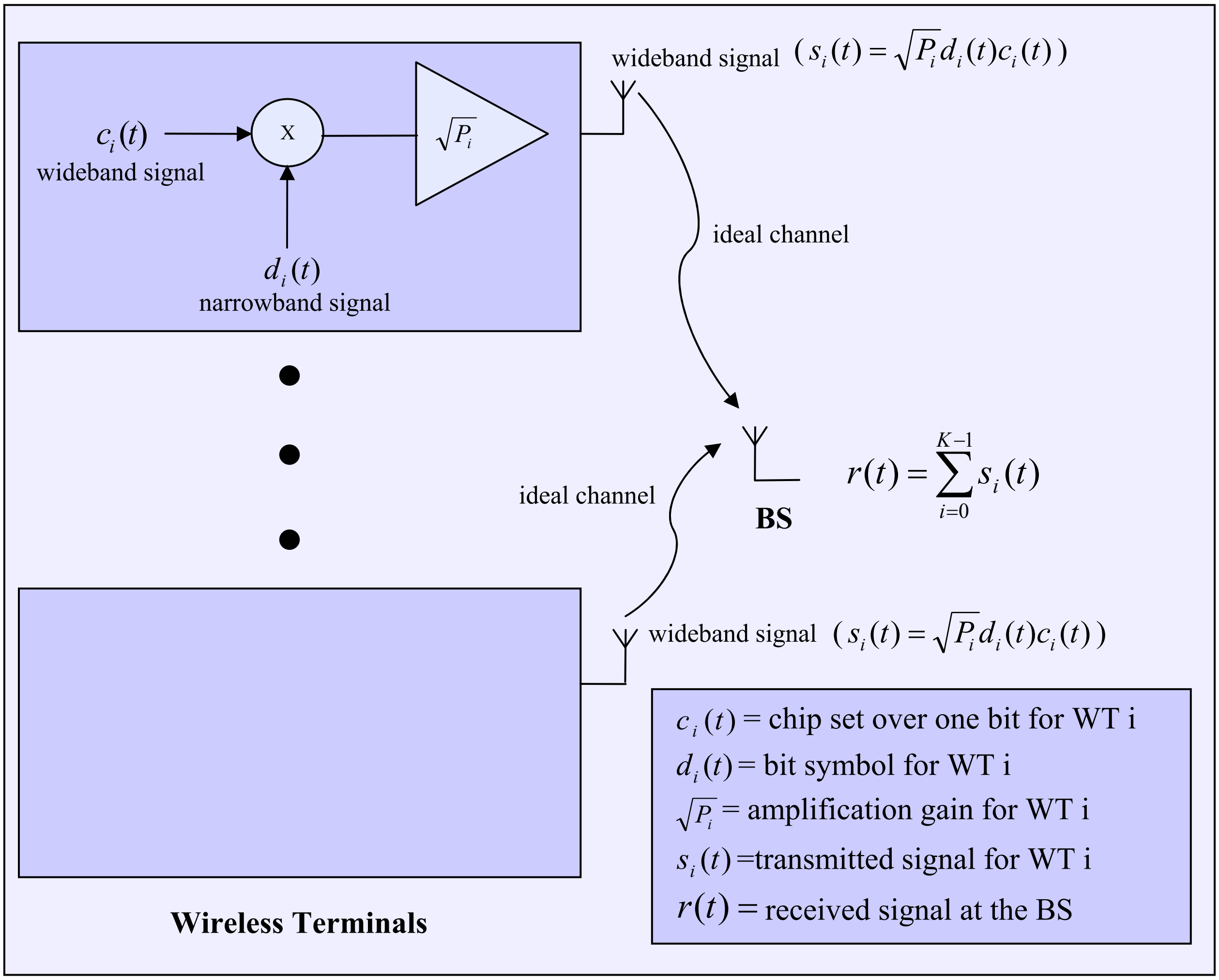

Figure 2.1: Basic CDMA uplink scenario

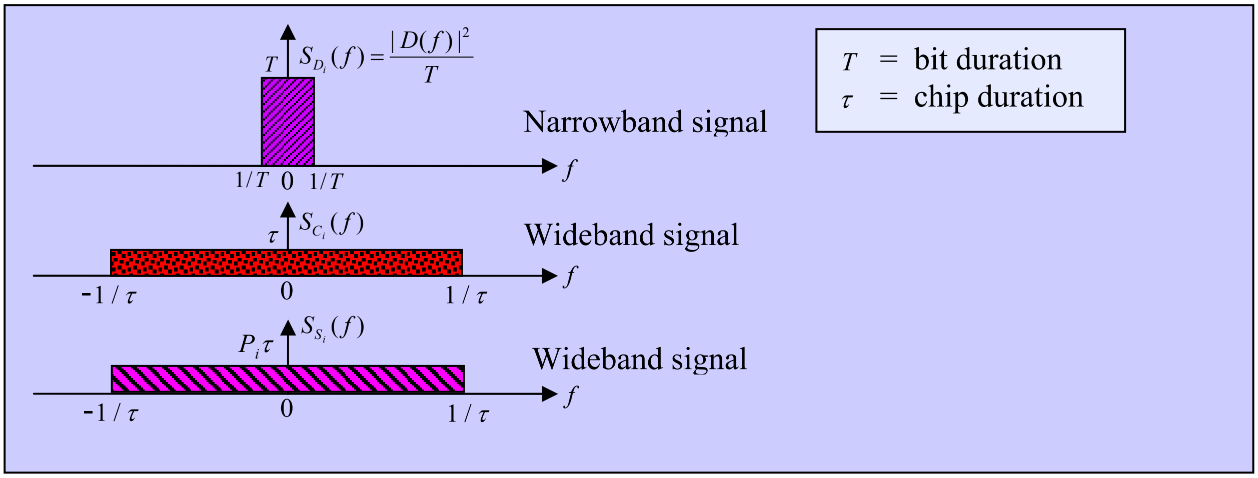

Figure 2.2: PSDs (from top to bottom) for the data, chip and transmitted signals

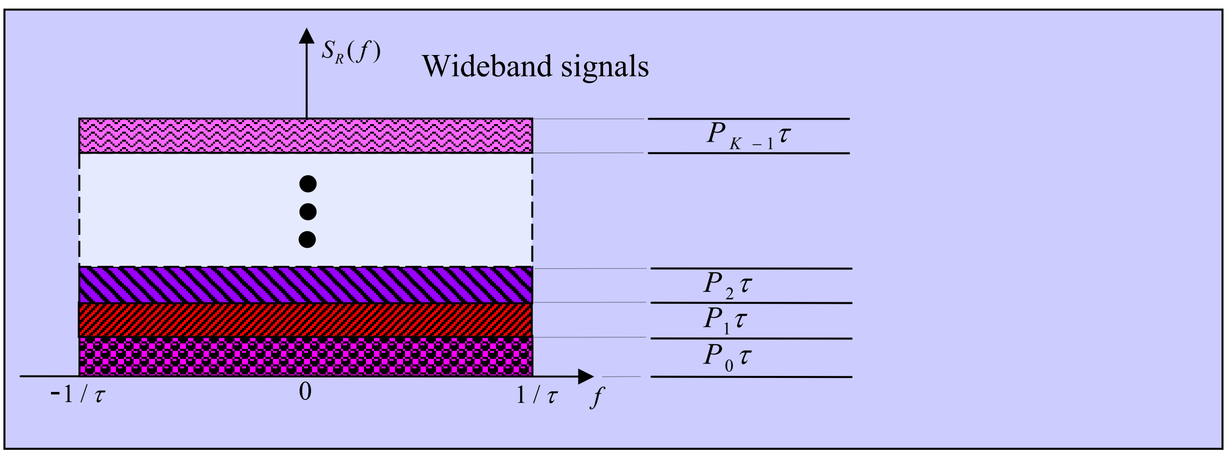

Figure 2.3: The PSDs of all the signals as seen by the receiver

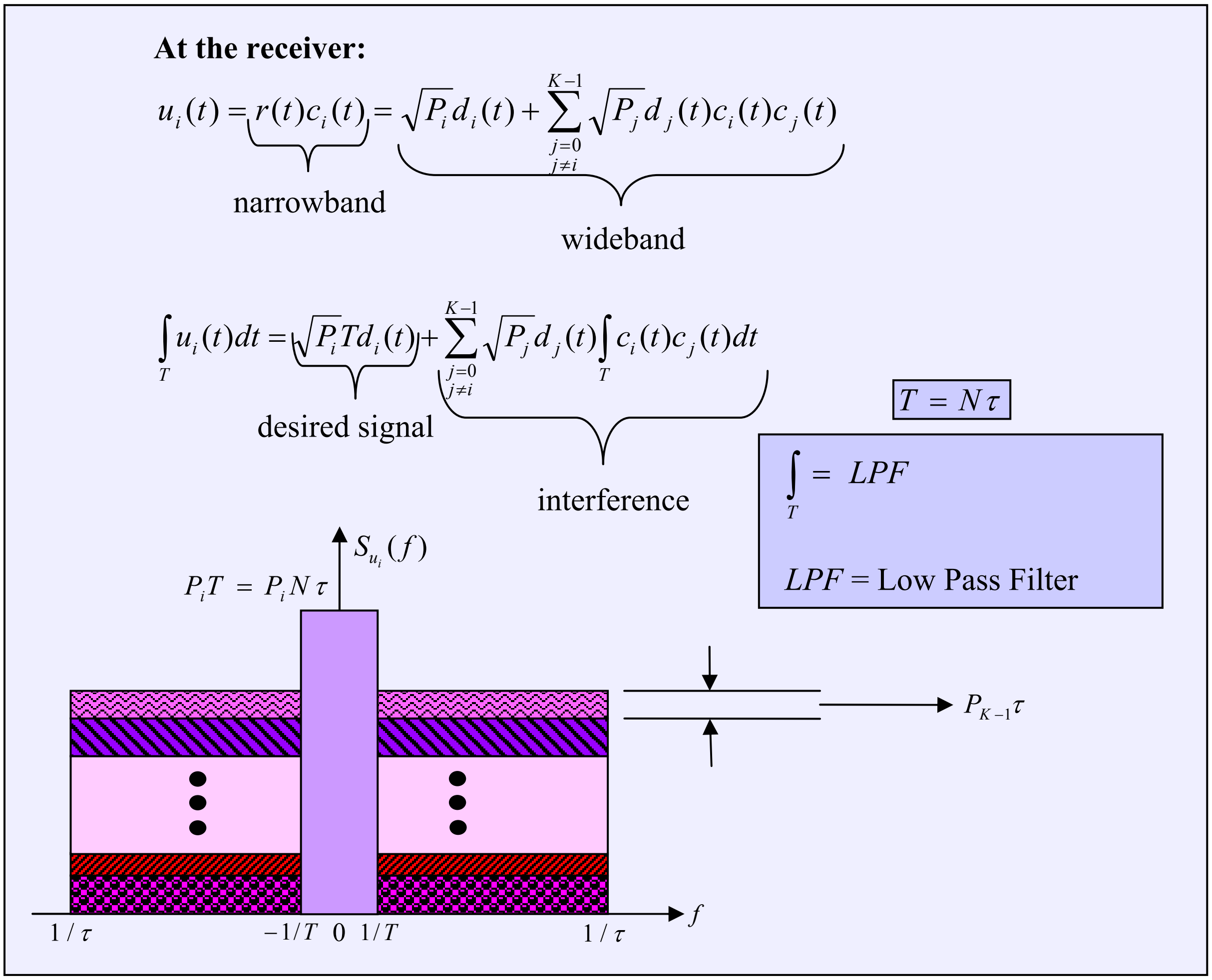

Figure 2.4: Decoding at the receiver

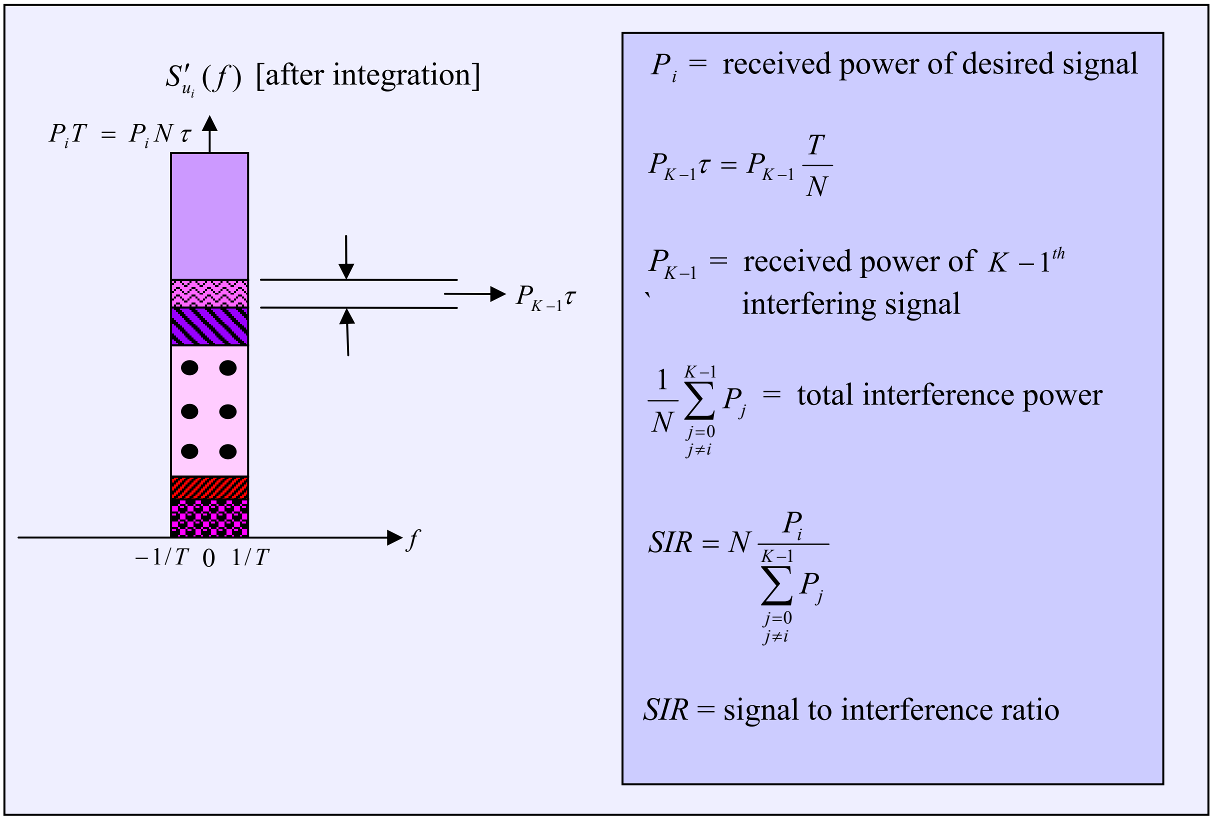

Figure 2.5: Decoding at the receiver shown with SIR equation

From the preceding derivation:

$$SIR = \gamma_i = N\frac{P_{R(i)}}{\sum_{\substack{j=0\\j\neq i}}^{K-1} P_{R(j)}} \tag{2.1}$$

N = spreading gain

K = number of WTs in the system

P_R = receive power

2.2 Power Allocation for the Single Hop Case

An optimal power allocation scheme for single hop CDMA networks was previously derived in [1], is effective in a centralized system (i.e. where there is a single many-to-one link) and may be suitable for future wireless systems where different types of traffic have to be accommodated [25, 26]. Similar results to [1] were found in [28] pertaining to power allocation; however, the ideal receive power in [28] varied among the WTs when noise and inter cell interference were not negligible, which makes it more complex than [1], where the receive power per class is constant even if noise and inter-cell interference is significant. The results of the derivations arrived at in [1] are shown in this section; however, in this paper a simpler method is used to arrive at the same results. A simpler derivation follows below which is from [6]:

When there is one WT class and perfect power control (i.e. all the WTs have the same adequate receive power at the base station) (2.1) becomes:

$$\gamma_i = N\frac{P_R}{\sum_{j=0}^{K-1} P_{R_j} - P_R} = N\frac{P_R}{P_R(K-1)} = \frac{N}{K-1} \tag{2.2}$$

N = spreading gain = T/τ = W/R_{bit}

K = number of WTs in the system

P_R = receive power

W = system bandwidth

R_{bit} = bit rate

According to [6], since each WT experiences the same SIR, bit rate and receive power, each WT consumes $1/K$ of the total resources available to the system, since there is only one WT class. Therefore, (2.2) can be rearranged to show the fraction of resources consumed by each WT; hence, (2.2) becomes:

$$\frac{1}{K} = f = \frac{\gamma}{N+\gamma} = \frac{R_{bit}\gamma}{W + R_{bit}\gamma} = \text{fractional consumption of each WT} \tag{2.3}$$

Also, because more resources cannot be consumed beyond what is available, we now have:

$$Kf < 1 \tag{2.4}$$

The above result can be extended to a multi-class system (i.e. one in which groups of WTs have different parameters such as SIR, spreading gain and bit rate) as shown below:

$$\sum_{l=1}^{L} K_l f_l < 1 \tag{2.5}$$

L = number of different classes

The equations derived above exclude noise; however, noise will now be accounted for. The effect(s) of noise will be explored using an example consisting of two WT classes, as shown below; however, the $\frac{P_2}{P_1} = \frac{f_2}{f_1}$ relation will be shown to be valid for the noiseless case first:

$$\frac{P_2}{P_1} = \frac{f_2}{f_1} \tag{2.6}$$

Assume that $n_i = \frac{P_i}{P_1}$

P_i = receive power for class i WTs, $i = 1, 2$

When there is no noise:

$$\gamma_1 = \frac{W}{R_{bit(1)}} \frac{P_1}{(K_1 - 1)P_1 + K_2 P_2} = \frac{W}{R_{bit(1)}} \frac{1}{(K_1 - 1) + K_2 n_2}$$

$$\gamma_2 = \frac{W}{R_{bit(2)}} \frac{P_2}{(K_2 - 1)P_2 + K_1 P_1} = \frac{W}{R_{bit(2)}} \frac{n_2}{(K_2 - 1)n_2 + K_1}$$

$$K_1 - 1 + K_2 n_2 = \frac{W}{\gamma_1 R_{bit(1)}} \Rightarrow K_1 + K_2 n_2 = \frac{W}{\gamma_1 R_{bit(1)}} + 1$$

$$K_1 + K_2 n_2 - n_2 = \frac{W n_2}{\gamma_2 R_{bit(2)}} \Rightarrow K_1 + K_2 n_2 = n_2\left(\frac{W}{\gamma_2 R_{bit(2)}} + 1\right)$$

Using (2.3) we have:

$$\therefore \frac{W}{\gamma_1 R_{bit(1)}} + 1 = n_2\left(\frac{W}{\gamma_2 R_{bit(2)}} + 1\right) \Rightarrow \frac{1}{f_1} = \frac{n_2}{f_2} \Rightarrow n_2 = \frac{f_2}{f_1} = \frac{P_2}{P_1} \tag{2.7}$$

Therefore, when there is no noise (2.6) holds true.

When there is noise:

$$\gamma_1 = \frac{W}{R_{bit(1)}} \frac{P_1}{(K_1 - 1)P_1 + K_2 P_2 + N_0 W} = \frac{W}{R_{bit(1)}} \frac{1}{(K_1 - 1) + K_2 n_2 + {}^{N_0 W}\!/_{P_1}}$$

$$\gamma_2 = \frac{W}{R_{bit(2)}} \frac{P_2}{(K_2 - 1)P_2 + K_1 P_1 + N_0 W} = \frac{W}{R_{bit(2)}} \frac{n_2}{(K_2 - 1)n_2 + K_1 + {}^{N_0 W}\!/_{P_1}}$$

$$K_1 - 1 + K_2 n_2 + N_0 W / P_1 = \frac{W}{\gamma_1 R_{bit(1)}} \Rightarrow K_1 + K_2 n_2 + N_0 W / P_1 = \frac{W}{\gamma_1 R_{bit(1)}} + 1$$

$$K_1 + K_2 n_2 - n_2 + N_0 W / P_1 = \frac{W n_2}{\gamma_2 R_{bit(2)}} \Rightarrow K_1 + K_2 n_2 + N_0 W / P_1 = n_2\left(\frac{W}{\gamma_2 R_{bit(2)}} + 1\right)$$

Using (2.3) we have:

$$\therefore \frac{W}{\gamma_1 R_{bit(1)}} + 1 = n_2\left(\frac{W}{\gamma_2 R_{bit(2)}} + 1\right) \Rightarrow \frac{1}{f_1} = \frac{n_2}{f_2} \Rightarrow n_2 = \frac{f_2}{f_1} = \frac{P_2}{P_1} \qquad \text{(identical to (2.7))}$$

Since (2.7) is equal to (2.6), noise has no effect on the fractional consumption and receive power ratios. It should be noted that when there is no noise only the ratios of P_i's matter, the actual receive power levels are of no consequence. However, when there is noise, not only do the P_i ratios matter, but there must also be a minimum receive power level in order to meet QoS requirements. An inspection of (2.1) will bear out the preceding conclusions.

Since noise does not affect the above ratios, it will decrease the SIR if put in the denominator of (2.1) and added to the interference. As a result, fewer WTs can be accommodated because more WTs will be unable to achieve their target SIR values at the BS due to the added noise. When these WTs are cutoff, due to the added noise, the denominator in (2.1) (when noise is added) may be reduced to its former state before the addition of noise, and thus the remaining WTs will be able to get adequate service. For example, if there are 10 WTs, each having a receive power of 1.0 unit (assume perfect power control), and there is a noise power of 2.0 units at the receiver:

$$SIR = \gamma_i = N \frac{P_i}{\sum_{\substack{j=0 \\ j \neq i}}^{K-1} P_j} = N \frac{1}{9} \text{ (before noise)}$$

$$SIR = N \frac{1}{9+2} \text{ (after noise the denominator increases)}$$

$$SIR = N \frac{1}{7+2} \text{ (two WTs have been dropped and now the SIR is okay)}$$

So from the preceding statements it can be concluded that added noise simply displaces WTs from the system. With this in mind, the receive power at the BS can be derived in terms of the noise power and the fractional consumptions using the two class example (class A and class B) below:

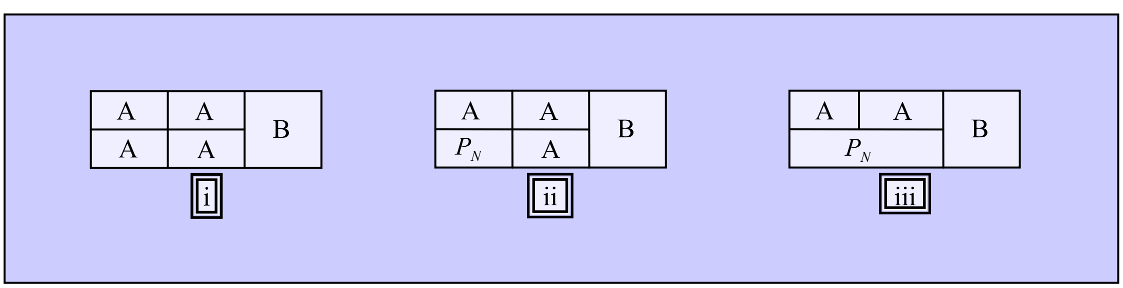

Figure 2.6: Example of noise displacement

Figure 2.6 shows examples of the effects of noise at the receiver (i.e. WT displacement); all three scenarios have the following parameters:

$$f_A = \frac{1}{6},\ f_B = \frac{1}{3},\ P_N = N_0 W = \text{noise power}$$

From scenario *ii* in Figure 2.6 we have:

$$P_A = N_0 W \Rightarrow f_A = f_{N_0 W} \Rightarrow \frac{P_A}{N_0 W} = 1 = \frac{f_A}{f_{N_0 W}}$$

From scenario *iii* in Figure 2.6 we have:

$$2P_A = N_0 W \Rightarrow 2f_A = f_{N_0 W} \Rightarrow \frac{P_A}{N_0 W} = \frac{1}{2} = \frac{f_A}{f_{N_0 W}}$$

From scenarios *ii* and *iii* in Figure 2.6 we get:

$$P_A = \frac{f_A N_0 W}{f_{N_0 W}} = \frac{f_A N_0 W}{1 - \sum_{j=0}^{K-1} f_j}$$

or more generally:

$$P_i = \frac{f_i P_N}{1 - \sum_{j=0}^{K-1} f_j} \tag{2.8}$$

P_i = receive power necessary at the BS for WT i to get adequate service

f_i = fractional consumption of WT i

K = number of WTs in the system

For Figure 2.6 scenario *iii,* $1 - \sum_{j=0}^{K-1} f_j = 1 - (2f_A + f_B)$. It should be noted that the inequality in (2.5) is confirmed in (2.8) (i.e. at no time can 100% of the resources be consumed). If 100% of the resources is used, (2.8) will go to infinity, indicating that it would take an infinite amount of power to accommodate a truly fully loaded system; an impossibility.

Now that (2.8) has been derived, the minimum acceptable link gain for hop 2 will be ascertained. When the link between a WT and the BS is inadequate, that WT cannot be connected to the BS and is cut off; these WTs become relayees. The WTs that can be connected to the BS become candidate relayers, these are the WTs that may be able to relay the signals of the relayees to the BS.

The $\sum_{j=0}^{K-1} f_j$ term in the denominator of (2.8) consists of all the candidate relayers, but no relayees, just prior to the start of relaying. When the first relayee attempts to find a relayer, the $\sum_{j=0}^{K-1} f_j$ term includes that relayee. For instance, if there are 10 candidate relayers, the $\sum_{j=0}^{K-1} f_j$ term includes 11 WTs. The computation of the minimum acceptable hop 2 link gain also includes those 11 WTs. When the second relayee attempts to find a relayer, the $\sum_{j=0}^{K-1} f_j$ term includes 12 WTs and the calculation of the minimum acceptable hop 2 link gain accounts for those 12 WTs. This process continues for the 3rd, 4th …… nth relayee, until all the relayees are processed. If a relayee cannot find a relayer, it is subtracted from the $\sum_{j=0}^{K-1} f_j$ term so that the minimum link gain calculation does not include a nonexistent WT, which would make the minimum link gain quantity unnecessarily high, possibly resulting in relayees being needlessly cut off. The minimum acceptable hop 2 link gain is derived as follows:

$$P_R = P_T G \Rightarrow G = \frac{P_R}{P_T}$$

For this project, G, above, becomes $G^{hop2}_{\min(i,k\to BS)}$, P_R becomes $P^{hop2}_{R,\min(i,BS)}$ and P_T becomes $P^{hop2}_{T,avail(i,k\to BS)}$.

Now we have:

- $$G^{hop2}_{\min(i,k\to BS)} = \frac{P^{hop2}_{R,\min(i,BS)}}{P_{T,avail(i,k\to BS)}} \quad (2.9)$$
- $G^{hop2}_{\min(i,k\to BS)}$ = minimum acceptable link gain on hop 2 for relayee i between relayer k and the BS
- $P^{hop2}_{R,\min(i,BS)}$ = minimum acceptable receive power for WT i at the BS
- $P^{hop2}_{T,avail(i,k\to BS)}$ = transmit power available at relayer k to transmit the signal for WT i to the BS.

In (2.9) the $P^{hop2}_{R,\min(i,BS)}$ term is computed using (2.8). It should be noted that the $P^{hop2}_{R,\min(i,BS)}$ quantity increases as the number of WTs increase, which increases $G^{hop2}_{\min(i,k\to BS)}$ and this, in turn, increases the required transmit power at the relayer to relay the signal. If there is insufficient power at the selected relayer to transmit the relayee's signal, the relayee tries to find another relayer, and if no other relayers are available, the relayee is cut off. This process will become clearer in Section 3.1 where a detailed example the system's operation is given.

2.3 Power Allocation for the Two Hop Case

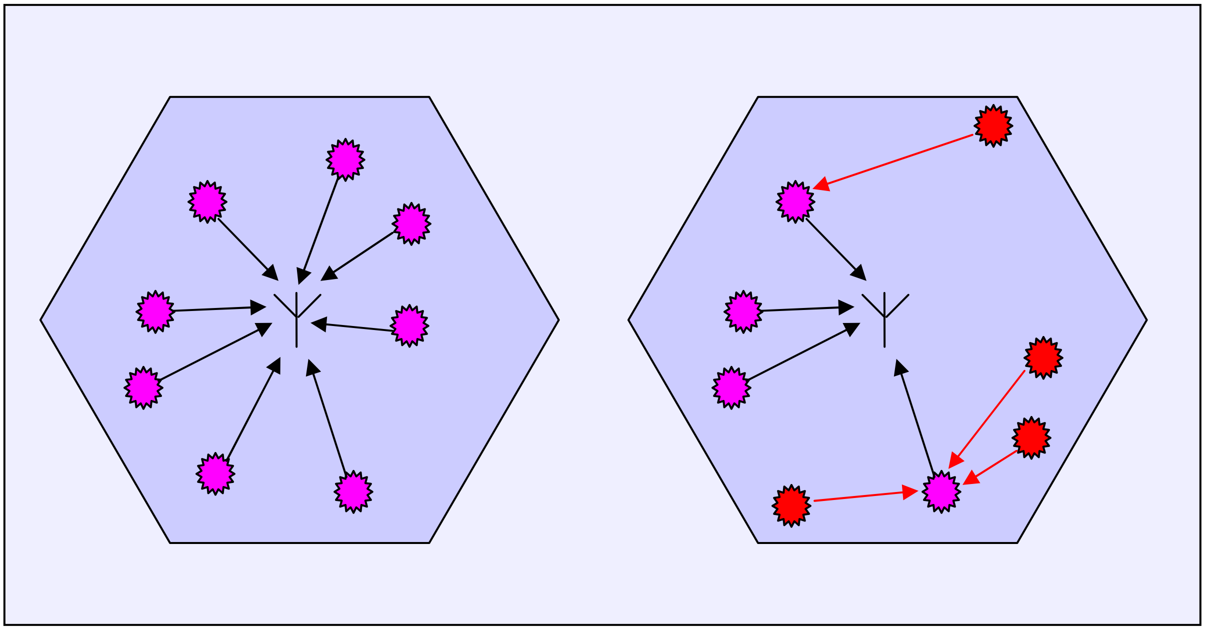

Figure 2.7: Two types of link configurations: a single many-to-one (centralized) link on the left, an example of one-to-one and several-to-one (decentralized) links shown on the right

Neither the power allocation scheme used in Section 2.2 nor the systems developed in [1, 2] can be used in a two hop system because the first hop is decentralized (i.e. there is no one recipient of all the signals that will ensure that they all meet their minimum targets or be cut off) and both Section 2.2 and [1, 2] assume centralized systems; Figure 2.7 demonstrates examples of these systems. Implementation of (2.8) demands centralization because the equation assumes that all the WTs' signals received at the BS meet their target values, and that those that do not are cut off. However, this is not the case for hop 1. On hop 1 there may be several WT signal recipients acting as mini base stations, each employing power control to ensure that the relayees using it achieve their targets. In this scenario, there may be significant interference from the relayees using adjacent relayers. The received powers from these interfering signals is not likely to be at their target values, this undermines the assumptions in (2.8), rendering it unusable for hop 1. It should be noted that each relayer may see two different types of interference: one from the WTs that are using it (these would be received at their target values) and the other from WTs that are using other relayers (these would be received at levels other than their target values). It is the latter type of interference that undermines the assumptions inherent in (2.8). Thus, the derivation of the minimum acceptable link gain on hop 1 will be done using (2.1) with noise added. It should be emphasized that the following power allocation development is the main analytical contribution of this thesis and is a first in the literature:

$$\gamma_{(i,k)} = N_{(i)} \frac{P_{R(i,k)}}{\sum_{\substack{j=0 \\ j\neq i}}^{K_R-1} P_{R(j,k)} + P_N} = \frac{N_{(i)} P_{T(i)} G_{(i,k)}}{\sum_{\substack{j=0 \\ j\neq i}}^{K_R-1} P_{T(j)} G_{(j,k)} + P_N} \tag{2.10}$$

$\gamma_{(i,k)}$ = *SINR* of relayee i at relayer k

$P_{R(i,k)}$ = receive power of relayee i at relayer k

$P_{R(j,k)}$ = receive power of interferer (another relayee) j at relayer k

$N_{(i)}$ = spreading gain for relayee i

K_R = number of relayees

$G_{(i,k)}$ = link gain between relayee i and relayer k

$G_{(j,k)}$ = link gain between interferer j and relayer k

$P_{T(i)}$ = actual transmit power of relayee i

$P_{T(j)}$ = actual transmit power of interferer j

P_N = noise power

(2.10) can be modified using the following assumptions:

- The relayee of interest (relayee i) is transmitting at its maximum power, $P_{T,\max(i)}$
- The minimum *SINR* (signal to interference and noise ratio) is maintained at the receiver (i.e. the relayer)
- Under the above conditions the transmission link cannot be below a certain minimum (providing the interference does not change), or else the relayee's target *SINR* value cannot be met

Using the above assumptions, (2.10) becomes:

$$\gamma_{\min(i,k)} = \frac{N_{(i)} P_{T,\max(i)} G^{hop1}_{\min(i,k)}}{\sum_{\substack{j=0 \\ j \neq i}}^{K_R - 1} P_{T(j)} G_{(j,k)} + P_N}$$

After rearrangement we get:

$$G^{hop1}_{\min(i,k)} = \frac{\gamma_{\min(i,k)} \left(\sum_{\substack{j=0 \\ j \neq i}}^{K_R - 1} P_{T(j)} G_{(j,k)} + P_N \right)}{N_{(i)} P_{T,\max(i)}} \tag{2.11}$$

$G^{hop1}_{\min(i,k)}$ = minimum acceptable hop 1 link gain between relayee i and relayer k

$\gamma_{\min(i,k)}$ = minimum acceptable *SINR* for relayee i at relayer k (from specifications)

$P_{T,\max(i)}$ = maximum allowed transmit power for relayee i (not necessarily its actual transmit power)

Note: the specifications are the parameters that must be met for the WT to obtain adequate service. The specifications include the bit rate, the minimum *SINR* and the spreading gain.

The reasons for the preceding assumptions should be more apparent after inspecting (2.11), as it can now be seen that $G^{hop1}_{\min(i,k)}$ can only be a minimum value if $\gamma_{(i,k)}$ and $P_{T(i)}$ are at their minimum and maximum values respectively. All the other variables in (2.10) cannot be varied (i.e. P_N cannot be changed, $P_{T(j)}$ and $G_{(j,k)}$ must reflect the actual transmit powers and link gains for the interferers, and $N_{(i)}$ is fixed from the specifications) so only $\gamma_{(i,k)}$ and $P_{T(i)}$ can be manipulated. Please note that (2.11) has to be solved iteratively, this process will be made clear in Section 3.1. In addition:

$$P_{R,\min(i,k)}^{hop1} = G_{\min(i,k)}^{hop1} P_{T,\max(i)} = \frac{\gamma_{\min(i,k)} \left[\sum_{\substack{j=0 \\ j \neq i}}^{K_R - 1} P_{T(j)} G_{(j,k)} + P_N \right]}{N_{(i)}} \tag{2.12}$$

$P_{R,\min(i,k)}^{hop1}$ = minimum receive power for relayee i at relayer k on hop1

The algorithm shown in (2.11) can work in a multi-cell environment by including the interference from relayees in the other cells in the numerator of (2.11). The algorithm can also be used in a multihop environment; however, its implementation would be very complex. The complexity is caused primarily by the need for link-by-link $G_{\min(i,k)}^{hop1}$ analysis and possible transmit power changes along the entire unlicensed multi-hop path of each relayee (i.e. instead of just having one link per relayee in the unlicensed bands, there may now be several). This analysis would have to be done whenever a new relayee attempts to find a path to the BS or whenever the transmit power of any WT in the same unlicensed band changed. There is also the issue of frequency management which is relevant because a relayer cannot receive and transmit at the same frequency without suffering feedback problems, thus, making it necessary to assign appropriate frequencies to each transceiver and use these frequency assignments in the above mentioned $G_{\min(i,k)}^{hop1}$ analysis.

2.3.1 Algorithm's Description

The algorithm described by (2.11) works by having each relayer function as a BS (i.e. by taking into account the interference from all other relayees, assigning adequate target receive powers to the relayees connected to it and employing power control to make sure these targets are met).

When the first relayee (i.e. relayee(0))tries to find a relayer, there is no interference from any other relayee because no other relayee is transmitting. Consequently, $G_{\min(0,9)}^{hop1}$ (it is assumed that this first relayee is attempting to connect with relayer(9)) can be easily computed because all the remaining terms (i.e. $\gamma_{\min(0,9)}$, P_N, $N_{(0)}$, $P_{T,\max(0)}$) are known. This first relayee's $G_{\min(0,9)}^{hop1}$ is then compared with its $G_{(0,9)}$ (i.e. its link gain with the relayer it's trying to establish a connection with). If this relayees' $G_{(0,9)} \geq G_{\min(0,9)}^{hop1}$, its hop 1 link is adequate to be used to transmit its signal, otherwise the link cannot be used (a more comprehensive look at how the relaying scheme deals with link failures can be found in Section 2.4). Assuming the link is adequate, (2.12) is used to compute $P_{R,\min(0,9)}^{hop1}$, after which the relayees' transmit power is computed according to $P_{T(0)} = \dfrac{P_{R,\min(0,9)}^{hop1}}{G_{(0,9)}}$. Please note that at this time $P_{T(0)} \leq P_{T,\max(0)}$ because $G_{(0,9)} \geq G_{\min(0,9)}^{hop1}$. Now the first relayee is connected to its relayer and is transmitting.

When the second relayee (i.e. relayee(1)) attempts to find a relayer, its $G_{\min(1,7)}^{hop1}$ (it is assumed that this second relayee is attempting to connect with relayer(7)) will take the transmission of the previous relayee (i.e. relayee(0)) into account. If $G_{(1,7)} \geq G_{\min(1,7)}^{hop1}$, relayee(1)'s hop 1 link is deemed satisfactory and it transmits at $P_{T(1)} = \dfrac{P_{R,\min(1,7)}^{hop1}}{G_{(1,7)}}$. At this point, relayee(0) will adjust its $P_{T(0)}$ to reflect the presence of relayee(1), which will then induce relayee(1) to adjust its $P_{T(1)}$. These transmit power adjustments will continue until $P_{T(0)}$ and $P_{T(1)}$ are constant, within a tolerance of $0.99 < \frac{P^{(n+1)}{}_{T(i)}}{P^{(n)}{}_{T(i)}} < 1.01$ or until a specified maximum number of transmit power adjustments or iterations (100 is chosen in this project) have occurred. If the relayees exceed this number, that scenario is ignored and not included in the system's throughput because reliable transmissions may never occur. In the above tolerance measure, $P^{(n)}{}_{T(i)}$ is relayee i's transmit power in the n^{th} iteration and $P^{(n+1)}{}_{T(i)}$ is relayee i's transmit power in the $(n+1)^{th}$ iteration. If other relayees attempt to find relayers the procedure discussed above still applies; please note that the relayees attempt to find relayers one at a time (i.e. two or more relayees do not join the network simultaneously). After Section 2.4 is read the operation of the relaying scheme will be clearer.

2.4 Relayer Selection Scheme

The type of relayer selection scheme employed in an interference limited system can significantly affect performance; this is borne out in [3]. The relayer selection scheme which yields the best performance in [3] minimizes bottlenecks on the paths chosen. Hence, a relayer selection scheme was developed which avoids bottlenecks and which also considers fair resource allocation. This section also discusses the relayer-BS and relayer-relayee communications because they are indispensable to the workings of this scheme.

When a WT tries to reach the BS unsuccessfully, the BS may have no knowledge of its efforts. However, the BS knows the number of WTs that are connected along with the class each connected WT is in. The WTs that tried unsuccessfully to reach the BS will try to find a relayer;

therefore, the candidate relayers collectively know the number of relayees (i.e. if they can be heard by the candidate relayers) and the classes they are in. The candidate relayers then transmit the above relayees' statistics (i.e. the classes they belong to and the numbers in each class) to the BS. The BS collects the statistics regarding all the relayees, assigns relayers to certain classes of relayees according to the relayer selection scheme, and sends a complete copy of the assignments to each candidate relayer. The candidate relayers then transmit these assignments to the relayees and the relayees in turn try to connect with the appropriate relayer.

The above method of conducting relayer assignments puts most of the complexity at the BS, which is less costly than equipping each WT with algorithms to compute relayer selection. In addition, delays are minimized and the spectrum is used more efficiently, because if the candidate relayers are to implement the relayer selection algorithm they need to communicate with each other, which takes longer than a simple direct transmission to the BS. Consequently, the spectrum can be reserved to transmit WT information for greater portions of time. Also, when the relayees are given the relayer assignments they can go directly to the relayers which are assigned to them, instead of attempting to find the appropriate relayer by trial and error; this also minimizes delays and results in more efficient spectrum utilization.

In this project there are two classes of WTs, class A and class B. Class A WTs consume less resources relative to class B WTs and thus have a lower fractional consumption.

In the relayer selection scheme, a class A relayee locates a candidate relayer which has a hop 2 link that is barely adequate for it (i.e. the class A relayee). Therefore, the hop 2 link must be greater than or equal to $G^{hop2}_{\min(i,k\rightarrow BS)}$. Providing that the corresponding hop 1 link is good enough, this relayee will use this *hop 1* → *hop 2* path. If the corresponding hop 1 link is not good enough (i.e. the link gain falls below $G^{hop1}_{\min(i,k)}$), the relayee will go to the candidate relayer with the next higher hop 2 link and if the corresponding hop 1 link is adequate, this link combination will be used. If there are no adequate link combinations, the relayee will be cut off.

Class B relayees utilize a different relayer selection scheme. Each class B relayee locates the candidate relayer with the highest hop 2 link gain and uses this relayer if the corresponding hop 1 link is adequate. If the corresponding hop 1 link gain is inadequate, the relayee will seek the Candidate relayer with the next lower hop 2 link gain and it will use this link combination if the hop 1 link is good enough. If no adequate link combinations are found, the relayee is cut off. It should be noted that no mention is made concerning relayer power restrictions, this is because the relayer power availability is included in the $G^{hop2}_{\min(i,k\rightarrow BS)}$ computation.

The above scheme aids in fair distribution of resources in the system. The intent is to prevent class A WTs from blocking class B WTs. This blocking is prevented by not allowing class A WTs to hog the links that class B WTs may need. The illustration below, in Figure 2.8, will help clarify this fair resource distribution concept.

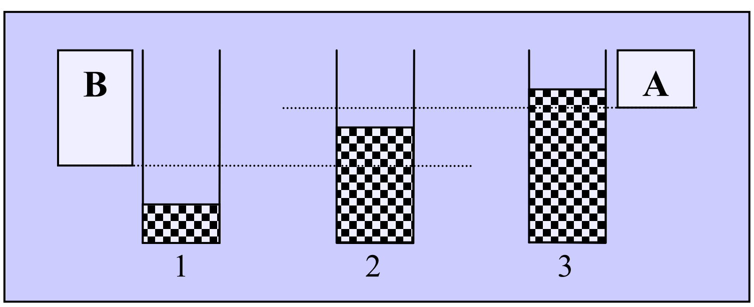

Figure 2.8: Bin demonstration for relayer selection scheme

In Figure 2.8, above, there are three bins at various states of fullness; bin 1 is the least full while bin 3 is the most full. It can be clearly seen that there can be no room in any bin for block B (representing class B WTs) if block A (representing class A WTs) is allowed to occupy bin 1.

However, if block A is placed in bin 2, block B can fit in bin 1. So, in the figure above, it can be clearly seen that the system's resources are better utilized by allowing class A WTs to use the links that are just adequate while letting class B WTs have the best links.

The relayer selection scheme could be extended to multi-hop use by forwarding the relayer assignments to each relayee along its multi-hop path; the method of computing the relayer assignments would not change. The path to the final relayer (i.e. the one which interfaces with the BS) would then be used if each of its links (the path to the final relayer may be composed of several links in the unlicensed bands) was adequate. If any of these links is inadequate, a new path to the final relayer could be computed or a new final relayer chosen and a new path to this latest final relayer computed. If no adequate paths could found, the relayee would be dropped.

Chapter 3 System Operations

This chapter describes how the system operates. At first, a comprehensive example is given, followed by descriptions of more operational details; the chapter is then concluded by descriptions of system extensions to multi class scenarios.

3.1 Example Showing System Operation

In this example the following values are assumed:

$P_{T,\max}$ = 0.1 Watt, $P_N = 1.3\times10^{-13}$ Watt

f_A = 0.1, f_B =0.2, γ_A = 10, γ_B =11.25, R_A = 50 Kbits/sec, R_B = 100 Kbits/sec

N_A = 90, N_B = 45, W = 4.5 MHz.

The following series of figures (Figures 3.1 to 3.6) graphically depict the sequence of events as each WT joins the system:

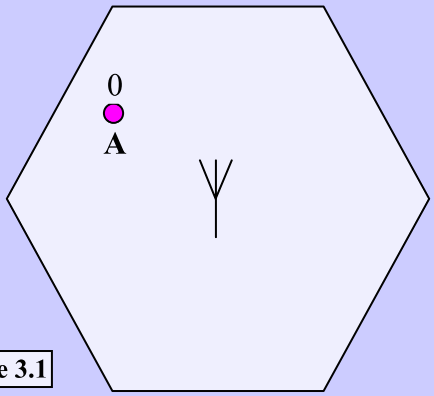

Figure 3.1

WT 0 joins the network:

a) is randomly assigned a geographic location
b) based on distance from BS and shadow fading, WT(0) has a LG of 1×10^{-12}; LG[0] = 1×10^{-12}
c) WT(0) has a 50:50 chance of being either a class A or class B WT; WT(0) is class A
d) check total resource consumption:

$$F=\sum_{i=0}^{K-1} f_i = 0.1$$

$F < 1.0 \therefore$ WT(0) is admitted.

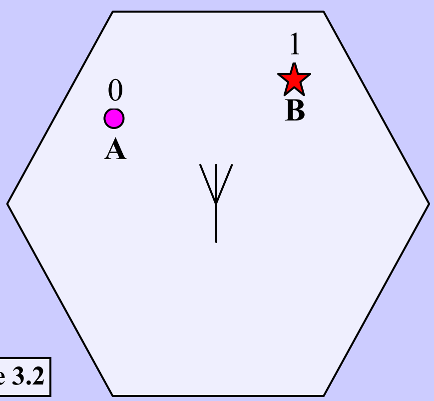

Figure 3.2

WT 1 joins the network:

e) is randomly assigned a geographic location
f) based on distance from BS and shadow fading, WT(1) has a LG of 1×10^{-15}; LG[1] = 1×10^{-15}
g) WT(1) has a 50:50 chance of being either a class A or class B WT; WT(1) is class B
h) check total resource consumption:

$$F=\sum_{i=0}^{K-1} f_i = 0.1+0.2 = 0.3$$

$F < 1.0 \therefore$ WT(1) is admitted.

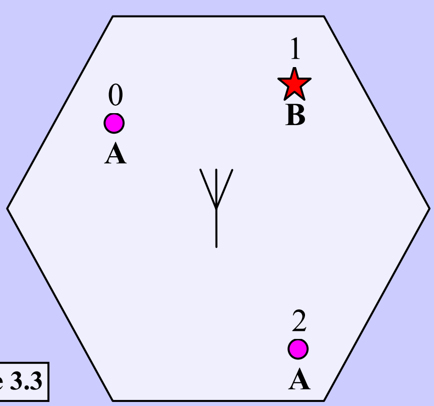

Figure 3.3

WT 2 joins the network:

i) is randomly assigned a geographic location
j) based on distance from BS and shadow fading, WT(2) has a LG of 4×10^{-14}; LG[2] = 4×10^{-14}
k) WT(2) has a 50:50 chance of being either a class A or class B WT; WT(2) is class A
l) check total resource consumption:

$$F=\sum_{i=0}^{K-1} f_i = 0.3+0.1 = 0.4$$

$F < 1.0 \therefore$ WT(2) is admitted.

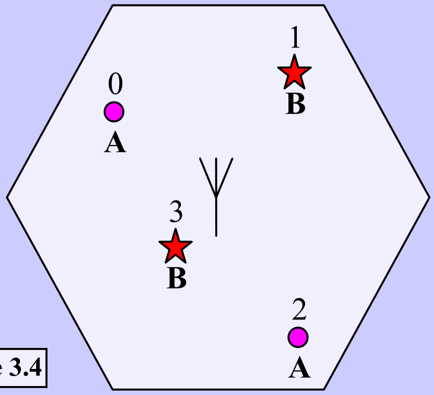

Figure 3.4

WT 3 joins the network:

m) is randomly assigned a geographic location

n) based on distance from BS and shadow fading, WT(3) has a LG of; 5×10^{-7}; LG[3] = 5×10^{-7}

o) WT(3) has a 50:50 chance of being either a class A or class B WT; WT(3) is class B

p) check total resource consumption:

$$F=\sum_{i=0}^{K-1} f_i = 0.4+0.2=0.6$$

$F<1.0 \therefore$ WT(3) is admitted.

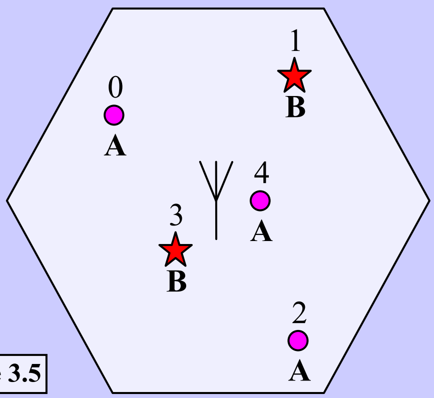

Figure 3.5

WT 4 joins the network:

q) is randomly assigned a geographic location

r) based on distance from BS and shadow fading, WT(4) has a LG of; 7×10^{-6}; LG[4] = 7×10^{-6}

s) WT(4) has a 50:50 chance of being either a class A or class B WT; WT(4) is class A

t) check total resource consumption:

$$F=\sum_{i=0}^{K-1} f_i = 0.6+0.1=0.7$$

$F<1.0 \therefore$ WT(4) is admitted.

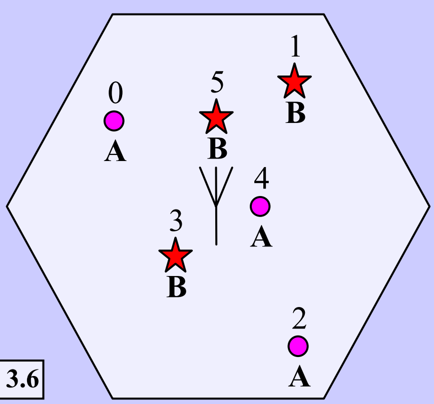

Figure 3.6

WT 5 joins the network:

u) is randomly assigned a geographic location

v) based on distance from BS and shadow fading, WT(5) has a LG of; 1×10^{-10}; LG[5] = 1×10^{-10}

w) WT(5) has a 50:50 chance of being either a class A or class B WT; WT(5) is class B

x) check total resource consumption:

$$F=\sum_{i=0}^{K-1} f_i = 0.7+0.2=0.9$$

$F<1.0 \therefore$ WT(5) is admitted.

Note: No other WT can join the network because the $\sum_{l=1}^{L} K_l f_l < 1$ inequality would be violated.

An analysis of the system's throughput is given below:

- If the WT can attain its $P_{R,\min(i,BS)}^{hop2}$ (i.e. the minimum receive power at the BS according to (2.8)) at the BS, it is assigned a bit rate and becomes a candidate relayer (i.e. it may relay signals for WTs whose $P_R < P_{R,\min(i,BS)}^{hop2}$).
- If the WT cannot attain $P_{R,\min(i,BS)}^{hop2}$ at the BS, it is assigned a bit rate=0 and becomes a potential relayee (i.e. it will need a relayer to transmit its signal to the BS).
- No WT is allowed to exceed $P_{T,\max}$.

$$P_{T(i)} = \frac{P_{R,\min(i,BS)}^{hop2}}{G_{(i,BS)}} \tag{3.1}$$

$P_{T(i)}$ = transmit power for WT i

$P_{R,\min(i,BS)}^{hop2}$ = minimum receive power for WT i on hop 2 at the BS

$G_{(i,BS)}$ = link gain between WT i and the BS

- All class A WTs have the same $P_{R,\min(i,BS)}^{hop2}$ (i.e. $P_{R,\min A}^{hop2}$)

$$P_{R,\min A}^{hop2} = \frac{0.1(1.3\times10^{-13}W)}{1-(0.1+0.2+0.1+0.2+0.1+0.2)} = 1.3\times10^{-13}W$$

- All class B WTs have the same $P_{R,\min(i,BS)}^{hop2}$ (i.e. $P_{R,\min B}^{hop2}$)

$$P_{R,\min B}^{hop2} = \frac{0.2(1.3\times10^{-13}W)}{1-(0.1+0.2+0.1+0.2+0.1+0.2)} = 2.6\times10^{-13}W$$

Note: In the ensuing computations, G[0] $= G_{(0,BS)}$ and G[1] $= G_{(1,BS)}$ etc.

- **WT(0)**

$$P_{T(0)} = \frac{P_{R,\min A}^{hop2}}{G_{(0,BS)}} = \frac{1.3\times10^{-13}W}{1\times10^{-12}} = 0.13\ \ W$$

$P_{T(0)} > P_{T,\max}\,(0.1\ W)$ $\therefore$ WT(0) is not allowed to transmit and becomes a relayee

WT(0) → relayee(0) & Rate(0)=0.

- **WT(1)**

$$P_{T(1)} = \frac{P_{R,\min B}^{hop2}}{G_{(1,BS)}} = \frac{2.6\times10^{-13}W}{1\times10^{-15}} = 260\ \ W$$

$P_{T(1)} > P_{T,\max}\,(0.1\ W)$ $\therefore$ WT(1) is not allowed to transmit and becomes a relayee

WT(1) → relayee(1) & Rate(1)=0.

- **WT(2)**

$$P_{T(2)} = \frac{P_{R,\min A}^{hop2}}{G_{(2,BS)}} = \frac{1.3\times10^{-13}W}{4\times10^{-14}} = 3.25\ \ W$$

$P_{T(2)} > P_{T,\max}\,(0.1\ W)$ $\therefore$ WT(2) is not allowed to transmit and becomes a relayee

WT(2) → relayee(2) & Rate(2)=0.

- **WT(3)**

$$P_{T(3)} = \frac{P_{R,\min B}^{hop2}}{G_{(3,BS)}} = \frac{2.6\times10^{-13}W}{5\times10^{-7}} = 5.2\times10^{-7}W$$

$P_{T(3)} < P_{T,\max}\,(0.1\ W)$ $\therefore$ WT(3) is allowed to transmit and becomes a candidate relayer

WT(3) → relayer(3) & Rate(3)=100 Kbits/sec.

- **WT(4)**

$$P_{T(4)} = \frac{P_{R,\min A}^{hop2}}{G_{(4,BS)}} = \frac{1.3\times10^{-13}W}{7\times10^{-6}} = 1.86\times10^{-8}W$$

$P_{T(4)} < P_{T,\max}$ (0.1 W) $\therefore$ WT(4) is allowed to transmit and becomes a candidate relayer

WT(4) → relayer(4) & Rate(4)=50 Kbits/sec

- **WT(5)**

$$P_{T(5)} = \frac{P_{R,\min B}^{hop2}}{G_{(5,BS)}} = \frac{2.6 \times 10^{-13} W}{1 \times 10^{-10}} = 0.0026 \ W$$

$P_{T(5)} < P_{T,\max}$ (0.1 W) $\therefore$ WT(5) is allowed to transmit and becomes a candidate relayer

WT(5) → relayer(5) & Rate(5)=100 Kbits/sec.

Total Throughput = 250 Kbits/sec (before relaying)

Table 3.1 shows the link gains between relayees and relayers; all these links are in the unlicensed bands. Relaying will be dealt with now using the link gains in Table 3.1:

	Relayee(0)	Relayee(1)	Relayee(2)
Relayer(3)	1×10^{-9}	1×10^{-15}	2×10^{-11}
Relayer(4)	2×10^{-13}	3×10^{-10}	5×10^{-10}
Relayer(5)	5×10^{-8}	7×10^{-8}	1×10^{-14}

Table 3.1: The link gains between the relayers and the relayees

The link gains between the relayers and the relayees are used as indicated in the example below:

$G_{(0,3)}$ = link gain between relayee(0) and relayer(3).

- **Relayee(0)**

  Relayee(0) is class A, so start with the weakest hop 2 link which is between relayer(5) and the BS.

$$P_{R,\min A(0)}^{hop2} = \frac{0.1\left(1.3 \times 10^{-13} W\right)}{1 - \left(0.2 + 0.1 + 0.2 + 0.1\right)} = 3.25 \times 10^{-14} W$$

$P_{R,\min A(0)}^{hop2}$ = minimum receive power at the BS for relayee(0) taking into account the three relayers and itself.

$$G_{\min(0,5\to BS)}^{hop2} = \frac{3.25\times10^{-14}W}{0.1W - 0.0026W} = 3.337\times10^{-13}$$

The term in the denominator above represents relayer(5)'s available transmit power ($P_{T,\max} - P_{T(5)} -$ power used in transmitting signals for any previous relayees [in this case there are no previous relayees]).

$G_{(5,BS)} = 1\times10^{-10} > G_{\min(0,5\to BS)}^{hop2}$ $\therefore$ relayer(5) is okay so far.

Check the corresponding hop 1 link:

$$G_{\min(0,5)}^{hop1} = \frac{10\left(\sum_{\substack{j=0\\ j\neq i}}^{K_R} 0\times G_{(j,k)} + P_N\right)}{90\times0.1W} = \frac{10\left(0+1.3\times10^{-13}W\right)}{90\times0.1W} = 1.444\times10^{-13}$$

$G_{(0,5)} = 5\times10^{-8} > G_{\min(0,5)}^{hop1}$ $\therefore$ relayer(5) is still okay.

Update the new transmit powers:

$$P_{T(0)} = \frac{P_{R,\min(0,5)}^{hop1}}{G_{(0,5)}} = \frac{G_{\min(0,5)}^{hop1}P_{T\max}}{G_{(0,5)}} = \frac{1.444\times10^{-13}\times0.1W}{5\times10^{-8}} = 288.8\times10^{-9}W$$

$$P_{T(5)} = \frac{P_{R,\min A(0)}^{hop2}}{G_{(5,BS)}} + 0.0026\ W(P_{T(5)previous}) = \frac{3.25\times10^{-14}W}{1\times10^{-10}} + 0.0026\ W{=}0.00293\ W$$

- **Relayee(1)**

Relayee(1) is class B, so start with the best hop 2 link; the best hop 2 link is between relayer(4) and the BS.

$$P_{R,\min B(1)}^{hop2} = \frac{0.2\left(1.3\times10^{-13}W\right)}{1-\left(0.2+0.1+0.2+0.1+0.2\right)} = 1.3\times10^{-13}W$$

$$G^{hop2}_{\min(1,4\to BS)} = \frac{1.3\times10^{-13}W}{0.1W - 1.86\times10^{-8}W} = 1.3\times10^{-12}$$

$G_{(4,BS)} = 7\times10^{-6} > G^{hop2}_{\min(1,4\to BS)}$ $\therefore$ relayer(4) is okay so far.

Check the corresponding hop 1 link:

$$G^{hop1}_{\min(1,4)} = \frac{11.25\left(288.8\times10^{-9}W\times2\times10^{-13} + 1.3\times10^{-13}W\right)}{45\times0.1W} = 3.25\times10^{-13}$$

$G_{(1,4)} = 3\times10^{-10} > G^{hop1}_{\min(1,4)}$ $\therefore$ relayer(4) is still okay.

$$P_{T(1)} = \frac{P^{hop1}_{R,\min(1,4)}}{G_{(1,4)}} = \frac{G^{hop1}_{\min(1,4)}P_{T,\max}}{G_{(1,4)}} = \frac{3.25\times10^{-13}\times0.1W}{3\times10^{-10}} = 108.3\times10^{-6}W$$

$$P_{T(4)} = \frac{P^{hop2}_{R,\min B(1)}}{G_{(4,BS)}} + 1.86\times10^{-8}W = \frac{1.3\times10^{-13}W}{7\times10^{-6}} + 1.86\times10^{-8}W = 3.717\times10^{-8}W$$

Recheck $G^{hop1}_{\min(0,5)}$ since relayee(1) is now transmitting:

$$G^{hop1}_{\min(0,5)} = \frac{10\left(108.3\times10^{-6}W\times7\times10^{-8} + 1.3\times10^{-13}W\right)}{90\times0.1W} = 8.57\times10^{-12}$$

$$P_{T(0)} = \frac{8.57\times10^{-12}\times0.1W}{5\times10^{-8}} = 17.14\times10^{-6}W$$

Since $5\times10^{-8} > 8.57\times10^{-12}$, relayer(5) is still okay.

Recheck $G^{hop1}_{\min(1,4)}$:

$$G^{hop1}_{\min(1,4)} = \frac{11.25\left(17.14\times10^{-6}W\times2\times10^{-13} + 1.3\times10^{-13}W\right)}{45\times0.1W} = 3.25\times10^{-13}$$

$G_{(1,4)} = 3\times10^{-10} > G^{hop1}_{\min(1,4)}$ $\therefore$ relayer(4) is still okay.

$$P_{T(1)} = \frac{P^{hop1}_{R,\min(1,4)}}{G_{(1,4)}} = \frac{G^{hop1}_{\min(1,4)}P_{T,\max}}{G_{(1,4)}} = \frac{3.25\times10^{-13}\times0.1W}{3\times10^{-10}} = 108.3\times10^{-6}W$$

Recheck $G^{hop2}_{\min(0,5\to BS)}$ since another WT has been added:

$$P^{hop2}_{R,\min A(0)} = \frac{0.1\left(1.3\times10^{-13}W\right)}{1-\left(0.2+0.1+0.2+0.1+0.2\right)} = 6.5\times10^{-14}W$$

$$G^{hop2}_{\min(0,5\rightarrow BS)} = \frac{6.5\times10^{-14}W}{0.1W-0.0026W} = 6.674\times10^{-13}$$

$G_{(5,BS)} = 1\times10^{-10} > G^{hop2}_{\min(0,5\rightarrow BS)}$ $\therefore$ relayer(5) is okay so far.

$$P_{T(5)} = \frac{P^{hop2}_{R,\min A(0)}}{G_{(5,BS)}} + 0.0026\ W(P_{T(5)previous}) = \frac{6.5\times10^{-14}W}{1\times10^{-10}} + 0.0026\ W = 0.00325\ \ W$$

So relayer(5) is still fine; consequently, $P_{T(1)}$ is still unchanged (because $G^{hop1}_{\min(1,4)}$ is still the same) and thus, $P_{T(0)}$ will not change and therefore, relayees (0) and (1) are stable. So we now have the following relayee → relayer connections: $\left[0\Rightarrow5,1\Rightarrow4\right]$.

- **Relayee(2)**

Relayee(2) is class A, so start with the poorest hop 2 link; the poorest hop 2 link is between relayer(5) and the BS.

$$P^{hop2}_{R,\min A(2)} = \frac{0.1\left(1.3\times10^{-13}W\right)}{1-\left(0.2+0.1+0.2+0.1+0.2+0.1\right)} = 1.3\times10^{-13}W$$

$$G^{hop2}_{\min(2,5\rightarrow BS)} = \frac{1.3\times10^{-13}W}{0.1W-0.00325W} = 1.344\times10^{-12}$$

$G_{(5,BS)} = 1\times10^{-10} > G^{hop2}_{\min(2,5\rightarrow BS)}$ $\therefore$ relayer(5) is okay so far.

Check the corresponding hop 1 link:

$$G^{hop1}_{\min(2,5)} = \frac{10\left(17.14\times10^{-6}W\times5\times10^{-8} + 108.3\times10^{-6}W\times7\times10^{-8} + 1.3\times10^{-13}W\right)}{90\times0.1W} = 9.52\times10^{-12}$$

$G_{(2,5)} = 1\times10^{-14} < G^{hop1}_{\min(2,5)}$ $\therefore$ hop 1 has *failed*.

Now go and choose the next higher hop 2 link and redo the hop 2 analysis; the next higher hop 2 link is between relayer(3) and the BS:

$$G^{hop2}_{\min(2,3\to BS)} = \frac{1.3\times10^{-13}W}{0.1W - 520\times10^{-9}W} = 1.3\times10^{-12}$$

$G_{(3,BS)} = 5\times10^{-7} > G^{hop2}_{\min(2,3\to BS)}$ $\therefore$ relayer(3) is okay so far.

Check the corresponding hop 1 link:

$$G^{hop1}_{\min(2,3)} = \frac{10\left(17.14\times10^{-6}W\times1\times10^{-9} + 108.3\times10^{-6}W\times1\times10^{-15} + 1.3\times10^{-13}W\right)}{90\times0.1W} = 163.5\times10^{-15}$$

$G_{(2,3)} = 2\times10^{-11} > G^{hop1}_{\min(2,3)}$ $\therefore$ relayer(3) is okay so far.

$$P_{T(2)} = \frac{163.5\times10^{-15}\times0.1W}{2\times10^{-11}} = 817.4\times10^{-6}W$$

$$P_{T(3)} = \frac{P^{hop2}_{R,\min A(2)}}{G_{(3,BS)}} + 5.2\times10^{-7}W = \frac{1.3\times10^{-13}W}{5\times10^{-7}} + 5.2\times10^{-7}W = 7.8\times10^{-7}W$$

Recheck $G^{hop2}_{\min(0,5\to BS)}$ and $G^{hop2}_{\min(1,4\to BS)}$ since another WT has been added:

$$P^{hop2}_{R,\min(0)} = \frac{0.1\left(1.3\times10^{-13}W\right)}{1-\left(0.2+0.1+0.2+0.1+0.2+0.1\right)} = 1.3\times10^{-13}W$$

$$G^{hop2}_{\min(0,5\to BS)} = \frac{1.3\times10^{-13}W}{0.1W - 0.0026W} = 1.335\times10^{-12}$$

$G_{(5,BS)} = 1\times10^{-10} > G^{hop2}_{\min(0,5\to BS)}$ $\therefore$ relayer(5) is okay so far.

$$P_{T(5)} = \frac{P^{hop2}_{R,\min A(0)}}{G_{(5,BS)}} + 0.0026W = \frac{1.3\times10^{-13}W}{1\times10^{-10}} + 0.0026\,W = 0.0039\,W$$

$$P^{hop2}_{R,\min B(1)} = \frac{0.2\left(1.3\times10^{-13}W\right)}{1-\left(0.2+0.1+0.2+0.1+0.2+0.1\right)} = 2.6\times10^{-13}W$$

$$G_{\min(1,4\to BS)}^{hop2} = \frac{2.6\times10^{-13}W}{0.1W - 1.86\times10^{-8}W} = 2.6\times10^{-12}$$

$G_{(4,BS)} = 7\times10^{-6} > G_{\min(0,5\to BS)}^{hop2}$ $\therefore$ relayer(4) is okay so far.

$$P_{T(4)} = \frac{P_{R,\min B(1)}}{G_{(4,BS)}} + 1.86\times10^{-8}W = \frac{2.6\times10^{-13}W}{7\times10^{-6}} + 1.86\times10^{-8}W = 5.574\times10^{-8}W$$

All the hop 2 links are fine and will remain stable unless there is a relayer switch, or if a link is terminated.

Recheck $G_{\min(0,5)}^{hop1}$:

$$G_{\min(0,5)}^{hop1} = \frac{10\left(108.3\times10^{-6}W\times7\times10^{-8} + 817.4\times10^{-6}W\times1\times10^{-14} + 1.3\times10^{-13}W\right)}{90\times0.1W} = 8.568\times10^{-12}$$

$G_{(0,5)} = 5\times10^{-8} > G_{\min(0,5)}^{hop1}$ $\therefore$ relayer(5) is still okay.

$$P_{T(0)} = \frac{8.568\times10^{-12}\times0.1W}{5\times10^{-8}} = 17.14\times10^{-6}W$$

Recheck $G_{\min(1,4)}^{hop1}$:

$$G_{\min(1,4)}^{hop1} = \frac{11.25\left(17.14\times10^{-6}W\times2\times10^{-13} + 817.4\times10^{-6}W\times5\times10^{-10} + 1.3\times10^{-13}W\right)}{45\times0.1W} = 1.347\times10^{-12}$$

$G_{(1,4)} = 3\times10^{-10} > G_{\min(1,4)}^{hop1}$ $\therefore$ relayer(4) is still okay.

$$P_{T(1)} = \frac{1.347\times10^{-12}\times0.1W}{3\times10^{-10}} = 4.49\times10^{-4}W$$

Recheck $G_{miin(2,3)}^{hop1}$:

$$G_{miin(2,3)}^{hop1} = \frac{10\left(17.14\times10^{-6}W\times1\times10^{-9} + 4.49\times10^{-4}W\times1\times10^{-15} + 1.3\times10^{-13}W\right)}{90\times0.1W} = 1.635\times10^{-13}$$

$G_{(2,3)} = 2\times10^{-11} > G^{hop1}_{\min(2,3)} \therefore$ relayer(3) is still okay.

$$P_{T(2)} = \frac{1.635\times10^{-13}\times0.1W}{2\times10^{-11}} = 8.174\times10^{-4}W$$

Recheck $G^{hop1}_{miin(0,5)}$:

$$G^{hop1}_{\min(0,5)} = \frac{10\left(4.49\times10^{-4}W\times7\times10^{-8}+817.4\times10^{-6}W\times1\times10^{-14}+1.3\times10^{-13}W\right)}{90\times0.1W} = 3.507\times10^{-11}$$

$G_{(0,5)} = 5\times10^{-8} > G^{hop1}_{\min(0,5)} \therefore$ relayer(5) is still okay.

$$P_{T(0)} = \frac{3.507\times10^{-11}\times0.1W}{5\times10^{-8}} = 7.014\times10^{-5}W$$

Recheck $G^{hop1}_{miin(1,4)}$:

$$G^{hop1}_{\min(1,4)} = \frac{11.25\left(7.014\times10^{-5}W\times2\times10^{-13}+817.4\times10^{-6}W\times5\times10^{-10}+1.3\times10^{-13}W\right)}{45\times0.1W} = 1.347\times10^{-12}$$

$G_{(1,4)} = 3\times10^{-10} > G^{hop1}_{\min(1,4)} \therefore$ relayer(4) is still okay.

$$P_{T(1)} = \frac{1.347\times10^{-12}\times0.1W}{3\times10^{-10}} = 4.49\times10^{-4}W$$

Recheck $G^{hop1}_{miin(2,3)}$:

$$G^{hop1}_{\min(2,3)} = \frac{10\left(7.014\times10^{-5}W\times1\times10^{-9}+4.49\times10^{-4}W\times1\times10^{-15}+1.3\times10^{-13}W\right)}{90\times0.1W} = 2.224\times10^{-13}$$

$G_{(2,3)} = 2\times10^{-11} > G^{hop1}_{\min(2,3)} \therefore$ relayer(3) is still okay.

$$P_{T(2)} = \frac{2.224\times10^{-13}\times0.1W}{2\times10^{-11}} = 1.112\times10^{-3}W$$

Since it is not feasible to continue with successive iterations, the example is concluded here and we now have the following relayee → relayer connections: $[0 \Rightarrow 5, 1 \Rightarrow 4, 2 \Rightarrow 3]$. In the code, the preceding iterative process would continue until: $0.99 < \frac{P^{(n+1)}{}_{T(i)}}{P^{(n)}{}_{T(i)}} < 1.01$ or until 100 iterations. If the preceding termination condition is not satisfied, the iterative process would be aborted and that particular scenario would not be included in the throughput because of the transmit power fluctuations, which may lead to relayer choice oscillations. In the termination condition, $P^{(n)}{}_{T(i)}$ is relayee i's transmit power in the n^{th} iteration and $P^{(n+1)}{}_{T(i)}$ is relayee i's transmit power in the $(n+1)^{th}$ iteration. In the above example, successive iterations correspond with the recheck operations as they pertain to relayee transmit power computations.

3.2 Additional System Details

In the preceding example, it was not feasible to show all the details involved in the system's operation because of the space that would be required. In addition, the intent of the example is to facilitate a basic understanding of the simulation procedures, thus, the additional system details were excluded. Also, including these details would have made the example unnecessarily tedious and complex. Therefore, two additional system processes are described in this section, they are: the Previous User Preservation (PUP) algorithm and the use of orthogonal codes and synchronicity to increase throughput; neither of these two processes is mentioned in the simulation plots although they are included in the simulation code.

3.2.1 Previous User Preservation (PUP) Algorithm

This algorithm is designed to prevent a new relayee from joining the network and thus cut off a previous relayee(s) that was successfully transmitting. The intent is to implement a fair procedure, which in this case, gives priority to the relayees that have successfully joined the network. Therefore, if a new relayee joins the network and its presence results in one or more previous relayees losing service, that new relayee is cut off and the state of the system is brought back to where it was before the arrival of the disruptive relayee.

3.2.2 Orthogonal Codes and Synchronicity

The algorithm involved in implementing orthogonal codes and synchronicity is implemented during relaying. During relaying, the signals of the relayees and the relayer are transmitted in the licensed bands using orthogonal codes; these orthogonal signals are also synchronized at the chip level. The synchronization is possible because the signals originate from the same device (i.e. the relayer). The result of this process is lower interference at the BS which leads to lower values for $G^{hop2}_{\min(i,k\rightarrow BS)}$ and ultimately higher throughput due to fewer relayees being cutoff. The illustration in Figure 3.7 will more clearly show how this 'Orthogonal Codes and Synchronicity' scheme works. It should be noted that this scheme cannot be used in the unlicensed bands due to the nature of the transmissions there. In the unlicensed bands the transmissions from each relayee cannot be synchronized in time because they originate from different sources, unlike each relayer which can synchronize its signal with those of its relayees.

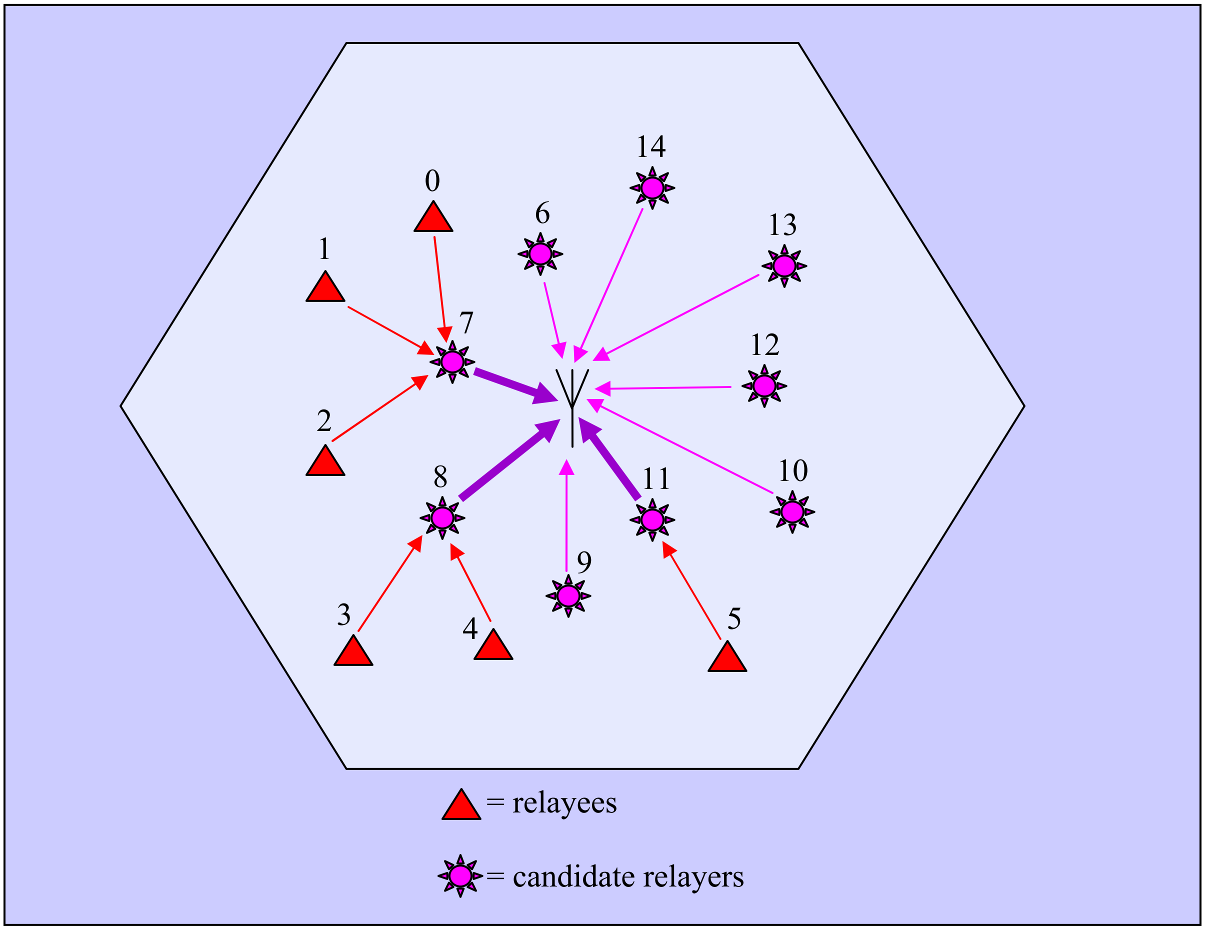

Figure 3.7: Synchronicity/orthogonality illustration

In Figure 3.7, all the candidate relayers are directly connected to the BS. The thick lines in the figure indicate that the relayer is carrying its own signal in addition to the signals for other relayees. In the above illustration, the following sets of signals would be synchronized and assigned orthogonal codes: (0,1,2,7), (3,4,8), (5,11). Each set of signals is not synchronous with the other set. For example, signal set (0,1,2,7) is not synchronized with set (3,4,8), but signal 0 is synchronous with 1, 2 and 7, and signal 3 is synchronous with 4 and 8. In this scheme, relayee(0) will only see interference from relayees(3,4,5) and relayers(8,11). Similarly, relayee(4) will only see interference from relayees(0,1,2,5) and relayers(7,11). The same interference reduction pattern applies to the other relayees (i.e. interference is not seen from any other WT with which the WT of interest is synchronized). The interference is reduced at the BS because the orthogonal codes sum to zero there. This zero sum only occurs when the codes are summed in their entire lengths (only synchronized signals can begin and end at the same points and thus sum to zero). Therefore, groups of signals that are synchronous within themselves (e.g. relayees(3,4)-relayer(8)) but not with other groups (e.g. the group, relayees(3,4)-relayer(8) is synchronous within itself but not with the group relayee(5)-relayer(11)) will not see interference from signals within its group but will see interference from signals outside its group. Please note that the interference reduction only takes place in the licensed bands as is indicated by the aforementioned $G^{hop2}_{\min(i,k\to BS)}$ reduction.

3.3 Algorithm Extensions to Multi-Class Scenarios

The algorithms developed for this project can be readily extended to accommodate more than two WT classes. This dictates the inclusion of WTs with several different fractional consumption figures, not necessarily different *SINR* requirements and spreading gains (according to (2.3) WTs with different *SINR* requirements and spreading gains may have the same fractional consumption figure). Therefore, the delineation between WT classes is only based on fractional consumption figures.

Since there are different fractional consumption figures corresponding to the number of WT classes, there must also be a corresponding number of different receive power levels for each WT class. These receive power levels are the levels necessary at the BS for adequate service in each class and are computed using (2.8). Based on the preceding receive power levels, the minimum acceptable link gains on hop 2 are calculated using (2.9). The minimum acceptable link gains on hop 1 are computed using (2.11) and are based on the required *SINR* and spreading gain of each WT class. The system operation can then proceed as per Section 3.1.

3.3.1 Multi-Class Relayer Selection Scheme

The multi-class relayer selection scheme is a modified and extended version of the relayer selection scheme given in Section 2.4; however, the relayer-BS and relayer-relayee communications still apply here, unchanged. This scheme is designed to incorporate fixed relayers only, accommodates any number of WT classes and does so with due attention to fairness and bottleneck avoidance (the minimum link gain requirements are still used to ensure this). Fixed relayers only are used in the scheme because exclusive use of this relayer type is later shown to be the most feasible of any relayer type or combination; however, the scheme can be easily modified to use other relayer types or combinations. This relayer selection method will be described in the ensuing paragraphs.

The relayer selection scheme works by assigning the relayees that consume the most resources to relayers with the best links to the BS. The relayees that have the next lower fractional consumptions are assigned the next worse links, this continues until the relayees with the lowest fractional consumptions are given the links that are left. The scheme will be better explained using the examples below:

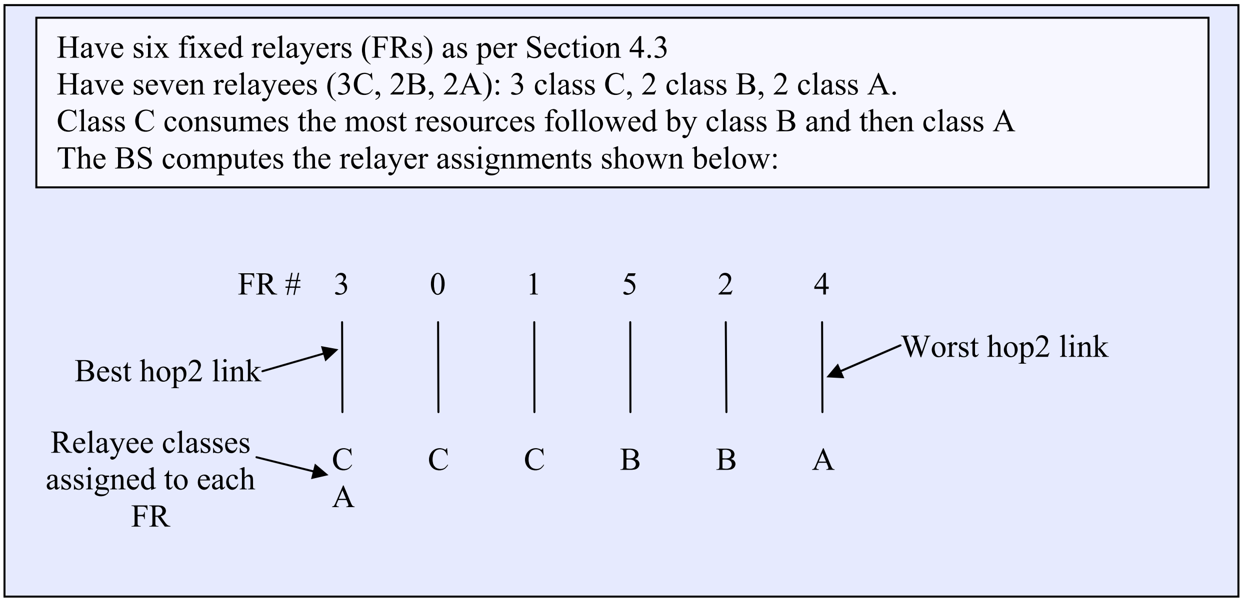

Figure 3.8: Relayer selection scheme example with seven relayees and six relayers

Figure 3.8 shows a possible relayer assignment scenario in which there are seven relayees and six relayers (FRs numbered 0 to 5). The relayers' hop 2 links are in descending order with relayer 3 having the best hop 2 link and relayer 4 having the worst link. Since there are more relayees than there are relayers, a wraparound scheme is used in the assignments, this is evident in relayer 3 having been assigned two relayees, one class A and one class C. The wraparound scheme is designed to put less power demand on the relayers with weaker links, so the extra relayees are assigned to relayers with the best links. The following example in Figure 3.9 will help clarify the preceding wraparound scheme:

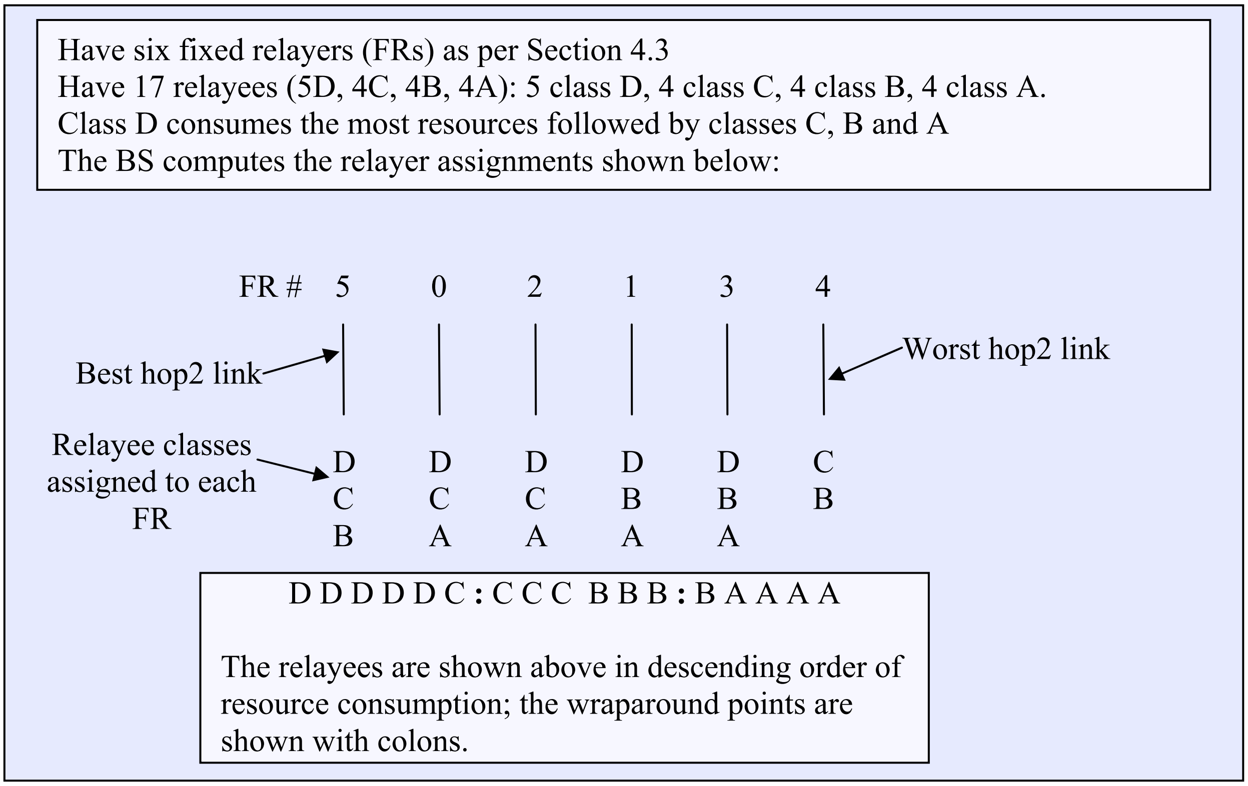

Figure 3.9: Relayer selection scheme example with 17 relayees and six relayers

Figure 3.9, above, demonstrates the wrap around scheme mentioned previously by using a scenario in which there are 6 relayers and 17 relayees. The wraparound system is designed to load each relayer appropriately (i.e. put greater demand on relayers with better hop 2 links and less on those with worse links). In addition, the wraparound system is easy to implement due to its simplicity, thus, the time spent by the BS computing the relayer assignments is minimized. The relayer selection scheme can be extended to include any number of classes. For example, there could have been 17 relayees from 17 different classes in Figure 3.9 (i.e. classes A to Q) with no changes to the way the relayer selection method works. An example showing how the above system works under various conditions, based on Figure 3.9, is given below:

In order to conserve space, only five relayees (two from class D and one from every other class) are used in this example, although many other relayees may find relayers. In addition, a lengthy numerical procedure is avoided because it is unnecessary to convey the concepts involved, consequently, the example is primarily qualitative. Also, it is assumed that the relayer-BS and the relayer-relayee communications have taken place and that each relayee is in possession of the relayer assignments worked out by the BS and shown in Figure 3.9.

The class A relayee first tries to establish a connection with relayer 0 because it is the first in the series of relayers assigned to class A relayees (the assignments are meant to put greater power burdens on relayers with better hop 2 links). This procedure applies to all classes and is different from the method outlined in Section 2.4 where the class A relayee starts with the assigned relayer having the worst hop 2 link (relayer 3 in this case) and uses it if it meets the minimum link gain requirements. This modified procedure has two advantages: (1) overall it decreases the power burden on the least capable relayers, (2) it is easier to implement because it is consistent with the method used by relayees in all the other classes, this will become clear as the example progresses. The relayee then determines that the corresponding hop 1 link at relayer 0 is inadequate for its needs, so it tries to establish a link with relayer 2, but again, the hop 1 link is inadequate, so it tries relayer 1. Relayer 1 has adequate hop 1 and hop 2 links, so relayer 1 is selected. If relayers 1 and 3 were inadequate, the relayee would try relayer 4 then 5, systematically going through all the relayers (this process applies to all relayees). If no adequate relayer was found, the relayee would be cut off. Please note that the modified procedure is not implemented in the simulations due to time constraints.

The class B relayee tries to establish a link with relayer 1 because, similar to the previous case, it is the first in the series of relayers assigned to class B relayees (the assignments are meant to put greater power burdens on relayers with better hop 2 links). The relayee cannot establish a link with relayer 1 because the hop 1 link is inadequate, so it successfully tries to establish a link with relayer 3.

The class C relayer tries to establish a link with relayer 4 (for the reason given in the preceding paragraph); however, it is unsuccessful because the hop 2 link is inadequate (the minimum link gain on hop 2 increases as its available relaying power diminishes). The relayee tries to establish links with relayers 5, 0, 2, then 1; it is finally successful with 3.

The first class D relayee tries to establish a link with relayer 5 (for the reason given previously); however, it is unsuccessful because either hop 1 or hop 2 is inadequate. The relayee then unsuccessfully tries to establish connections with relayers 0, 2, 1, and 3; it finally succeeds with relayer 4. The next class D relayee first tries to connect with relayer 5 and succeeds in doing so.

The above described relayer selection scheme appears to be successful at fair resource allocation and avoiding bottlenecks in a multi-class system. It may also promote efficient spectrum utilization, and minimize delays and WT terminal complexity. Therefore, it could significantly enhance the appeal and performance of multi-class cellular CDMA relaying networks.

Chapter 4 Simulation Results

The simulation results are discussed in this section and a simulation flow chart, which gives an overview of the simulation process, is shown in Figure 4.1. The simulation graphs consist of bar plots, capacity curves and throughput curves. The bar plots show the average number of times relayers transmit their own signals along with the signals of various numbers of relayees, and also, the average number of times relayers only transmit their own signals; all these plots are done with 18 WTs. The capacity curves are derived from the bar plots and they show the capacities of the system with and without relaying. The throughput curves simply show the average throughput of the system as the number of WTs increase from 1 to 35. The throughput curves are plotted for the following three scenarios: WT relayers only, fixed relayers only and a mixture of both WT and fixed relayers. The plots involving fixed relayers are not discussed until Section 4.3. Please note that any throughput plot not identified as including fixed relayers, only includes WT relayers.

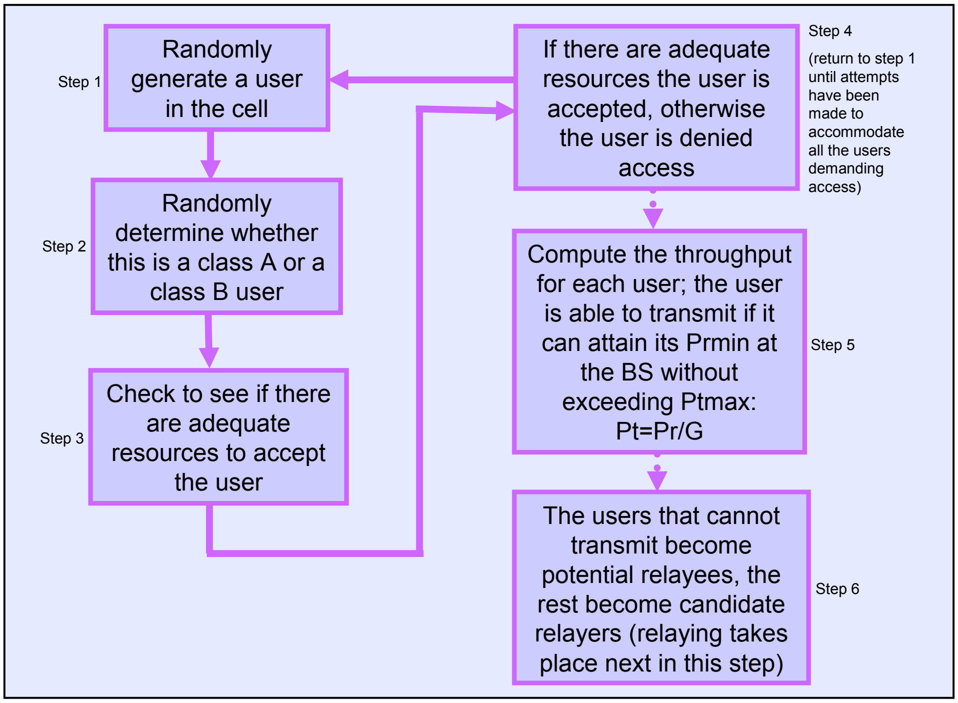

Figure 4.1: Simulation flow chart

4.1 Simulation Parameters

The parameters used in the simulations are outlined in this section. Listing these parameters will aid in understanding the results. The list follows below:

- Cell radius: varies from 500 m to 1732 m
- Maximum transmit power: varies between 0.1 W and 1.0 W
- Noise power: 1.306×10^{-13} W
- Propagation constant: 4.0 [35]
- System bandwidth: 5 MHz
- $f_A = \frac{1}{51}$, $f_B = \frac{1}{11}$
- $N_A = 500$, $N_B = 100$

- $SINR_A = SINR_B = 10$
- $R_A = 10$ Kbits/sec, $R_B = 50$ Kbits/sec

In the model a close in reference distance (i.e. d0) of 10 meters is used because free space propagation would only occur at approximately a 10 meter radius around the antenna in an urban environment [35]. The 1732 m cell radius is based on the *R* obtained when two cells are immediately beside each other with a 3000 m distance between their centers. However, only one cell is used in these simulations.

4.2 WT Relayers

The WTs simulation results will be discussed in this section. Please note that the results obtained for the WT relayers are pessimistic, because they assume that each WT relayer is transmitting its own signal all the time. In reality however, this is not the case because there several idle WTs which can be utilized more effectively as relayers because they have more power available for transmission. For the results to be properly interpreted, the graphs will be explained in the next few paragraphs; these explanations apply to fixed relayers as well..

The throughput plots show the 'Required Cumulative Throughput' on the x-axis and the 'Actual Cumulative Throughput' on the y-axis. The 'Required Cumulative Throughput' is the throughput that is required to service all the WTs in the system; this quantity increases as the number of WTs increase, hence the term cumulative. The 'Actual Cumulative Throughput' is the throughput that the system can supply to the WTs under current conditions (e.g. power cap, cell size). In all the throughput curves, each point represents the number of WTs in the system at that point. For example, one WT is indicated by the point closest to the origin, the 'two WTs' point is indicated by the next point to the right, and so on, for three through thirty five WTs. These WT points are vertically aligned on the different curves in each figure.

The throughput plots can be found in Sections 4.2.3 and 4.3; they consist of the following four curves:

- **The 'Ideal Throughput' curve** has no power cap or resource restrictions and is a straight 45 degree line (to be expected when points on the x and y axes correspond). Please note that this line theoretically extends to infinity, but it is cut short in the figures to make the other curves legible.
- **The 'Performance Benchmark' curve** has no power cap but has resource restrictions, and is the benchmark by which the system's performance is judged.
- **The 'Without Relaying' curve** shows the results obtained when there is no relaying and there are power and resource restrictions.
- **The 'With Relaying' curve** is the 'Without Relaying' curve with relaying added.

The bar plots show the 'Number of Signals Transmitted per relayer' on the x-axis and the 'Relative Frequency of Signal Transmissions' on the y-axis. If the relayer is only transmitting its own signal, the x-axis has a value of 1, if it is transmitting for one relayee the x-axis has a value of 2, if it is transmitting for two relayees the x-axis has a value of 3 etc. The y-axis shows the average number times that relayers transmit signals for various numbers of relayees, from 0 (1 on the x-axis) to 9 (10 on the x-axis). The bar plots were simulated with 18 WTs because it makes analyses simpler as it is the highest number of WTs that can be accommodated while preserving a 1:1 ratio between class A and class B WTs. This will become clearer in the ensuing analyses dealing with the correlations between the bar plots and the throughput curves. The figures and the discussions for each bar plot are in Section 4.2.1. The capacity curves simply show the system capacity on the y-axis and the cell radius on the x-axis.

4.2.1 Bar Plots

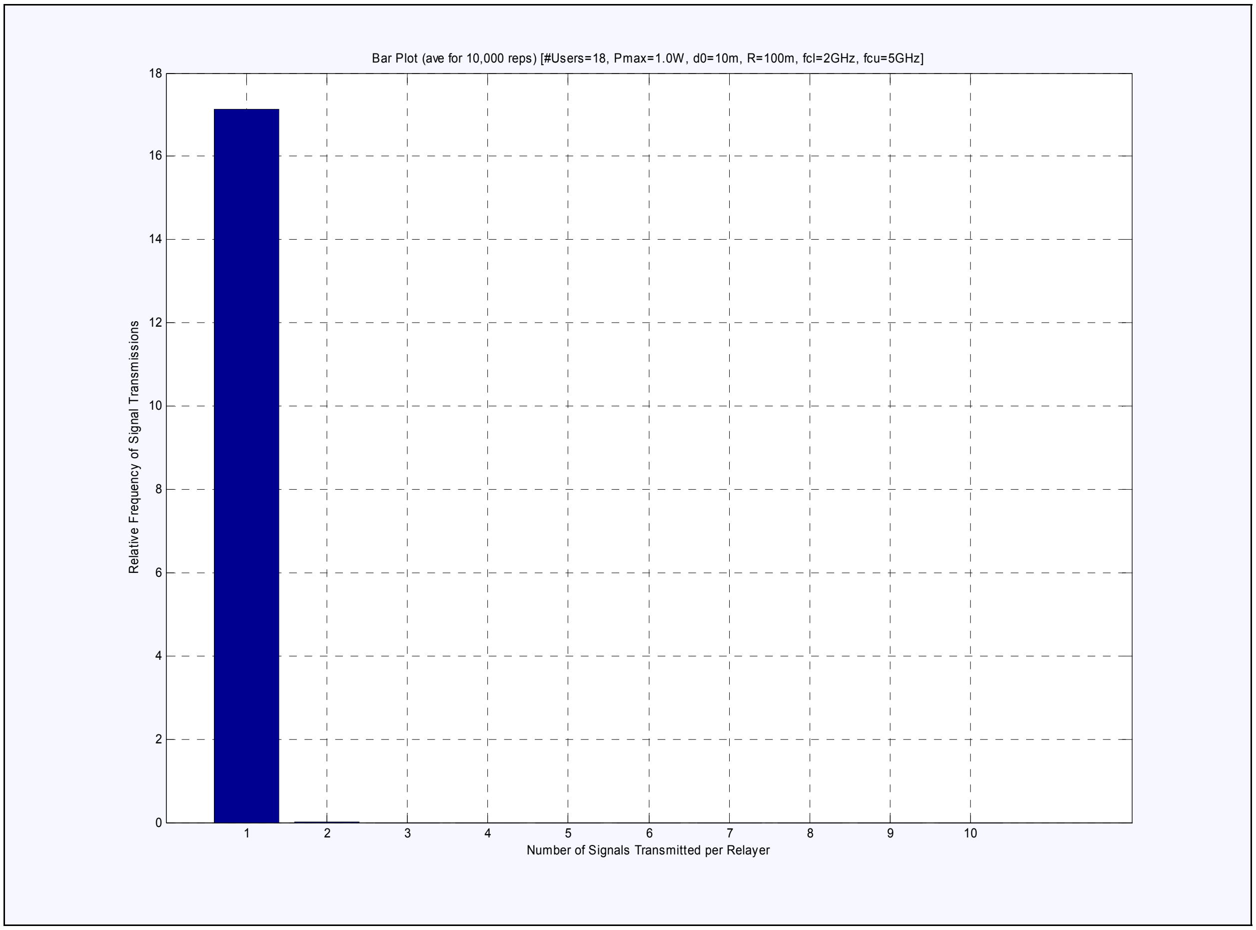

Figure 4.2: Bar plot for cell radius=100 m and maximum transmit power=1.0 W

Figure 4.2 shows the bar plot obtained in a network where there is a very small cell and a high WT power cap; it is included to show that under very good propagation conditions relaying is almost never used. The figure indicates that almost all the WTs have a direct link to the BS (i.e. on average approximately 17.1 WTs have a direct link) and only 0.03 on average utilize relaying. Since the capacity of the system, with such a small cell size and high power cap, is only 17.13, the other 0.87 WTs must be accounted for. This 17.13 WT capacity occurs because only 10 of the possible 19 different A:B WT combinations, when 18 WTs attempt to join the network, can be accommodated without equaling or exceeding the resource limit of 1.0. When any of the remaining nine combinations attempts to join, the number of WTs in that combination is cut back until the resource limit is satisfied according to (2.5). Consequently, the average capacity of the system, even with very small cells, is less than 18. Therefore, resource restrictions and not propagation conditions or the power limit, are primarily responsible for WTs not being able to get service in Figure 4.2.

Since relaying use is negligible (relaying is used, but it is barely noticeable), it may be wise not to implement this relaying scheme when the cell radius is below a certain threshold. Simulations were done for cases where R (cell radius) = 250 m, resulting in negligible relaying, bearing out the above conclusion. Relaying use was observed to be insignificant until $R \geq 500$ m; thus, only these cases are explored in the remainder of the simulation results.

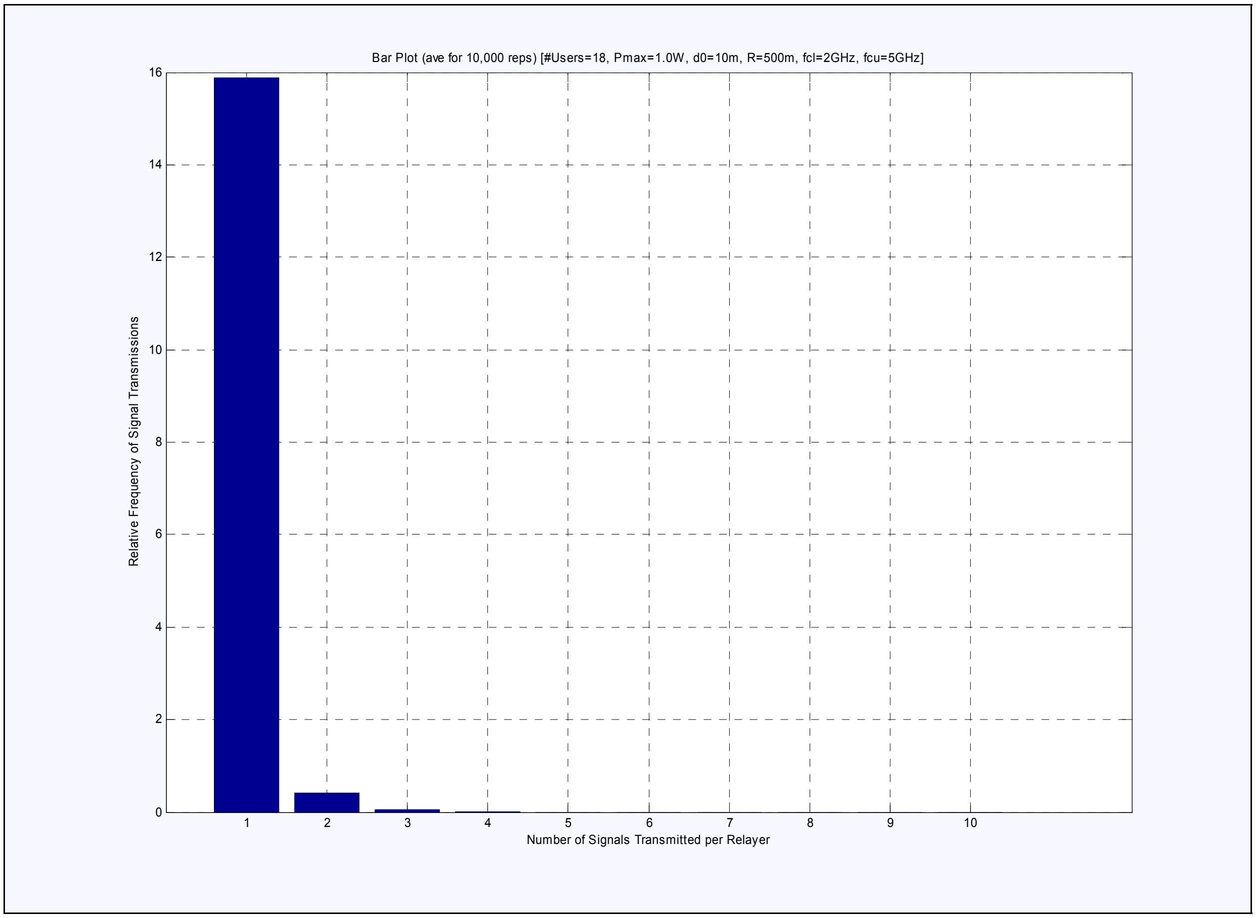

Figure 4.3: Bar plot for cell radius=500 m and maximum transmit power=1.0 W

Figure 4.3 shows the results obtained for a small cell having WTs with a high power cap. It can be seen in Figure 4.3 that as the cell radius increases the number of WTs having direct connections to the BS decreases. This occurs because distance attenuation increases as the cell radius increases (the same number of WTs is uniformly distributed in a larger area). As a result, the average number of WTs having direct connections is now approximately 16.46 (15.9+0.5+0.06), instead of 17.1 when the radius was 100 m. However, due to relaying, the total number of WTs being serviced is now 17.08 (15.9 direct, 1.0 through two signal transmissions [includes the relayer], and 0.018 through three signal transmissions [includes the relayer]), which is almost equal to the previous case in Figure 4.2. Therefore, relaying significantly helped increase the number of WTs that could be serviced.

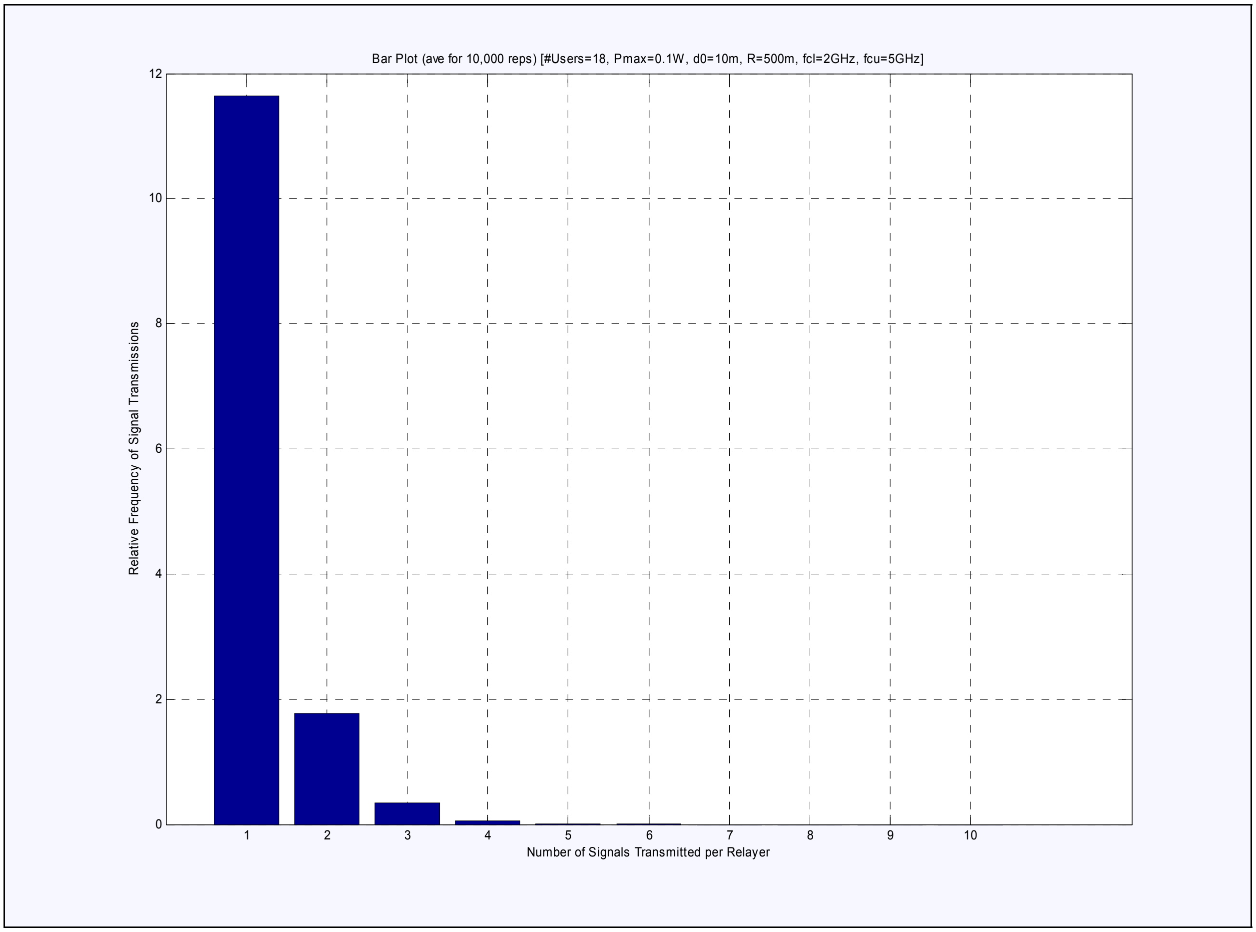

Figure 4.4: Bar plot for cell radius=500 m and maximum transmit power=0.1 W

Figure 4.4 shows the results obtained for a small cell having WTs with a low power cap. The simulation conditions under which Figure 4.4 was produced were identical to those for Figure 4.3 except for the reduced transmit power cap of 0.1 W. As a result of the power cap reduction, fewer WTs have direct links to the BS; approximately 11.6 (these WTs are not doing any relaying) versus 15.9. In addition, relaying is utilized to a greater degree, as can be seen in the increase in the number of multi-signal transmissions (1.8 double signal transmissions=3.6

WTs, 0.38 triple signal transmissions=1.14 WTs and 0.08 quad signal transmissions=0.32 WTs). Now the total number of WTs being serviced is approximately 16.66 vs. 17.08 when there was a 1.0 W power cap. This reduction exists because some WTs still cannot reach the BS through relaying because the low power cap increases the minimum acceptable link gain on both hops and consequently, adequate links cannot be found for these WTs. Again, relaying has increased the service levels significantly (without relaying the service level would approximately be = 11.6+1.8+0.38+0.08=13.86 vs. 16.66).

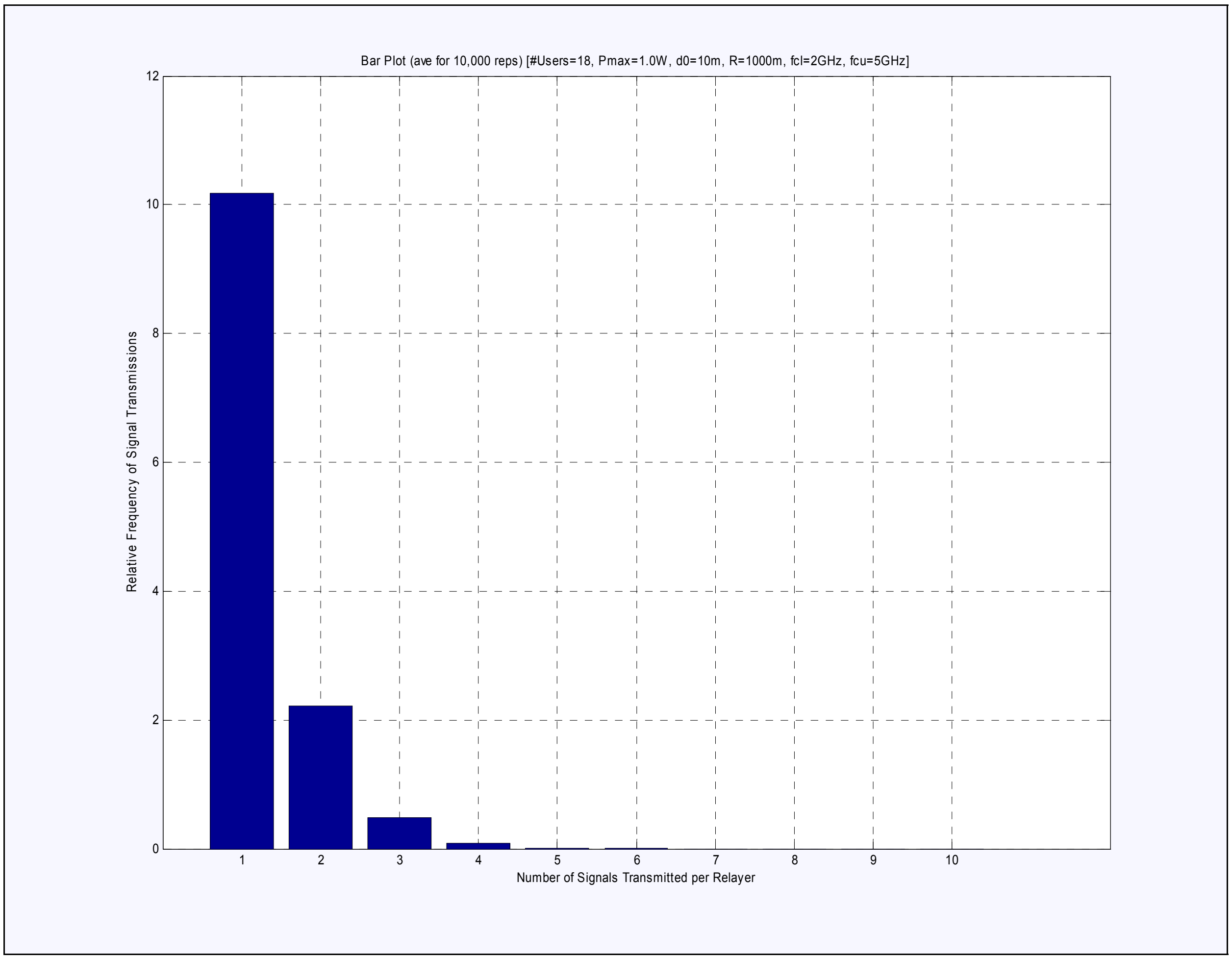

Figure 4.5: Bar plot for cell radius=1000 m and maximum transmit power=1.0 W

The cell radius was doubled to 1000 m and the power cap was increased to 1.0 W when Figure 4.5 was simulated and it shows the results obtained when a medium size cell has WTs with a high power cap. The effects of doubling R can be clearly seen, as the average number of non-relaying direct connections (i.e. these WTs are not relaying any signals) to the BS decreased from 15.9 (Figure 4.4 with the same power cap) to 10.2 here. Relaying again played a significant role as the number of multi-signal transmissions increased; here there are approximately 2.2 two-signal transmissions (4.4 WTs), 0.5 three-signal transmissions (1.5 WTs) and 0.1 four-signal transmissions (0.4 WTs). Thus, there are approximately 16.5 WTs that are serviced. Therefore, the conclusion may be made that the effects of increasing R can be at least partially offset by increasing the power cap; this can be borne out by comparing the total WT service levels in Figures 4.4 (16.66 WTs) and 14 (16.5 WTs). Without any relaying the approximate WT service level would be =10.2+2.2+0.5+0.1=13.0 vs. 16.5 with relaying; thus, relaying is a significant aid.

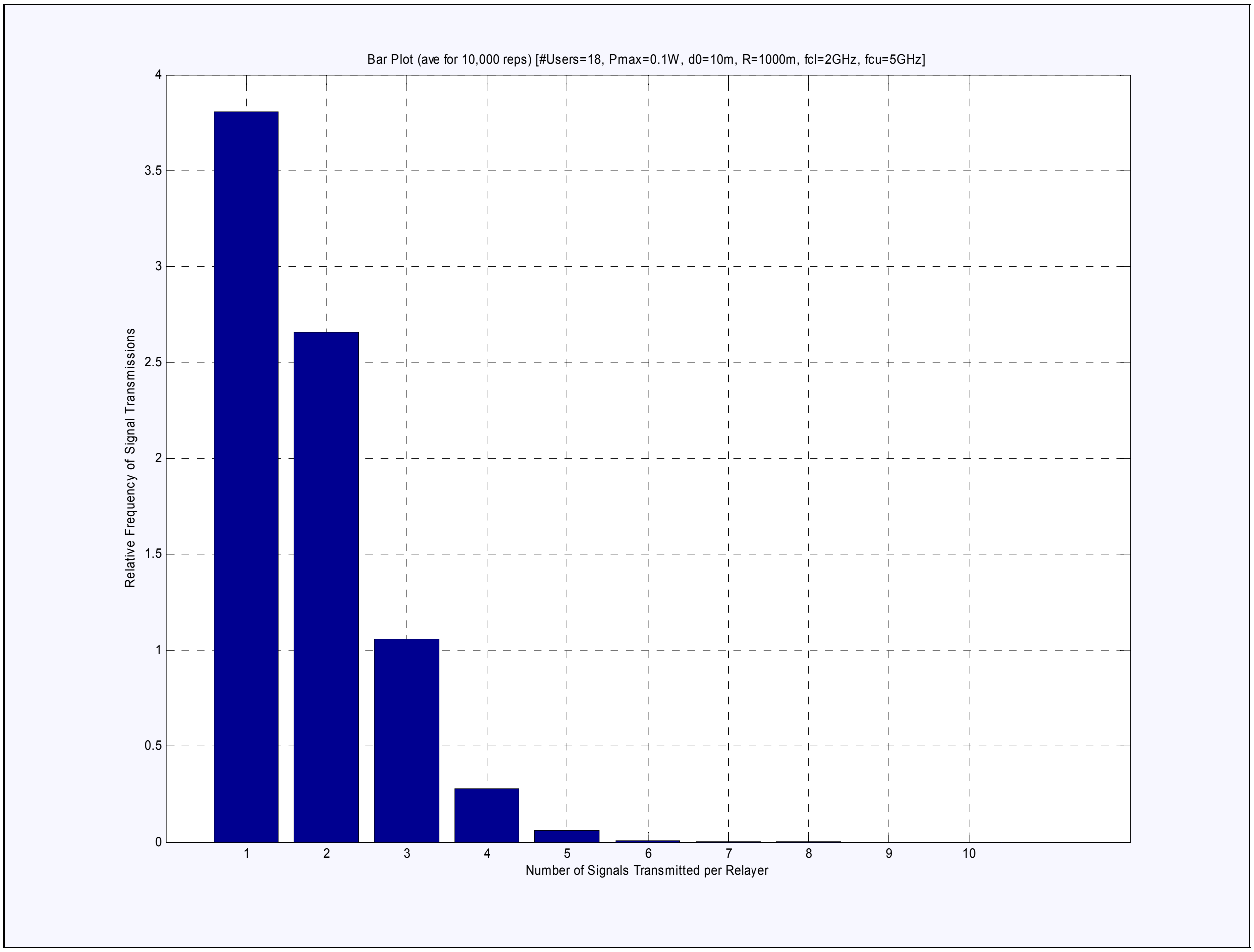

Figure 4.6: Bar plot for cell radius=1000 m and maximum transmit power=0.1 W

Relative to Figure 4.5, Figure 4.6 has a power decrease to 0.1 W and it demonstrates the results obtained when a medium size cell has WTs with a low power cap. The results in Figure 4.6 are as expected: an increase in multi-signal transmissions and a lower WT service level. As anticipated, the number of WTs having direct connections to the BS and not doing any relaying, decreased dramatically from Figure 4.5 (10.2 vs. 3.8). Since this is a larger cell, such a decrease is expected because the signal attenuates as D^{-4}, where $D =$ distance, and the transmit power is too low to allow for adequate receive power levels at the BS. As a result, relaying was more heavily utilized in the simulation and this is evident in the approximate number of multi-signal transmissions as follows: double signal transmissions=2.7 (5.4 WTs), triple signal transmissions=1.06 (3.18 WTs), quad signal transmissions=0.29 (1.16 WTs), five-signal transmissions=0.06 (0.3 WTs) and six signal transmissions =0.02 (0.12 WTs). This yields an approximate total service level of 13.96 WTs, which is lower than the figure obtained in Figure 4.5 (16.5 WTs). As was explained earlier, this decrease is due to the inability of some WTs to find adequate links because of the increase in $G_{\min(i,k)}^{hop1}$ and $G_{\min(i,k\to BS)}^{hop2}$, which in turn, are attributable to the lower transmit power cap. Relaying is helpful here, because without it there would only be approximately 8.03 (3.8+2.7+1.06+0.29+0.06+0.02) WTs serviced, vs. 13.96 with relaying.

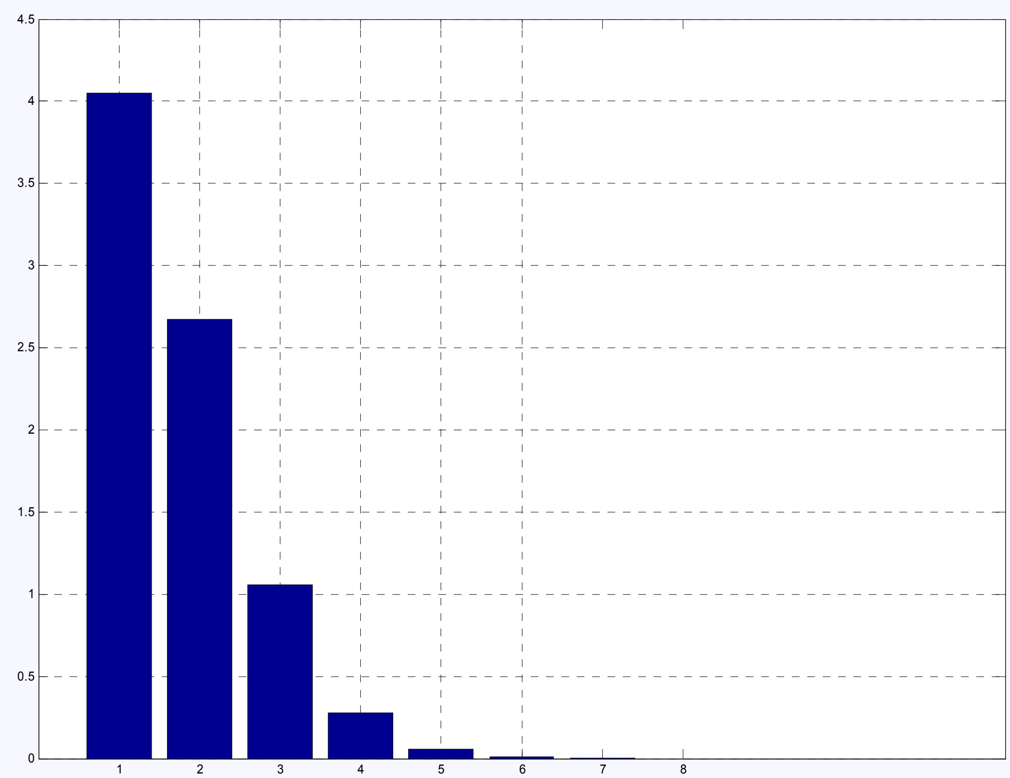

Figure 4.7: Bar plot for cell radius=1732 m and maximum transmit power=1.0 W

Figure 4.7 exhibits the results obtained when a large cell has WTs with a high maximum transmit power level. Figure 4.7 displays results that are very similar to those in Figure 4.6, showing that an increase in *R* can at least be partially offset by increasing the transmit power, as was stated in the analysis of Figure 4.5. In fact, the average number of WTs having direct non-relaying connections to the BS increased slightly in Figure 4.7 to 4.06, up from 3.8 in Figure 4.6. The number of multi-signal transmissions in Figure 4.7 is almost identical to those in Figure 4.6 (double signal transmissions=2.7 [5.4 WTs], triple signal transmissions=1.07 [3.21 WTs], quad signal transmissions=0.29 [1.16 WTs], five-signal transmissions=0.07 [0.35 WTs], six-signal transmissions=0.02 [0.12 WTs]), further showing that an increase in *R* can at least be partially offset by increasing the transmit power. Again, relaying aids the WT service level, because without relaying it would be 8.21 (4.06+2.7+1.07+0.29+0.07+0.02) vs. 14.3 with relaying.

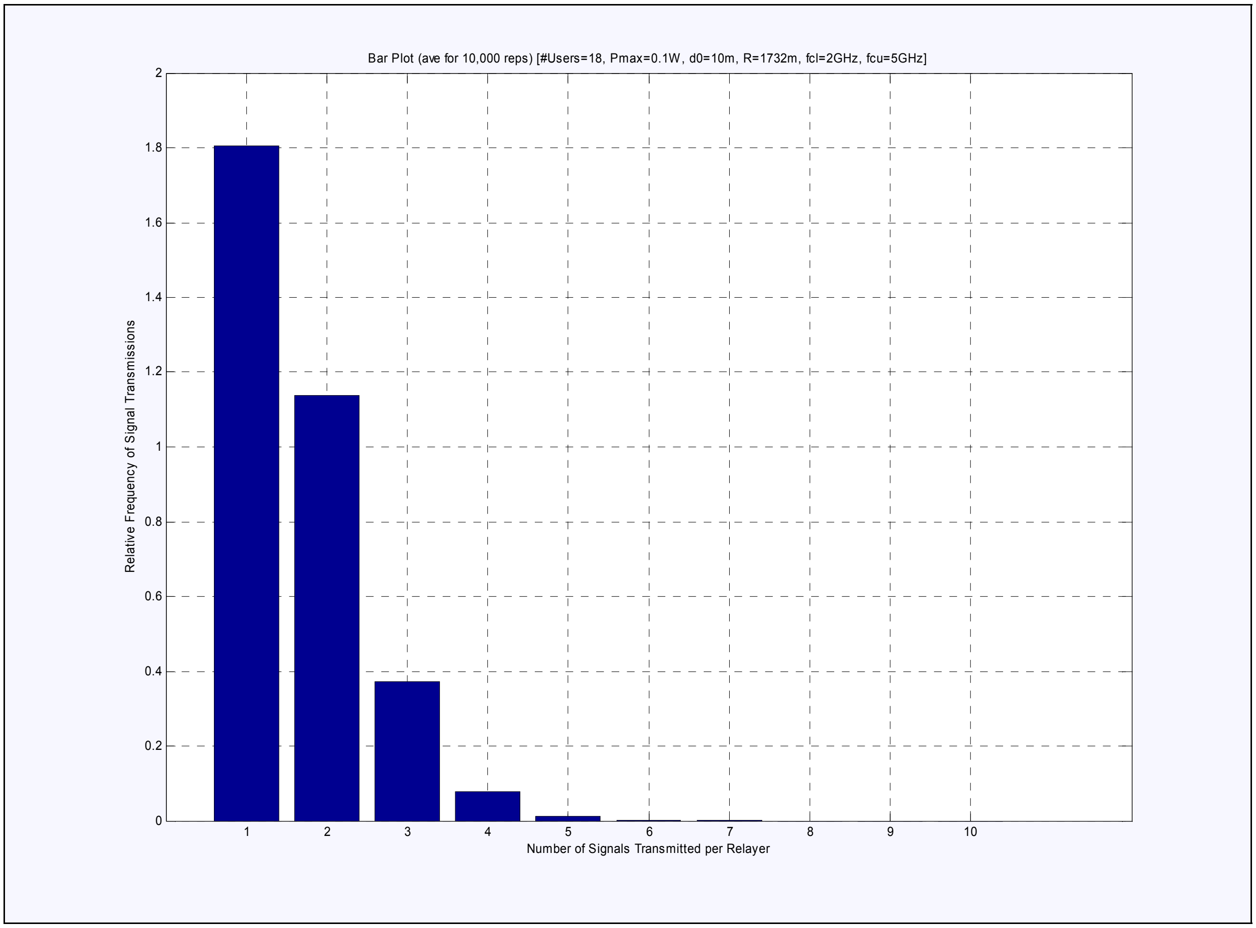

Figure 4.8: Bar plot for cell radius=1732 m and maximum transmit power=0.1 W

The results of decreasing the maximum transmit power for WTs in a large cell are displayed in Figure 4.8. As can be readily seen, there is a dramatic decrease in the number of WTs that have direct links to the BS that are not doing any relaying; here there are approximately 1.8 vs. 4.06 WTs in Figure 4.7. This decrease is primarily due to the reduced power cap, which results in fewer WTs being able to meet their minimum receive power levels at the BS. The number of multi-signal transmissions have also decreased (1.14 two-signal transmissions (2.28 WTs), 0.38 three-signal transmissions (1.14 WTs), 0.08 four-signal transmissions (0.32 WTs), 0.016 five-signal transmissions (0.08 WTs)), which may seem unexpected; however, this can also be accounted for by the lower power cap. The reduced power cap lowered the amount of power available for relayers to transmit signals for relayees, so a relayer would only be able to transmit signals for fewer relayees. In addition, the reduced power cap increased $G_{\min(i,k \to BS)}^{hop2}$, which generally made each relayee demand more power from each relayer, making it more difficult for the relayers to accommodate more relayees. There were also fewer relayees that were allowed to transmit because $G_{\min(i,k)}^{hop1}$ was increased by the power cap decrease. This increase in $G_{\min(i,k)}^{hop1}$ made it impossible for an increased number of relayees to find adequate links to relayers. As a result of the power cap decrease, the WT service level fell dramatically to 5.62 WTs from 14.3 WTs in Figure 4.7; however, relaying was still helpful because without it the WT service level would have been 3.416.

4.2.2 Capacity vs. Range Curves

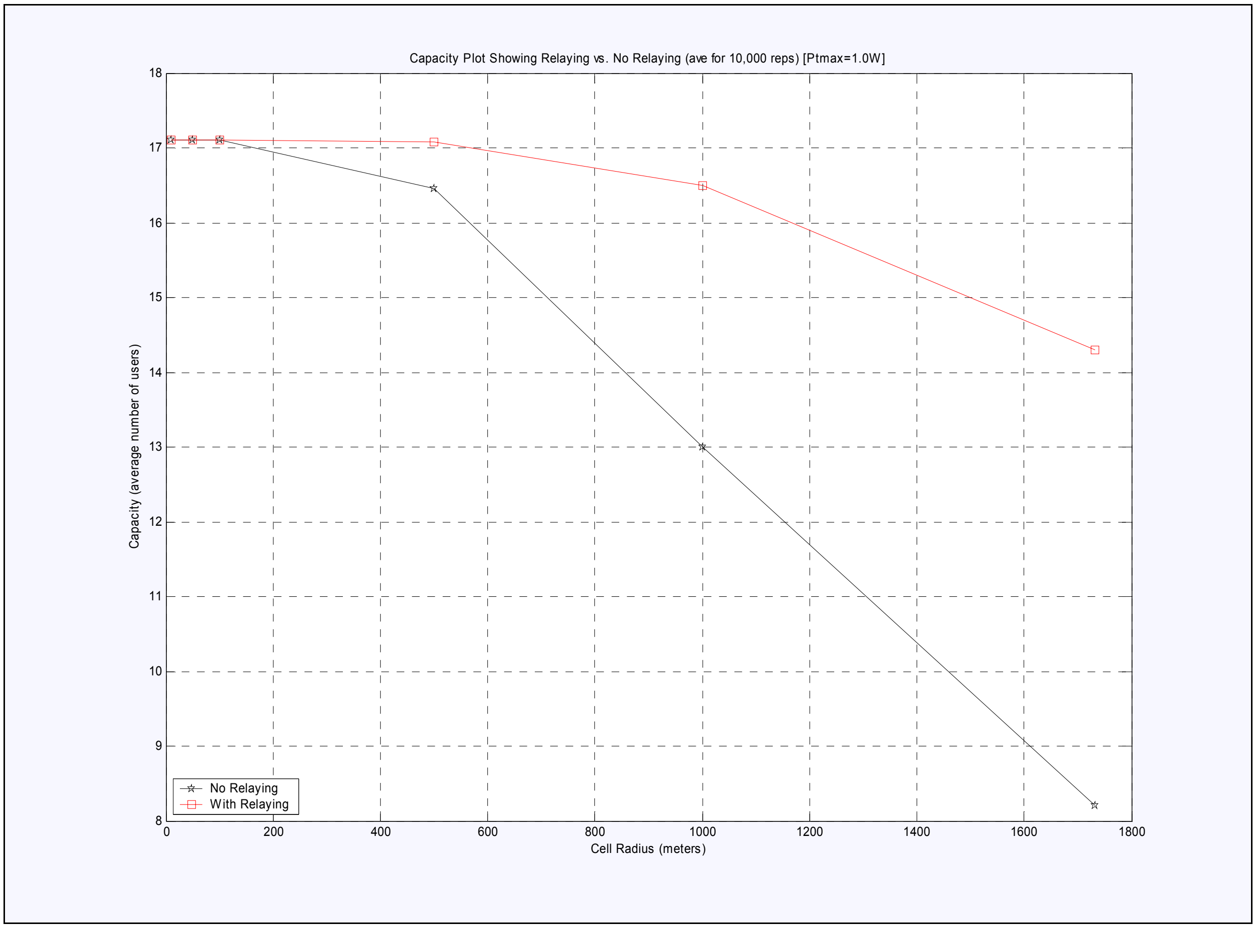

Figure 4.9: Capacity curves with maximum transmit power = 1.0 W

Figure 4.9 shows the capacity gains that are obtained when the power cap is set to 1.0 W in cells of various radii. It is apparent from the figure that the capacity gains due to relaying increase as the cell radius increases, this trend will continue until the cell radius becomes too large to support increasing numbers of adequate relaying links. Therefore, the relaying capacity gains are expected to decrease when the cell becomes large enough to reduce the numbers of relaying links that are adequate for transmission. The above stated gains increase occurs because fewer WTs are able to connect to the BS as the cell radius increases; a significant proportion of these WTs are able to get connected to the BS when relaying is used.

In Figure 4.9 the average capacity of the system, even with very small cells (i.e. with radii less than 500 m), is approximately 17.13 WTs. The reason for this lower than expected capacity was explained in the exposé on Figure 4.2, so please see Section 4.2.1.

It should be noted that Figure 4.9 shows a possible range extension of factor two. This can be seen by observing that cells with 500 m and 800 m radii, which do not employ relaying, have capacities that are very similar to 1000 m and 1700 m radii cells which employ relaying. Similar results can also be found in [4, 7].

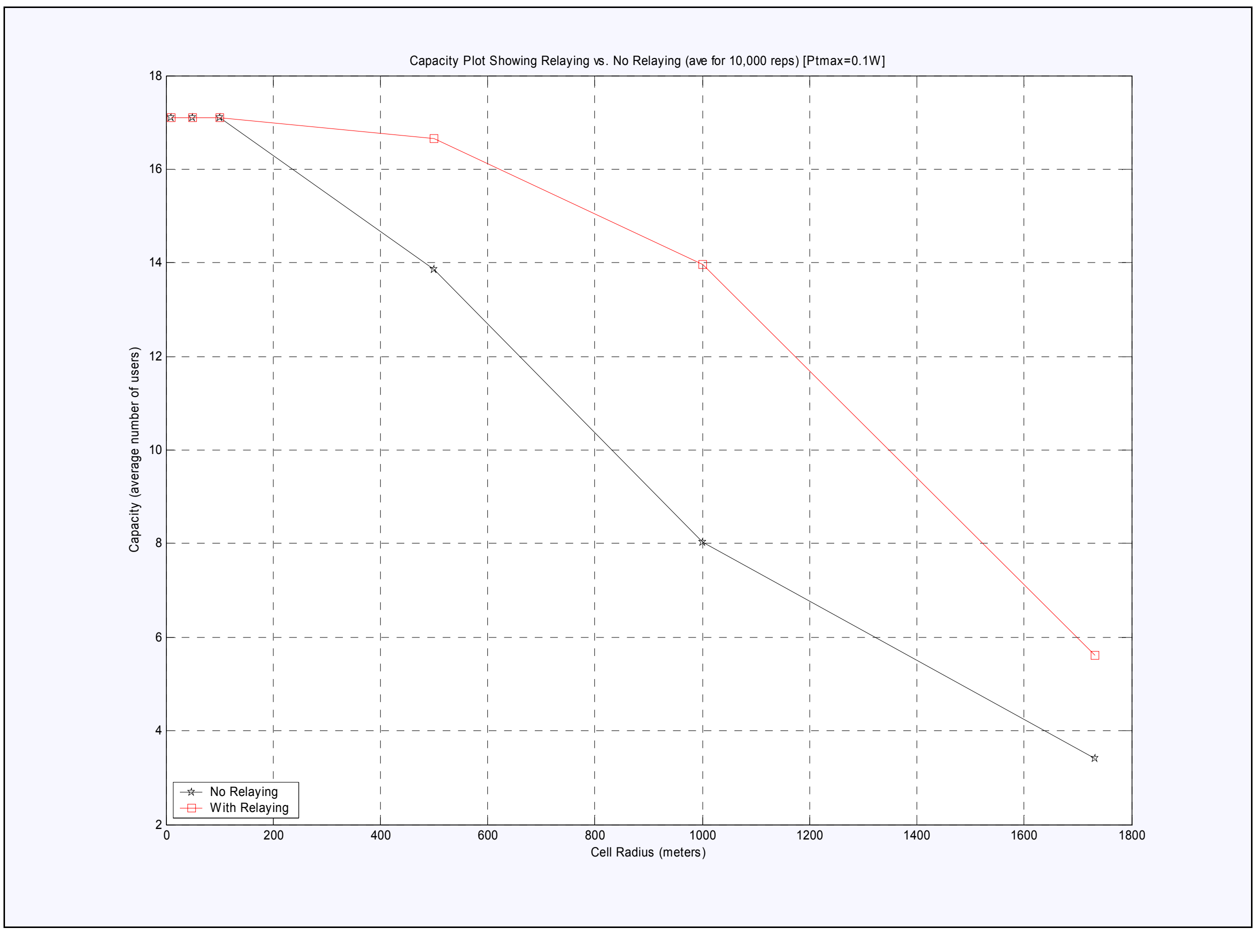

Figure 4.10: Capacity curves with maximum transmit power = 0.1 W

Figure 4.10 shows the capacity gains with relaying for cells with various radii when the power cap is 0.1 W. In the figure, the relaying capacity gains increase with the cell radius until the radius is 1000 m. When the cell radius exceeds 1000 m, the gains due to relaying decrease because the number of adequate relaying links decreases. The point at which the relaying capacity gains starts to decrease is apparent in Figure 4.10 and not Figure 4.9 because of the lower power cap used in Figure 4.10. This lower power cap increases the minimum acceptable link gain resulting in fewer acceptable links and thus fewer WTs transmitting. In Figure 4.10 the average capacity of the network, even with small cells, is again 17.13 WTs, not 18. The explanation for this is the same as was given previously for Figure 4.2.

From Figures 4.9 and 4.10, it can be concluded that relaying increases the capacity of two hop CDMA networks as long as the cells are not too large to support a significant number of adequate relaying links. This number of adequate relaying links decreases more rapidly with increased cell size when the power cap is low, because the minimum acceptable link gain increases as the power cap decreases.

Range extension, as noted in Figure 4.9, is also evident in Figure 4.10; however, unlike Figure 4.9, the factor decreases as the cell radius increases due to higher minimum link gain values caused by the low power cap.

4.2.3 Throughput Curves

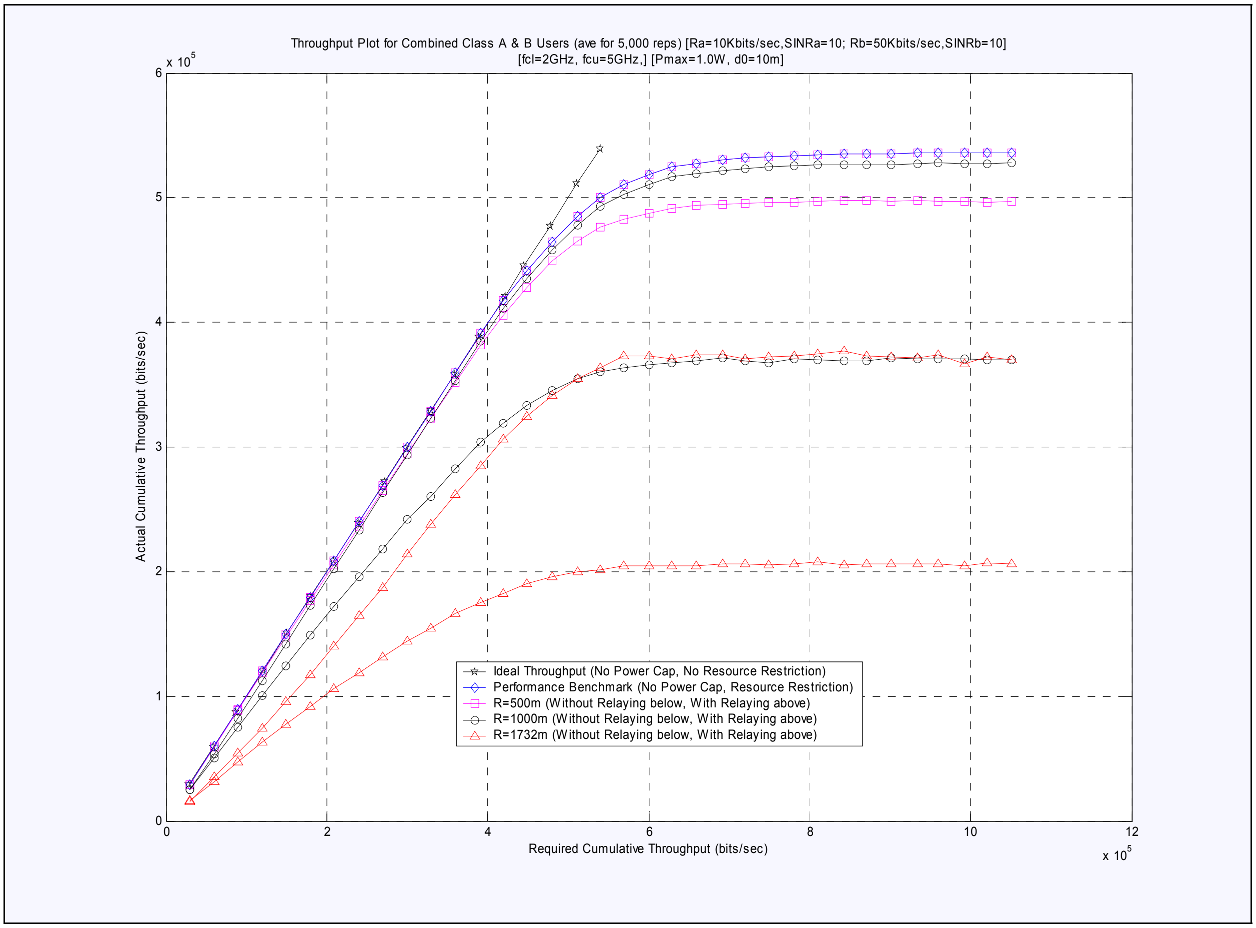

Figure 4.11: Throughput curves for various cell radii with maximum transmit power=1.0 W

The curves in Figure 4.11 represent throughputs for cells with various radii; all the curves have the same power cap (1.0 W) and the same number of WTs (i.e. from 1 to 35, as explained earlier). Please note that the numerical analysis in this section and subsequent sections is done at the 18 user point, because it is the highest point which yields a 50:50 class A:B split; also, it is done to be consistent with the bar plots. Each curve, except the ideal one, has a plateau (i.e. it is saturated), which is due to resource limitations. As the number of WTs entering the system increases, the available resources to accommodate them decreases until no more WTs can be allowed in; hence, only the WTs that were allowed in contribute to the throughput. This is similar to a scenario in which there is a restaurant with limited seating capacity, at which there is a queue; the system is represented by the restaurant and the queue is represented by the WTs that want access. For illustrative purposes, the inequality of (2.5) will be ignored in this example. The restaurant has two table sizes: one for two people and one for four people; these represent the fractional consumptions of the WTs. There are 24 people in the queue in groups of twos and fours, and the restaurant can only seat 16 people. The people are taken into the restaurant in the following grouping sequence: two, four, four, two, two. Now there are 14 people inside the restaurant, but there are still two seats left and 10 people are waiting to be seated. At this point, the next group in the queue consists of four people, they will be denied access because only two spaces are left; however, following them is a group of two people who are let in. Since the restaurant is full (i.e. it is saturated), nobody else is let in although the queue still has eight people in it. Here the service levels of the restaurant are indicative of the people inside, just as how the throughput in the system represents only those WTs that were allowed access.

When the cell radius is 500 m the throughput of the system without relaying is not far from the limit of attainment (i.e. the 'Performance Benchmark' curve), while the relaying curve is virtually identical with this limit. The performance benchmark is the highest throughput possible, is akin to the 'theoretical estimation' curves in Figure 6 in [30] and is the goal of relaying; it will be abbreviated PB from now on. Relaying is helpful here, but its impact is not great because the cell is not big, and thus, does not have a large proportion of poor links. The throughput increase due to relaying is approximately 38 Kbits/sec, which is only a 7.7% increase. The saturation point at this radius begins sooner than it does on the PB curve, at 24

WTs, indicating that the system's throughput limitations are more power dependent. Since the relaying curve is almost identical to the PB curve, they both have the same saturation point of 25 WTs.

The 1000m curve, without relaying, starts to saturate sooner than the PB curve (23 WTs vs. 25 WTs), which indicates that the 1000 m curve's throughput is primarily limited by power limitations rather than by resource restrictions. This is to be expected because more transmit power is required to attain adequate receive power at the BS for larger cells. The saturation point with relaying is shifted to 25 WTs, indicating that relaying makes the system's throughput less limited by power restrictions. The throughput, with relaying, when R=1000 m, shows an approximate 159 Kbit/s increase over the corresponding curve without relaying; this is a dramatic 43.1% increase and is very close to the PB curve. In addition, the performance exceeds that of the 500 m curve without relaying by approximately 31 Kbits/sec, indicating that relaying can at least compensate for an increase in cell size. Unlike the case when R=500 m, relaying not only has benefits when there are many WTs in the system, but also when there are only a few. This can be borne out by examining the R=1000 m curves where significant throughput increases are evident even when there are only five WTs in the system.

When the cell radius increases to 1732m, the throughput of the system without relaying drops by approximately 158 Kbits/sec relative to the corresponding case when R=1000 m. This result shows that the increased cell radius results in worse links, resulting in many WTs being unable to attain their minimum receive power at the BS. This curve starts to saturate when there are only 18 WTs in the system, which is earlier than the previous curves. This early saturation point shows that the system's throughput, at this radius, is primarily restrained by power limitations because fewer WTs have adequate power to attain service. It is interesting to note that the corresponding relaying curve has a higher saturation point (20 WTs), indicating that the throughput is less restricted by power limitations. Fortunately, relaying increased the throughput by approximately 76%; the largest increase thus far. In addition, the relaying curve here is very similar to the non-relaying curve when *R*=1000 m (except when there are less than 14 WTs), showing again that relaying can at least partially compensate for the effects of larger cell radii.

The preceding observation is important because of the potential for reducing the number of base stations in a certain area. For example, if the performance achieved with *R*=1000 m is adequate, then when relaying is incorporated *R* can be increased to 1732 m without a performance penalty. The area served by the 1732 m radius cell is three times greater than the area served by the *R*=1000 m cell ($\left(\frac{1732}{1000}\right)^2 = 3$); therefore, one BS can be used instead of three, which is a 67% reduction in the number of base stations. This finding is especially relevant to urban areas because they have very poor propagation environments and thus require several base stations for adequate coverage, which can be very costly [21, 23].

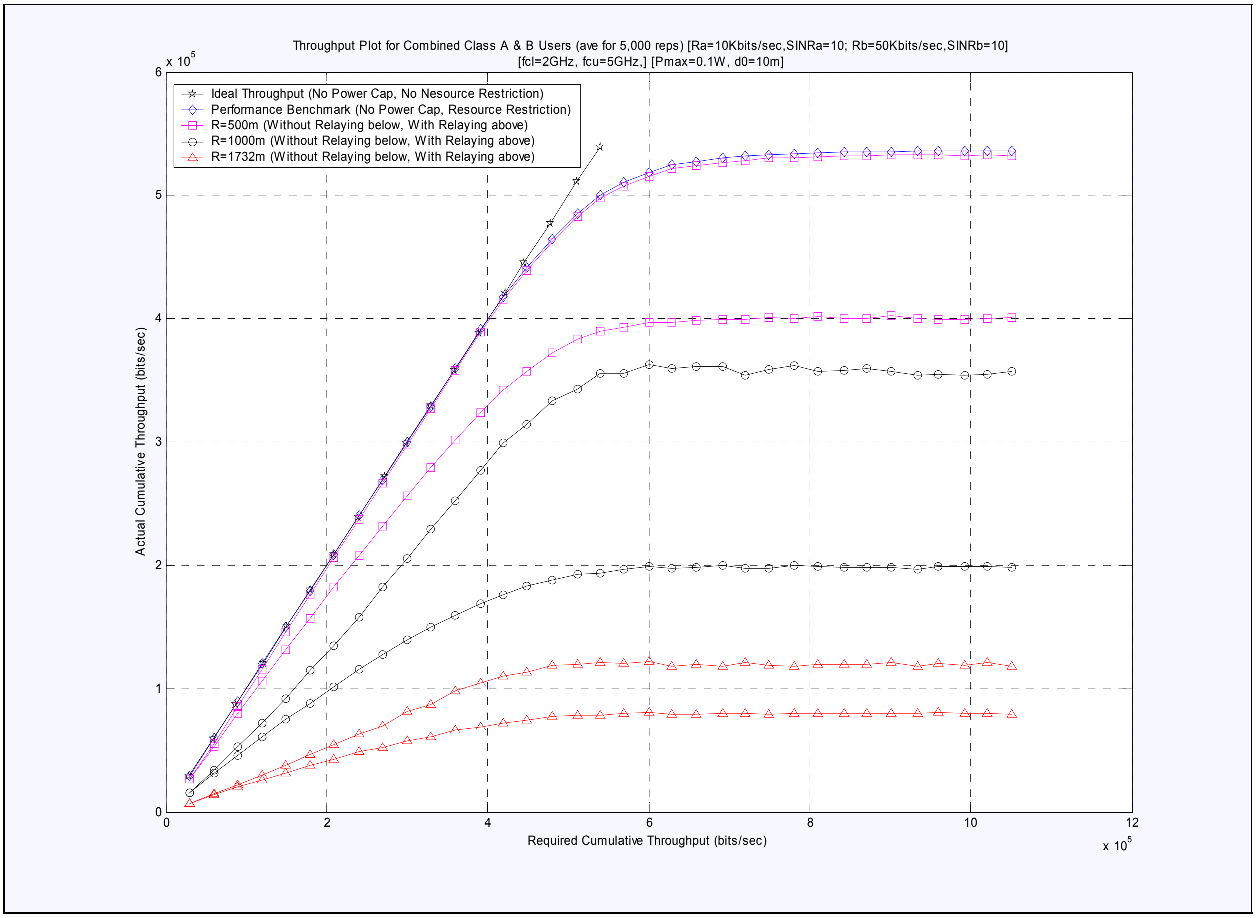

Figure 4.12: Throughput curves for various cell radii with maximum transmit power=0.1 W

All the curves in Figure 4.12, which display throughput results for cells with various radii, show worse performance than their counterparts in Figure 4.11. This is to be expected, since the power cap has been reduced to 0.1 W, resulting in fewer WTs being able to meet their target receive power figures.

Unlike the corresponding case in Figure 4.11, relaying when R=500 m yields significant gains in throughput. Here, relaying results in an approximate 131 Kbits/sec throughput improvement over the non-relaying case; this is a 33% increase vs. a 7.7% increase when the power cap was 1.0 W. The relaying curve is almost equal to the PB curve, so it has a saturation point of 25 WTs. The ‘Without Relaying’ curve, on the other hand, has a saturation point that has been pushed back to 22 WTs, indicating that its throughput is more limited by power restrictions in comparison to the 1.0 W case. Unlike the 1.0 W case, relaying has significant benefits when there are as few as five WTs. These benefits increase as the number of WTs increase and level off when there are 25 WTs.

The saturation point for the ‘Without Relaying’ curve when R=1000 m, has been pushed back to 20 WTs, showing that its throughput is more limited by power restrictions relative to the 1.0 W case. The saturation point for the relaying curve is at 22 WTs, indicating that relaying makes the throughput less limited by power restrictions. Using relaying yields an approximate 157 Kbits/sec increase in throughput, which is a substantial 79% improvement. As in the 500 m case above, relaying results in significant improvements when there are as few as five WTs; however, in this case, the benefits level off sooner at 22 WTs.

The results obtained when R=1732 m are very poor with and without relaying. In this case, relaying yields a mere 38 Kbits/sec improvement in throughput. This is an approximate 48% increase; however, the results fall far short of the PB curve, so they are not considered desirable. This case shows the limitations of this two hop relaying scheme; hence, a multi-hop scheme would be more desirable here. With a multi-hop scheme, the distances traveled by the relayers’ signals would be shorter, so power limitations would be less of a problem since the signals would not attenuate as much before being relayed. On the other hand, a multi-hop scheme for this system would be horrendously complex, as preliminary work has shown.

Overall, this relaying scheme improves the system’s throughput considerably especially when R=1000 m, in which case, the yields are substantial with either a 1.0 W or a 0.1 W power cap. The R=500 m case only yields significant increases due to relaying when the power cap is set at 0.1 W, which shows that this relaying scheme may only be worthwhile in smaller cells when the power cap is set low. Relaying yields substantial gains when *R*=1732 m and the power cap is set at 1.0 W; however, when the power cap is set at 0.1 W, the gains obtained from relaying are not enough to make it desirable, as was discussed in the previous paragraph. So when there are large cells and low power caps in a system, this relaying scheme is not favorable, but a multi-hop scheme may yield greater gains. However, a multi-hop system will introduce delays, which may not be suitable for some applications [24].

Some of the preceding results have been corroborated by other researchers; this can be seen in [31]. The results from [31] agree with the results in Figures 4.11 and 4.12 regarding small cells (i.e. only low relayer transmit power is necessary in order to obtain significant relaying yields). This can be confirmed by comparing the '500 m With Relaying' curves in Figures 4.11 and 4.12. In [31] the small cell has a 200 m radius, while a corresponding 500 m radius small cell is used in this report. However, the conclusions arrived at in [31] would even be more apparent if this report used a similar size cell because lower transmit power levels would be required to achieve adequate performance. Therefore, when relaying is used in interference limited systems with small cells, low power caps are preferable.

4.2.4 Relations Between Bar Plots and Throughput Curves

In Figure 4.3 there are an average of 16.46 WTs that have direct connections to the BS. Please note that there are an average of 1.0 double-signal transmissions and 0.18 triple signal transmissions, which include the relayer; therefore, there has to be 15.9+1.0/2+0.18/3 WTs with direct connections to the BS. Since there is a 50:50 split between class A and class B WTs, there should be a throughput of approximately 493.8 Kbits/sec ([16.46/2]10 Kbits/sec + [16.46/2]50

Kbits/sec) at the 18 WT point on the '500 m Without Relaying' curve in Figure 4.11. An examination of Figure 4.11 shows that when there are 18 WTs in the system, the throughput is 475 Kbits/sec, which falls short of the throughput predicted from Figure 4.3. This shortfall indicates that there is a greater portion of class A WTs that are able to directly connect with the BS, so there is not a 50:50 split between the class A and class B WTs at this stage, instead, the A:B split may be closer to 53:47. This should be expected because class B WTs have higher minimum receive power levels at the BS and the relayers, and thus are more likely to miss their targets. Figure 4.3 also shows that there is an average of 1.18 (1.0+0.18) WTs involved in multi-signal transmissions, since this includes the relayer, only 0.62 (0.5+0.12) WTs are relayed on average. Using the 50:50 assumption, it would be expected that there would be a 18.6 Kbits/sec (0.62[50 Kbits/sec]+0.62[10 Kbits/sec]) throughput increase due to relaying; however, this is not the case, as an examination of the relaying curve for the *R*=500 m case will show in Figure 4.11. Instead of getting a throughput of approximately 493.6 Kbits/sec (475 Kbits/sec+18.6 Kbits/sec), the throughput is 500 Kbits/sec, so relaying actually accounts for 25 Kbits/sec of the throughput. This shows that primarily class B WTs, on average, are relayed (0.62*0.76[50 Kbits/sec]+0.62*0.24[10 Kbits/sec]=25.05 Kbits/sec). This forces the conclusion that, on average, primarily class B WTs were unable to get direct links to the BS and thus become relayees; from the preceding sentence, the A:B relaying ratio is 24:76. This is to be expected because class B relayees have higher $G^{hop2}_{\min(i,k\rightarrow BS)}$'s due to higher receive power targets making them less likely than class A WTs to find adequate links to the BS, and consequently, they compose the greater portion of relayees. For the *R*=500 m, *Pmax*=1.0 W case, both the bar plot and the throughput curves correlate well and meet expectations, but not using the 50:50 class split, which appears to be only suitable for the ideal curves.

When the power cap is reduced to 0.1 W, the bar plot for the *R*=500 m case in Figure 4.4 indicates a drop in the number of WTs with direct links to the BS to approximately 13.86 (11.6+1.8+0.38+0.08). This is an approximate 15.8% drop from the previous case in the last paragraph. However, there is a corresponding 17.9% drop in throughput from 475 Kbits/sec in Figure 4.11 to 390 Kbits/sec in Figure 4.12. This larger drop in throughput is to expected, because with a lower power cap the class B WTs, in greater proportion, are unable to get direct links to the BS, and since they have five times the throughput of class A WTs, their relative reduction has a greater impact on the total throughput. A similar situation exists with relaying. In Figure 4.4 there are an average of 2.8 (1.8+0.38*2+0.08*3) WTs that use relaying, up from 0.62 previously, which is a 352% increase. The corresponding relaying curve in Figure 4.12 indicates a 320% increase. This indicates that the successful relayees, relative to the previous case, are composed of a greater portion of class A WTs; this will be borne out by the forthcoming analysis. From Figure 4.12, the 'Without Relaying' curve for this case has a throughput of 390 Kbits/sec which corresponds to an A:B ratio of approximately 55:45 (0.55*13.86[10 Kbits/sec]+0.45*13.86[50 Kbits/sec]=388.1 Kbits/sec). This ratio shows that, relative to the previous case, more class B WTs do not have direct links to the BS and thus a greater portion of them make up the relayee population. According to the *R*=500 m plot in Figure 4.12, the throughput due to relaying is approximately 105 Kbits/sec, which yields an approximate A:B ratio of 31:69 (0.31*2.8[10 Kbits/sec]+0.69*2.8[50 Kbits/sec]=105.28 Kbits/sec). The above results indicate that fewer class B WTs get relayed although they compose a larger proportion of the relayees. This is to be expected because class B WTs have higher $G_{\min(i,k)}^{hop1}$'s and $G_{\min(i,k\to BS)}^{hop2}$, so they are less likely to find suitable links. In addition, class B WTs place higher power demands on relayers; therefore, they are less likely to find relayers. The preceding disadvantages suffered by class B WTs are made worse by the low 0.1 W power cap that exists in this case.

There are approximately 13 WTs with direct connections to the BS when R=1000 m and $Pmax$=1.0 W. This results in a throughput of 362 Kbits/sec at the 18 WT point in Figure 4.11. From this figure, the A:B WT ratio can be estimated to be 55:45 (0.55*13[10 Kbits/sec]+0.45*13[50 Kbits/sec]=364 Kbits/sec), this ratio is identical to the one obtained for the previous case. Please note that both cases would have very close ratios if they were determined to greater degrees of precision, instead of estimating them to the closest percentage point. The precision is limited to a percentage point because it is sufficient to conduct the analysis and come to valid conclusions. Since these ratios are the same, the statement made earlier that power cap increases can at least partially compensate for increased R, is confirmed again here. According to Figure 4.11, the throughput contribution due to relaying in this case is 132 Kbits/sec, which corresponds to an A:B ratio of 31:69 (0.31*3.5[10 Kbits/sec]+0.69*3.5[50 Kbits/sec]=131.6 Kbits/sec). Again, the estimated ratio is identical to that of the R=500 m, $Pmax$=0.1 W case, giving further validation to the aforementioned $Pmax$-R (i.e. power cap-cell radius) effect.

When R=1000 m and $Pmax$=0.1 W, there are an average of 8.03 WTs with direct connections to the BS, which corresponds to an approximate throughput of 193 Kbits/sec according to Figure 4.11. The above throughput gives an estimated A:B ratio of 65:35 (0.65*8.03[10 Kbits/sec]+0.35*8.03[50 Kbits/sec]=192.72 Kbits/sec). This ratio shows that the proportion of class B WTs with direct connections to the BS has decreased further because of their higher receive power targets at the BS. As a result, class B WTs also make up an increased portion of the relayees. The ensuing analysis will determine how successful these relayees are at getting through to the BS via relayers. From Figure 4.6, the average number of WTs utilizing relaying is 6.03 and Figure 4.12 indicates that the throughput from relaying is approximately 157 Kbits/sec. Hence, the A:B ratio is estimated to be 60:40 (0.6*6.03[10 Kbits/sec]+0.4*6.03[50 Kbits/sec]=156.78 Kbits/sec). This ratio attests that class A WTs are much more successful at being relayed, especially considering that class B WTs make up a greater proportion of the relayees. The reasons for this can be found in the last few sentences of the paragraph preceding the previous one.

The average number of WTs having direct connections to the BS when *R*=1732 m and *Pmax*=1.0 W is 8.21, which is very close to the figure of 8.03 obtained for the previous case. The corresponding throughput according to Figure 4.7 is 202 Kbits/sec, which yields an A:B ratio of 63:37 (0.63*8.21[10 Kbits/sec]+0.37*8.21[50 Kbits/sec]=203.61 Kbits/sec). This ratio is very close to the one in the preceding paragraph, showing that performance between both scenarios is very close. The average number of WTs using relaying is 6.09, this number yields a relaying throughput of 164 Kbits/sec according to Figure 4.11. The A:B ratio corresponding to this throughput is estimated to be 58:42 (0.58*6.09[10 Kbits/sec]+0.42*6.09[50 Kbits/sec]=163.21 Kbits/sec). Again, this ratio is very close to the ratio obtained in the previous paragraph. Since the ratios between this case and the preceding one are so close, the same analytical conclusions apply to both; therefore, there is no need to repeat them here. This case again attests to the validity of the statement concerning the *Pmax-R* effect, since increases in *R* and *Pmax* resulted in performance figures that are very close to those obtained in the previous case.

The proportion of class B WTs not having direct connections to the BS increased significantly, relative to the preceding case, when *R*=1732 m and *Pmax*=0.1 W. This is obvious from the A:B ratio estimate of 67:33 (0.67*3.416[10 Kbits/sec]+0.33*3.416[50Kbits/sec]=79.25

Kbits/sec), obtained from Figures 4.8 and 4.12, where the average number of WTs with direct connections to the BS and the throughput they generate are 3.416 and 79 Kbits/sec respectively. This result is not surprising, because the lower power cap makes it more difficult for the WTs to achieve their target receive powers at the BS. In addition, class B WTs have higher cut off rates because they have higher receive power targets. Also, the large cell causes a larger portion of WTs to have poor links due to the increased attenuation, and class B WTs suffer disproportionately because they need better links than class A WTs to achieve their target receive power at the BS. Not many relayees are successful in finding relayers, as the low number of WTs utilizing relaying (i.e. on average 2.2) attests to; however, the forthcoming analysis will show which class of WTs is more successful. According to Figure 4.12, the 2.2 relayees, on average, that utilize relaying contribute a throughput of 42 Kbits/sec, this yields an estimated A:B ratio of 77:23 (0.77*2.2[10 Kbits/sec]+0.23*2.2[50 Kbits/sec]=42.24 Kbits/sec). Since class B WTs make up more than one half of the relayees but they only compose 23% of the successful ones, it can be stated that class A WTs are more successful.

4.3 Fixed Relayers

Fixed relayers are included in this project to determine whether there are any throughput gains by including them, and also to ascertain whether it may be feasible to use only fixed relayers. A brief overview of the system with fixed relayers ensues in the next paragraph, followed by a discussion of the results obtained when they are used by themselves and when they are used with WT relayers.

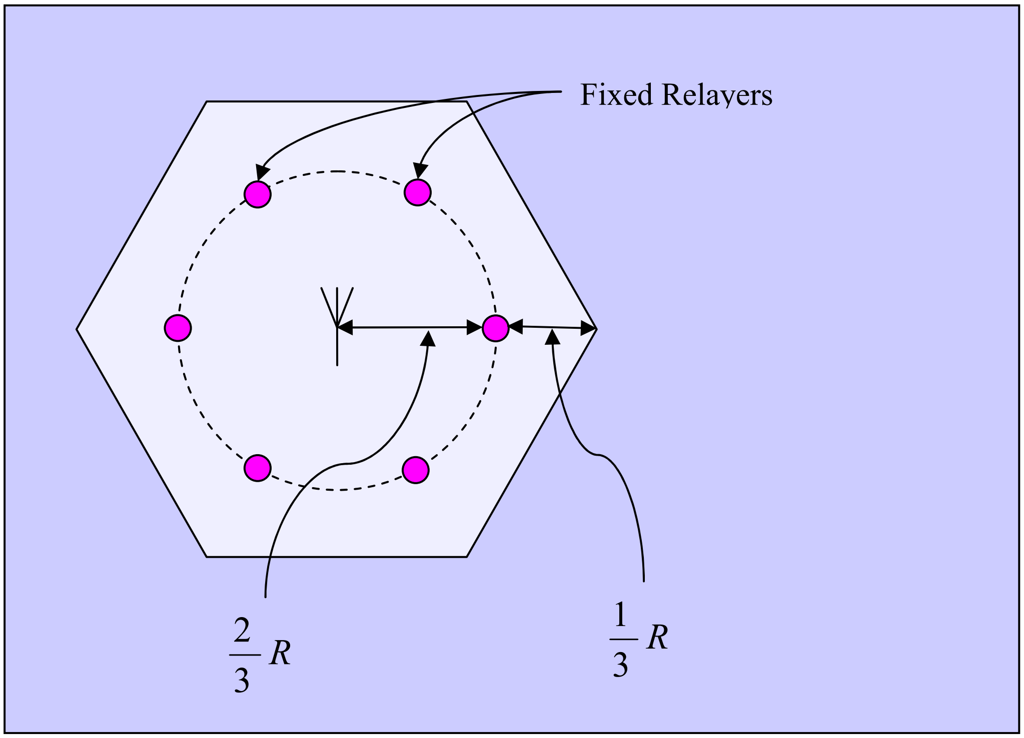

Figure 4.13: Fixed relayer layout

Figure 4.13 shows the layout of the fixed relayers in the cell. This configuration is chosen because simulations at other radii locations yielded lower throughputs; it was also chosen in [7]. Each Fixed relayer is 10 m high, has an omni-directional antenna and has a maximum transmit power of 2.0 W all the time, no matter what level the WT power cap is set to. The power is increased because power is not as limited with these units as it is with the WTs, because the fixed units can derive their energy from the local power grid. Energy consumption is an issue with WTs because batteries have a very limited energy supply, which will run out no matter how efficient the electronics are. Fixed relayers, on the other hand, have an infinite energy supply because the local grid will be able to supply them with energy indefinitely. Power is also an issue with WTs because higher rates of energy use will drain the batteries faster. Fixed relayers do not have an infinite power supply because the grid can only support a limited rate of energy consumption; however, this limit is likely to be greatly in excess of the fixed relayers demands, so power is less of an issue. Although power is not a significant issue, there is a point of diminishing returns regarding the fixed relayers power cap. This was shown in [22] (with a system consisting of four fixed relayers) where there was a negligible throughput increase when the relayers power cap was increased from 30dBm (1.0 W) to 37 dBm (5.01 W). The previously mentioned point of diminishing returns is most likely related to the type of traffic being conveyed, as high bit rate traffic demands more power than low bit rate traffic. Hence, when there is adequate power to convey the traffic, adding more power does not enhance performance.

The propagation constant between the BS and the fixed relayers is reduced to 2.5 from 4.0 because the signals along these paths experience much less attenuation due to fewer obstructions, resulting in approximate free space attenuation. Also, the log-normal shadowing standard deviation, along the above paths, is reduced to 4dB from 8dB due to more uniform levels of clutter (i.e. there are lower levels of signal variation because of objects in the signal path).

In the simulations, the fixed relayers are treated as WT relayers with higher power caps. Therefore, nothing changed except for the constant presence of these six additional relayers.

It should be noted that interference to surrounding cells and to other fixed relayers can be reduced by installing a directional transmit antenna on each fixed relayer which is aimed at its BS. However, the receive antenna should remain omni-directional for optimum WT reception. This scheme was not pursued during the course of this project due to time constraints. Time constraints also prevented the simulation of bar plots for fixed relayers and the derivation of the corresponding ‘Capacity vs. Range Curves’.

4.3.1 Fixed Relayers Only

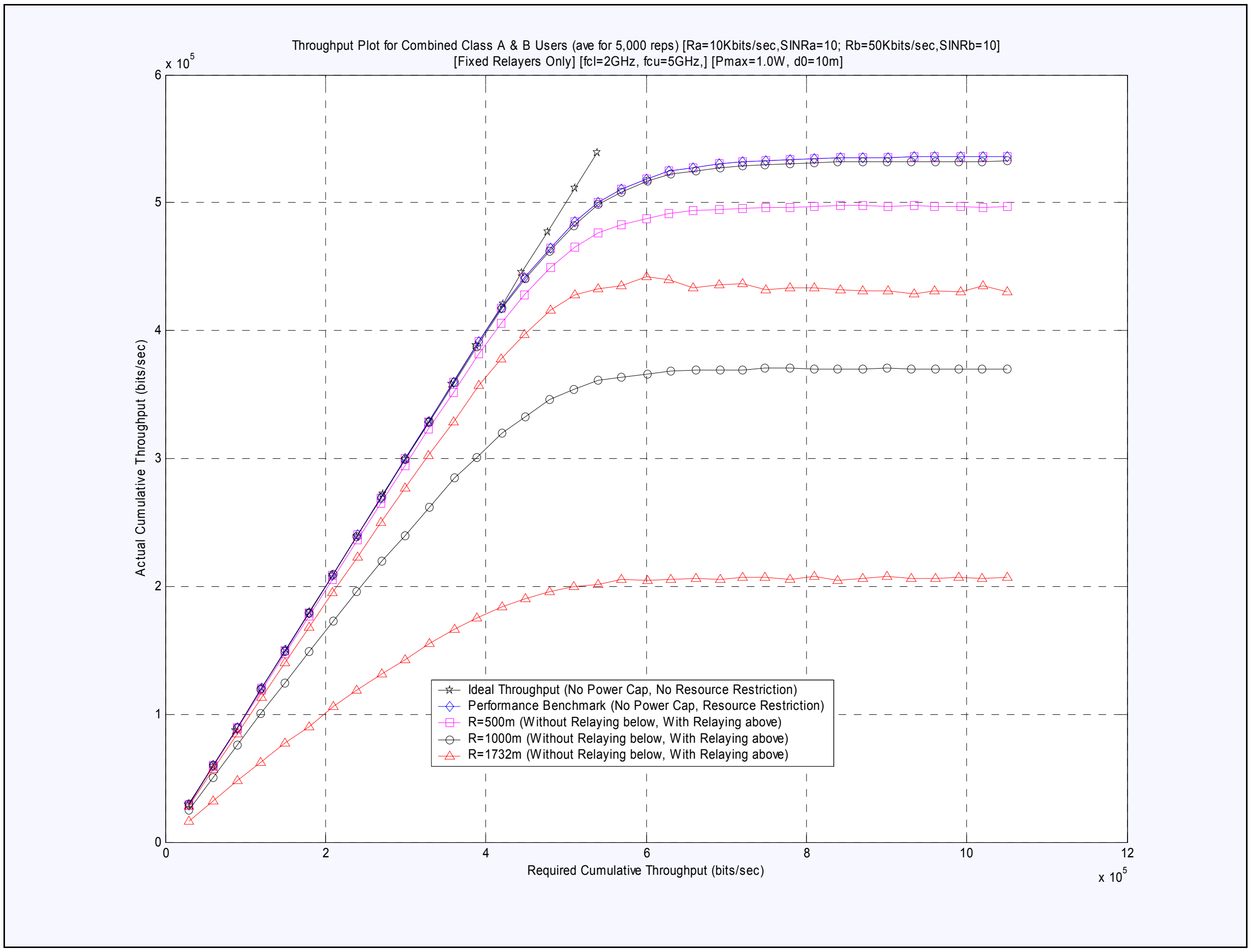

Figure 4.14: Throughput curves for various cell radii (fixed relayers only, WT *Pmax*=1.0 W, FR *Pmax*=2.0W)

The curves in Figure 4.14 show the throughput results obtained when only fixed relayers are used and the WT power cap is 1.0 W. In all instances, except when *R*=500 m, the performance gains obtained when only fixed relayers are used are greater than the cases when only WT relayers are utilized, this can be borne out by comparing Figures 4.11 and 4.14. All the ensuing numerical comparisons will be done at the 18 WT point in order to be consistent with the preceding analyses for Figures 4.11 and 4.12. These relative improvements are due to the higher fixed relayer power cap (2.0 W), the better hop 2 links (propagation constant=2.5, shadowing standard deviation = 4 dB) and the optimized layout that the fixed relayers have.

The most dramatic increase in throughput occurs when R=1732 m, in this case there is a 18.0 % throughput increase (366 Kbits/sec vs. 432 Kbits/sec) over the WT relayer only case. This result shows that the primary impediment to improved performance in large cells is hop 2 because the primary differences between the fixed and the WT relayer cases are on this hop.

When R=1000 m and only fixed relayers are used, the increase in throughput is insignificant relative to the WT relayer only case (494 Kbits/sec versus 496 Kbits/sec). Therefore, it is not feasible to install fixed relayers in a medium size cell when the WT power cap is high. This conclusion applies to the case when R=500 m as well; here, relaying put the throughput at the performance benchmark with only WT relayers, so there is no more room for improvement.

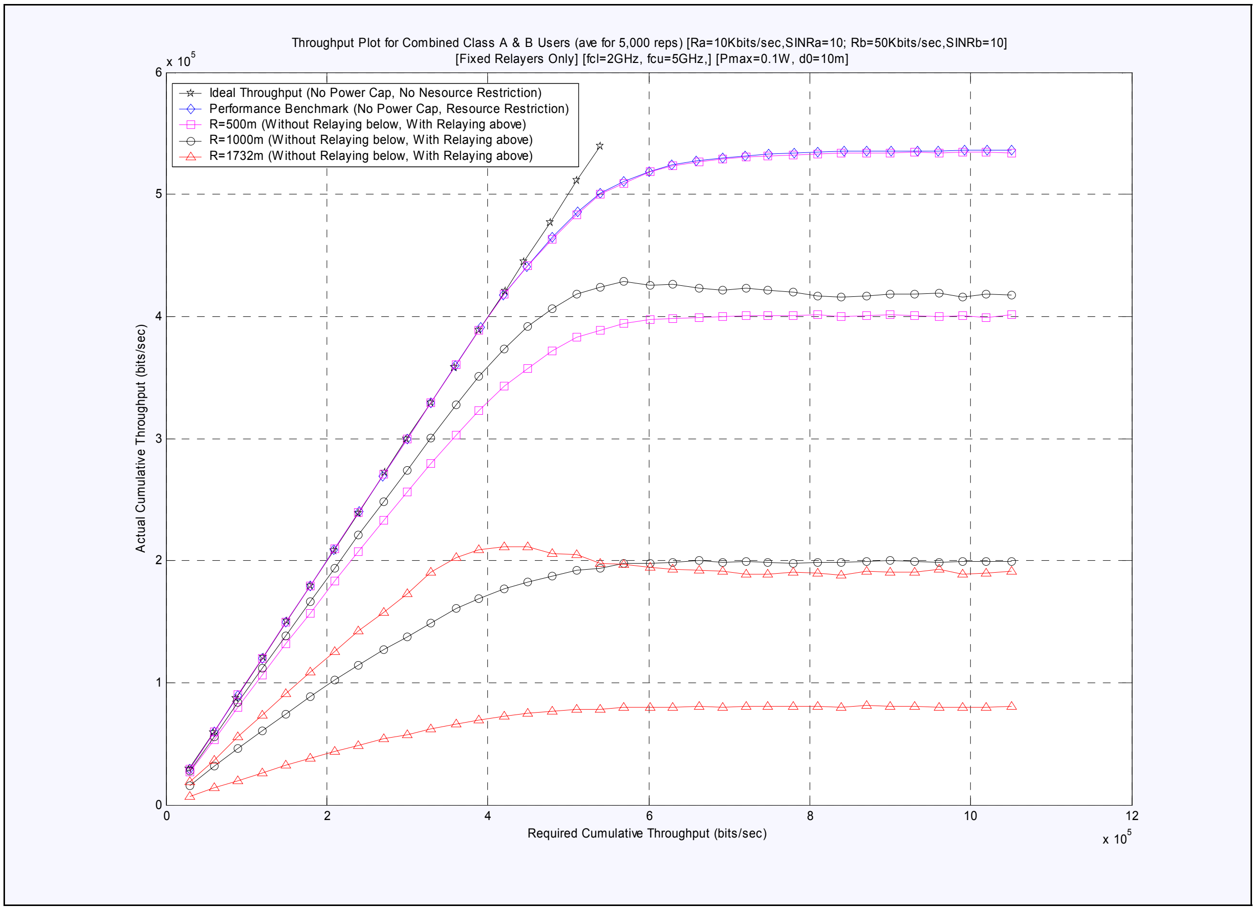

Figure 4.15: Throughput curves for various cell radii (fixed relayers only, WT *Pmax*=0.1 W, FR *Pmax*=2.0W)

The throughput curves when the WT power cap is set to 0.1 W and only fixed relayers are used, is shown in Figure 4.15. For all radii there are performance improvements relative to the cases when only WT relayers are utilized. The reasons for these improvements can be found above in the exposé on Figure 4.14. As done previously, all the ensuing numerical comparisons will be performed at the 18 WT point.

The '1732 m With Relaying' curve in Figure 4.15 shows substantial throughput improvements over the corresponding WT relayer only case found in Figure 4.12 (197 Kbits/sec vs. 121 Kbits/sec). However, the '1732 m With Relaying' curve in Figure 4.15 has some peculiar characteristics which warrant explaining. These explanations will be primarily focused on the first hop and the WT power cap of 0.1 W because the hop 2 relaying link is the same as the 1.0 W case in Figure 4.15, since the fixed relayers did not have a power cap change. This curve's throughput increases up to when there are 14 WTs in the network (where it peaks) and it starts to decrease at the 16th WT. The decreasing trend continues up until there are 24 WTs, after which it levels off. The previously stated increases and leveling off trends are to be expected; however, the throughput decreases are unusual.

The decreasing trend, noted above, is the result of the interference limited nature of CDMA networks. When there are 14 or 15 WTs in the network, the throughput peaks; however, when the 16th WT joins, the throughput decreases because of the additional relayee(s) that create extra interference on hop 1. This extra interference and the reduced power cap of 0.1 W increases $G_{\min(i,k)}^{hop1}$ making it impossible for as many class B relayees, relative to when there were 14 or 15 WTs in the system, to find adequate hop 1 links. Thus, it is not possible to increase the number of relayees, beyond a certain number, without having a decrease in the throughput. Class B relayees are particularly vulnerable to the extra interference and the reduced power cap because they have higher $P_{R,\min(i,k)}^{hop1}$ values due to their larger fractional consumption figure. Since the class B relayees have higher $P_{R,\min(i,k)}^{hop1}$ values and the links are worse due to the larger cell radius, they are less likely to find relayers because the increasing total number of WTs gives rise to an increasing number of relayees. This reduction in successful class B relayees causes a corresponding reduction in the throughput, because class B WTs have throughputs that are five times higher than class A WT's (i.e. 50 Kbits/sec vs. 10 Kbits/sec). The demonstration of a few possible class B relayee failures in Figure 4.16 will aid in the explanation. In Figure 4.16 it is assumed that the number of WTs with direct connections to the BS remains constant along with their average class A:B ratios. Therefore, only the relayees are allowed to affect the variations in the total throughput.

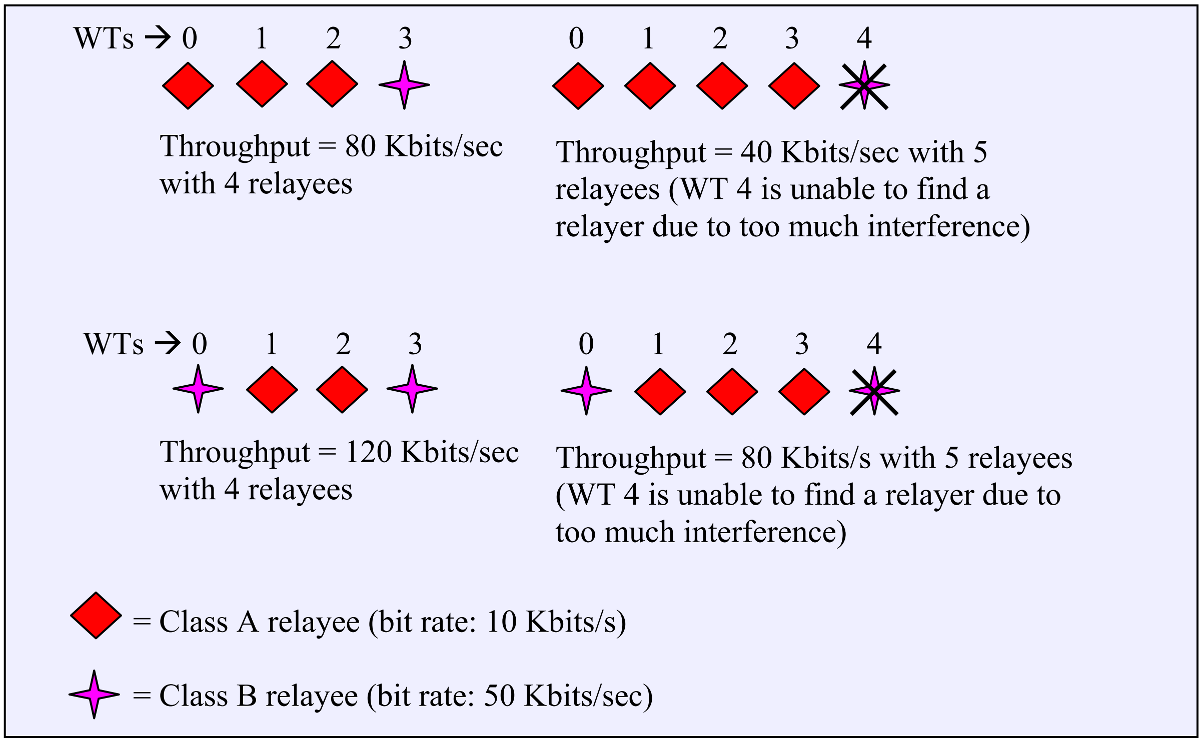

Figure 4.16: Various scenarios explaining decreasing throughput

The corresponding throughput plots with no fixed relayers (Figure 4.12) do not show this decreasing trend. This is so because the relayers power limit of 0.1 W results in higher $G_{\min(i,k\rightarrow BS)}^{hop2}$ levels which prevents many relayees with good hop 1 links from getting connected. However, because the fixed relayers have a 2.0 W power limit, the $G_{\min(i,k\rightarrow BS)}^{hop2}$ is lowered substantially, so hop 2 is no longer the impediment it once was. Thus, more relayees with good hop 1 links are able to get connected. It should be noted that the interference limited characteristics of hop 1, described above, existed previously but it was not obvious because of the throttling effects of the relayers low power limit on hop 2. Despite the decreasing throughput, the '1732 m With Relaying' curve in Figure 4.15 has significantly higher throughput than its counterpart in Figure 4.13. It should also be noted that range extension is possible because the 1732 m radius cell, with fixed relaying, can now perform at least as well as a 1000 m radius cell without relaying, resulting in a possible 67 % reduction in the number of base stations. Please note that this range extension is only possible up until the 19 WT point, after this the performance of the '1000 m Without Relaying' curve has superior performance.

The '1000 m With Relaying' curve in Figure 4.15 shows a significant 21.1 % throughput increase relative to the '1000 m With Relaying' curve in Figure 4.13 (424 Kbits/sec versus 350 Kbits/sec). In addition, the use of fixed relaying in the R=1000 m cell can result in range extension, because the performance of the 1000 m radius cell exceeds that of the 500 m radius cell without relaying. This range extension can now allow the use of one BS where four would have to be installed if the R=500 m cell's performance was needed in the area serviced by the R=1000 m cell. In contrast, the '500 m With Relaying' curve in Figure 4.15 shows a very small 1.0 % throughput increase over its counterpart in Figure 4.12 (500 Kbits/sec versus 495 Kbits/sec).

Fixed relaying yields significant throughput gains over WT only relaying in: large cells when there are high and low power caps, medium size cells when the power cap is low and never in small cells. In addition, range extension possibilities are evident when the power cap is low in medium and large cells.

4.3.2 Fixed and WT Relayers

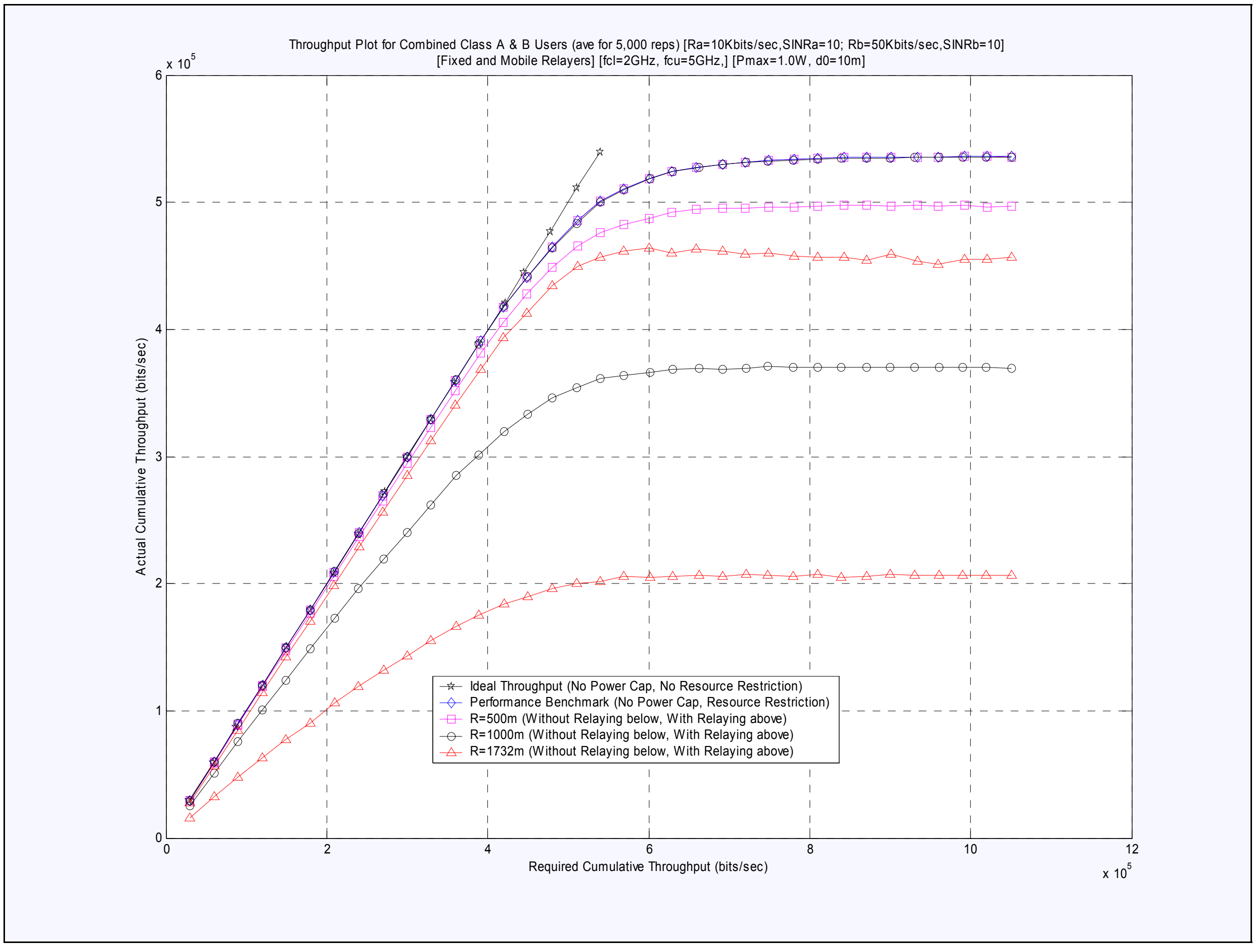

Figure 4.17: Throughput curves (various cell radii, fixed and WT relayers, WT *Pmax*=1.0 W, FR *Pmax*=2.0W)

The throughput curves when fixed and WT relayers are employed and the WT power cap is 1.0 W are shown in Figure 4.17, where performance improvements are obvious in all cases except when R=500 m. As was done previously, these improvements will be quantified at the 18 WT point for the prior stated reason.

When R=1732 m there is a modest 5.3 % increase (432 Kbits/sec versus 455 Kbits/sec) in throughput over the corresponding case when only fixed relayers are employed. However, this allows the 1732 m radius cell to almost equal the performance of the 500 m radius cell (475 Kbits/sec). Since the performance of the *R*=1732 m cell employing both fixed and WT relayers, greatly exceeds that of the 1000 m radius cell with no relaying, it may be possible that the *R*=1732 m cell has performance that is equal to that of a 588 m cell (linear interpolation). This leads to a range extension factor of 8.7 ($(1732/588)^2$), which may lead to substantial cost savings.

There is an insignificant throughput increase of 0.8 % when *R*=1000 m and both fixed and WT relayers are used, over the corresponding case when only fixed relayers are utilized (496 Kbits/sec versus 500 Kbits/sec). This small increase occurs because the '1000 m With Relaying' curve (Figure 4.14) is close to the performance benchmark and thus, no significant throughput increase is possible. The '500 m With Relaying' curve was already at the performance benchmark prior to the combined use of fixed and WT relayers; therefore, it experienced no performance gains.

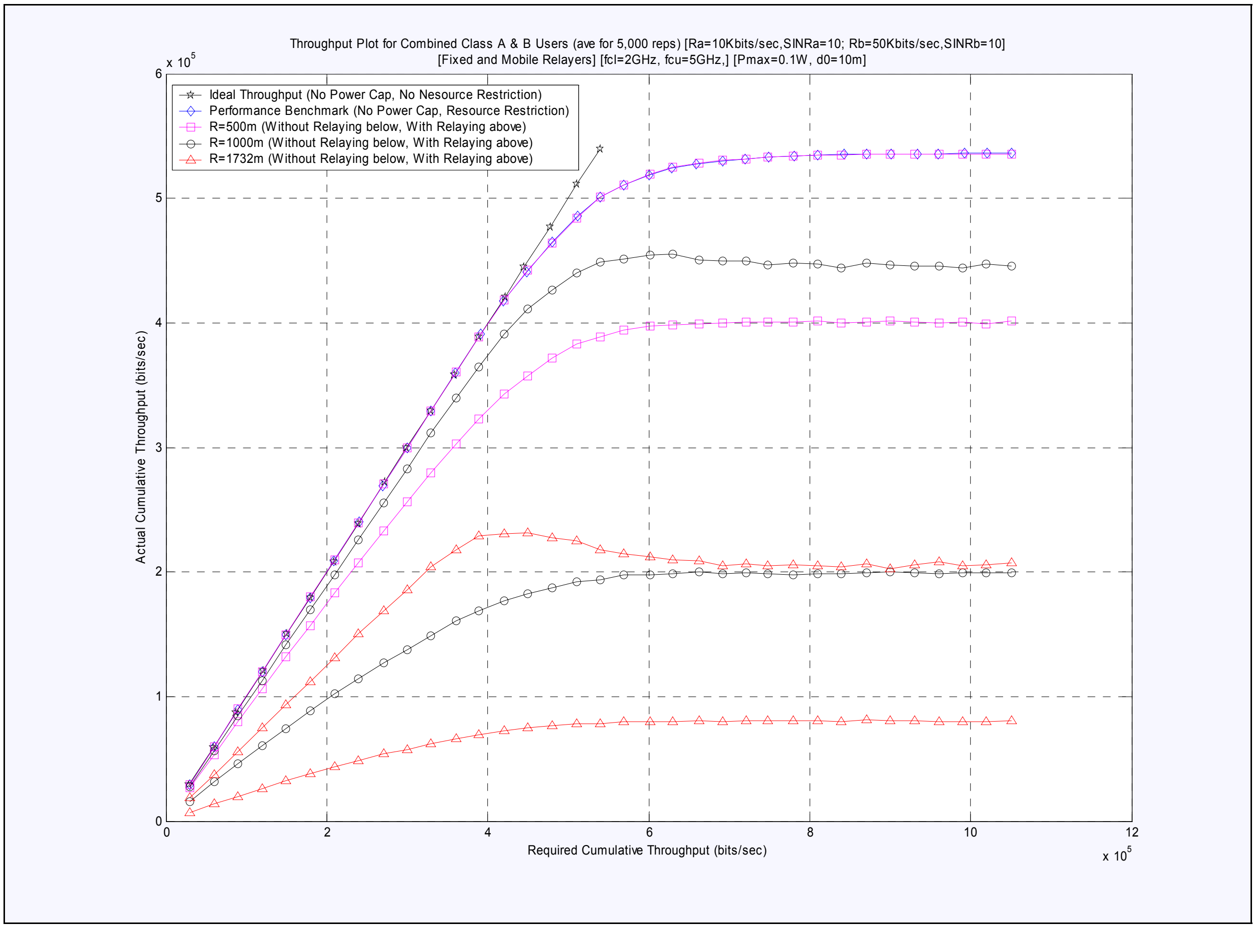

Figure 4.18: Throughput curves (various cell radii, fixed and WT relayers, WT *Pmax*=0.1 W, FR *Pmax*=2.0W)

The results of simulating various radii cells employing both fixed and WT relaying, with a 0.1 W WT power cap, are shown in Figure 4.18. Performance improvements are evident in all cases, except when *R*=500 m. Again, numerical comparisons will be done at the 18 WT point for the reason given previously.

The '1732 m With Relaying' curve in Figure 4.18 has a significant 11.2 % throughput increase over its counterpart in Figure 4.15 (from 197 Kbits/sec to 219 Kbits/sec). It is also obvious that the '1732 m With Relaying' curve now has superior throughput levels at all WT points, relative to the corresponding 1000 m fixed relayer only case in Figure 4.15. Thus, the use of both fixed and WT relayers makes range extension more feasible in this instance, than with the use of only fixed relayers. The throughput curve obtained when R=1732 m when both fixed and WT relayers are employed, exhibits peculiar traits that are very similar to those obtained in the corresponding curve in Figure 4.15. Since the only difference between Figures 4.15 and 4.18 is the addition of WT relayers, which does not affect the way the CDMA systems are implemented, the exposé on Figure 4.15 is sufficient to explain the above stated peculiar traits.

When R=1000 m and there is combined use of fixed and WT relayers, a modest 5.9% throughput increase exists over the case when there are only fixed relayers (from 424 Kbits/sec to 449 Kbits/sec). However, because the 'R=500 m With Relaying' curve was already at the performance benchmark when only fixed relayers were utilized, it shows no throughput increase when fixed and WT relayers are combined.

In summary, the use of only fixed relayers is apparently the most feasible way to maximize the system's throughput. Fixed relayers consistently outperform WT relayers in all simulated scenarios, but especially in large and medium size cells with low power caps. The combined use of fixed and WT relayers yields greater gains over the use of only fixed relayers; however, these gains are modest at best and thus are not considered worthy of the cost of attainment. The use of fixed relayers alone has another significant advantage, that is, the simplification of WT terminals. The WT terminals will still have to transmit in the unlicensed bands when they use the fixed relayers, so they will still need two transceivers (one for the licensed bands and the other for the unlicensed bands); however, they will no longer be functioning as relayers, and so they will not need multiple transceivers which may have to function simultaneously. This elimination of multiple transceivers and decoding from the WT terminals will result in lower power consumption and less costly WT units, which can be smaller and lighter. Also, the problem of inducing WTs to leave their WT devices on for relaying will no longer exist. In addition, since advancements in battery technology are lagging the progress being made in computing and communications, power issues become even more important [27]. Further, installing fixed relayers will not be very difficult because they require no cabling to the BS, only a power supply which can be sourced from electric utility wires, so power will not be an issue as with WT relayers. As a result of all the preceding advantages, fixed relaying is a more viable alternative to performance enhancement in CDMA networks.

4.4 Expected Results

The expected results from the simulations are discussed in this section, primarily using mathematical analysis. This is done to see whether the ‘Ideal Throughput’ curve in the ensuing results behaves as the mathematics predicts it should. The ‘Ideal Throughput’ curve is obtained when there are no power caps or restrictions on the number of WTs that can enter the system (i.e. resource restrictions) and is only given for comparative purposes. This ideal curve is produced based on having a 50:50 chance of getting either a class A or a class B WT, this fact is fundamental to the following mathematical discourse:

WT Sequence	# Class A	# Class B
AA	2	0
AB	1	1
BA	1	1
BB	0	2

Table 4.1: All possible sequences for two WTs

# Class A	# Class B	Probability	Throughput (Kbits/sec)
2	0	1/4	20
1	1	2/4	60
0	2	1/4	100

Table 4.2: Probabilities and throughputs for different combinations of two WTs

The expected throughput from Tables 4.1 (shows all possible sequences when 2 WTs are in the network) and 4.2 (shows the throughputs possible from the various WT sequences) would be:

$$\left(\frac{1}{4}\right)20 + \left(\frac{2}{4}\right)60 + \left(\frac{1}{4}\right)100 = 60\,\text{Kbits/sec}$$

The expected throughput quantity of 60 Kbits/sec corresponds with the throughput obtained from the ideal curves in the simulation results (Figures 4.11, 4.12, 4.14, 4.15, 4.17, 4.18). For further verification, the expected throughput when three WTs are in the system will be analyzed below:

WT Sequence	# Class A	# Class B
AAA	3	0
AAB	2	1
ABA	2	1
ABB	1	2
BAA	2	1
BAB	1	2
BBA	1	2
BBB	0	3

Table 4.3: All possible sequences for three WTs

# Class A	# Class B	Probability	Throughput (Kbits/sec)
3	0	1/8	30
2	1	3/8	70
1	2	3/8	110
0	3	1/8	150

Table 4.4: Probabilities and throughputs for different combinations of three WTs

The expected throughput from Tables 4.3 (shows all possible sequences when 3 WTs are in the network) and 4.4 (shows the throughputs possible from the various WT sequences) would be:

$$\left(\frac{1}{8}\right)30+\left(\frac{3}{8}\right)70+\left(\frac{3}{8}\right)110+\left(\frac{1}{8}\right)150=90\,\text{Kbits/sec}$$

Again, the expected results correspond with the simulation results from the ideal throughput curves (Figures 4.11, 4.12, 4.14, 4.15, 4.17, 4.18).

Another verification pertains to the maximum number of WTs that can be accommodated in the system using a 1:1 ratio between class A and class B WTs. The mathematical analysis is shown below and is based on (2.5):

$$K_A f_A + K_B f_B < 1$$

With a 1:1 ratio between class A and class B WTs we now have:

$$\frac{K}{2} f_A + \frac{K}{2} f_B < 1 \Rightarrow \frac{K}{2}\left(\frac{1}{51}\right)+\frac{K}{2}\left(\frac{1}{11}\right)<1 \Rightarrow K < 18.1$$

K : total number of WTs, it cannot be fractional

In addition, the inequality in equation (2.5) must be satisfied, so K =18.

When K =18, there are, on average, 9 class A WTs and 9 class B WTs; therefore, the expected throughput should be 540 Kbits/sec, which corresponds with the value in the ideal curves (Figures 4.11, 4.12, 4.14, 4.15, 4.17, 4.18). Also, in [30] there is a curve (i.e. the 'offered load' curve in Figure 6) that exhibits identical traits to the ideal curve contained in this section, further confirming its accuracy.

Chapter 5 Conclusions and Future Work

5.1 Concluding Remarks

This project has shown that relaying is a feasible way to improve the performance of CDMA networks. Three different types of relaying schemes were investigated in this project: the first employed WT relayers only, the second used fixed relayers exclusively, and the third utilized a combination of fixed and WT relayers.

Results from the first relaying scheme indicate it can produce substantial throughput increases in medium size cells (i.e. cells which have an approximate 1000 m radius), with both high and low power caps (i.e. the maximum transmit power). The results also indicate that small cells (i.e. cells which have an approximate 500 m radius) derive modest benefits when a high power cap is used, but substantial benefits when the power cap is low. However, the results show that large cells (i.e. cells which have an approximate 1700 m radius) only benefit significantly if the power cap is high.

Performance improvements are greater in all cell radii when the second relaying scheme is employed, relative to the improvements seen with the first relaying scheme. Again, the results indicate that medium size cells experience substantial throughput increases with high and low power caps. The results for small cells are as stated in the previous paragraph, where the first scheme is discussed; however, the magnitude of the improvements is now greater. Unlike the case in the first scheme, large cells show dramatic performance enhancements when the power cap is high and modest gains with a low power cap.

When the third relaying scheme is employed, performance enhancements are greater still. However, the performance enhancements, relative to the fixed relayer only case, are modest at best, therefore the case for scheme three is not strong.

Of the three relaying schemes, the second one is the most appealing. The implementation of fixed relayers is not difficult and they can tap into the local power grid, so transmit power is not an issue. With the utilization of only fixed relayers, the WTs can be made simpler and lighter because they do not need to perform relaying, instead, the complexity can be transferred to the fixed relayers. This complexity transfer will result in longer battery lives for the WTs. Also, the problem of inducing subscribers to keep their WTs on, even when they are not using them, is no longer an issue with the use of only fixed relayers.

The range extension resulting from the implementation of the relaying scheme developed during the course of this research, is significant. This result is highly desirable because it can result in considerable monetary savings, as one BS employing relaying may be able to provide the same level of service as a much smaller cell which does not utilize relaying. Therefore, it may not be necessary to build additional BSs to give sufficient service to a larger area.

5.2 Future Work

The results obtained from this project are encouraging; therefore, this scheme appears to be worthy of further consideration because of the beneficial results obtained. Consequently, the future work on this project will entail the design of a multi-hop scheme to extend the benefits of the two hop system to very large cells and cells with very low power caps. The need for this development can be seen in the results obtained when very large cells are combined with low WT power caps. However, this multi-hop design could take a few months to develop due to its awesome complexity. In addition to the multi hop scheme mentioned above, the system designed during the course of this research may also experience significant benefits from the multi-class relayer selection scheme proposed in Section 3.3.1. Therefore, meaningful performance gains may be obtained when the above mentioned multi hop and multi-class relayer schemes are combined.

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