Multi-hop relaying networks in TDD-CDMA systems

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Abstract

The communications phenomena at the end of the 20th century were the Internet and mobile telephony. Now, entering the new millennium, an effective combination of the two should become a similarly everyday experience. Current limitations include scarce, exorbitantly priced bandwidth and considerable power consumption at higher data rates.

Relaying systems use several shorter communications links instead of the conventional point-to-point transmission. This can allow for a lower power requirement and, due to the shorter broadcast range, bandwidth re-use may be more efficiently exploited. Code division multiple access (CDMA) is emerging as one of the most common methods for multi user access. Combining CDMA with time division duplexing (TDD) provides a system that supports asymmetric communications and relaying cost-effectively. The capacity of CDMA may be reduced by interference from other users, hence it is important that the routing of relays is performed to minimise interference at receivers.

This thesis analyses relaying within the context of TDD-CDMA systems. Such a system was included in the initial draft of the European 3G specifications as opportunity driven multiple access (ODMA). Results are presented which demonstrate that ODMA allows for a more flexible capacity coverage trade-off than non-relaying systems. An investigation into the interference characteristics of ODMA shows that most interference occurs close to the base station (BS). Hence it is possible that in-cell routing to avoid the BS may increase capacity. As a result, a novel hybrid network topology is presented. ODMA uses path loss as a metric for routing. This technique does not avoid interference, and hence ODMA shows no capacity increase with the hybrid network. Consequently, a novel interference based routing algorithm and admission control are developed. When at least half the network is engaged in in-cell transmission, the interference based system allows for a higher capacity than a conventional cellular system. In an attempt to reduce transmitted power, a novel congestion based routing algorithm is introduced. This system is shown to have lower power requirement than any other analysed system and, when more than 2 hops are allowed, the highest capacity.

The allocation of time slots affects system performance through co-channel interference. To attempt to minimise this, a novel dynamic channel allocation (DCA) algorithm is developed based on the congestion routing algorithm. By combining the global minimisation of system congestion in both time slots and routing, the DCA further increases throughput. Implementing congestion routed relaying, especially with DCA, in any TDD-CDMA system with in-cell calls can show significant performance improvements over conventional cellular systems.

Declaration of originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the Department of Electronics and Electrical Engineering at The University of Edinburgh.

Thomas Rouse

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I would like to thank Prof. Steve Mclaughlin for supervising the work leading to the completion of this thesis. Not only has he been supremely helpful on numerous technical matters, but his considerate, informed, and down to earth approach has been invaluable when things didn't happen quite the way I'd expected.

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Acronyms and abbreviations

3G	3rd Generation
3GPP	3rd Generation Partnership Project
BS	Base Station
cdf	cumulative distribution function
COST	European CO-operation in the field of Science and Technical research
CPU	Central Processing unit
C/I	Carrier to Interference ratio
CDMA	Code Division Multiple Access
DAG	Directed Acyclic Graph
DARPA	Defense Advanced Research Projects Agency
DCA	Dynamic Channel Allocation
DL	Downlink
DRP	Dynamic Routing Protocol
DS	Direct Sequence
DSDV	Destination-Sequenced Distance-Vector
DSR	Dynamic Source Routing
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
FP	Forwarding Protocol
FTP	File Transfer Protocol
GB	GigaByte
GPRS	General Packet Radio Service
HD	Hard Disc
HIPERLAN	HIgh PERformance Radio Local Area Network
IARP	IntrAzone Routing Protocol
IC	Integrated Circuit
IERP	IntErzone Routing Protocol

IP	Internet Protocol
kB	kiloByte
kbps	kilobits per second
LAN	Local Area Network
LOS	Line of sight
MAC	Medium Access Control
MC-CDMA	Multi-carrier CDMA
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MS	Mobile station
ODMA	Opportunity Driven Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
ORACH	ODMA Random Access Channel
PC	Power Control
PRNet	Packet Radio Network
PS	Pseudo Noise
QoS	Quality of Service
RAM	Random Access Memory
RF	Radio Frequency
RFID	Radio Frequency IDentification
RTS	Request To Send
RWN	Reconfigurable Wireless Network
Rx	Receive
SDP	SemiDefinite Program
SSA	Signal Stability-based Adaptive
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TELNET	TELecommunications NETwork access
TORA	Temporally Ordered Routing Protocol
TS	Time Slot
Tx	Transmit
UL	Uplink

UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
WAP	Wireless Access Protocol
ZRP	Zone Routing Protocol

Nomenclature

α_i	QoS requirement for user i
β	power control convergence co-efficient
ϵ_j	bit energy to interference ratio at receiver j
ϵ_{max}	largest achievable bit energy to interference ratio
ϵ_{min}	minimum acceptable bit energy to interference ratio
$\eta[i]$	unspread noise at i
Γ	correlation matrix
$\Gamma[u, j]$	path gain from transceiver u to transceiver j
λ	largest real eigenvalue of a positive definite matrix, or Perron-Frobeneous eigenvalue
ν	iteration number
σ	variance of log-normal shadowing
σ_P	log-normal approximation of variance of received power due to multipath fading, imperfect power control and shadow fading
ξ	log-normal shadowing variable
ζ	time discrete link incidence flow matrix disregarding sources and sinks
A	node-link incidence matrix
B	path gain matrix normalised by QoS requirement
b	vector of required transmit power before interference
c_i	BS for user i
d	transmitter-receiver distance in m
D	total number of destinations
D_i	set of BSs available to user i
E	number of active links experiencing co-channel interference
E_i^0	initial available energy at node i
E_i^R	residual available energy at node i
f	number of floors in path loss model
G	path gain matrix

h_{vi}	number of hops in slot v related to user i
H	time discrete path gain matrix
I	total interference power
I_{ad}	adjacent cell interference
I_{MAI}	interference from in-cell users
I_{margin}	increase in transmitted power required to mitigate in-cell interference
I_{ODMA}	additional interference due to relaying
$I_k^{(\nu)}$	total interference at receiver k iteration ν
k_1, k_2	path loss exponents
l	link
L	path loss
M	number of calls in a cell
M_{MAX}	upper bound on number of supported calls
$m_P(M)$	mean received power from M users
n	number of users
N	receiver thermal noise
$O(M)$	probability of outage due to power control infeasibility with M users
P	power vector
p_m	acceptable probability of outage
P_i	transmitted power of user i
P_i^{max}	maximum possible transmitted power of user i
P_i^{min}	minimum possible transmitted power of user i
$P^{(\nu)}$	power vector at iteration ν
$P_i^{(\nu)}$	transmitted power of user i at iteration ν
P_{rx}	common received power
P_{uj}	received strength at receiver j of signal from transmitter u
P_{ij_k}	received power at receiver j from the route starting at i, hop k
pg	processing gain
Q	QoS requirement matrix
r	cell radius
R_i	residual capacity at node i

S_{cell}	cell radius
$s_n^{(d)}$	flow injected by n destined for d
T	time discrete-link incidence matrix
t_l	traffic for link l
$U(.)$	complementary cdf of zero mean, unit variance Gaussian random variable
v	time slot number
W	bandwidth
$x_l^{(d)}$	flow vector for link l destination d
Z	path gain matrix normalised by pg
∞	broken route metric

Chapter 1
Introduction

1.1 Introduction

How much information can we use? To answer this it may be useful to examine the exponential growth of computing power and storage ability. 20 years ago a personal computer with 64kB RAM, with little or no fixed storage was considered adequate. Now a standard computer may be supplied with over 10000 times this amount of memory and a hard drive (HD) capacity some 5000 times greater than just 10 years ago[1]. Someone living in the ’80s or early ’90s would probably have felt that they could never utilise the apparently gargantuan storage of 100GB+. Indeed even $>$2GB was not anticipated by Microsoft in 1995[2]. The truth is, now that we have this available, it is once again merely adequate. The concurrent increase in processing power, and the growth of multimedia has meant that applications and the data they require or generate has grown to fill the available space.

In comparison, the rate at which data may be sent between distant computers or other digital devices over a twenty year period, for a home user with a state-of-the-art modem, has only risen by about 400 fold[3]. This is even more significant given that many felt the early modems were inadequate. A few years ago this might not have been a cause for concern, but the meteoric rise of the Internet means that here is a computing bottleneck that should not be ignored. The situation is even worse for mobile users. Until recently, transfer speeds were sufficient only for text and highly optimised data. Now users have a choice between the recently emerging 3rd Generation (3G) systems, which given the right conditions bring data rates up to that achieved on fixed lines, or 802.11 [1] access points now appearing at limited locations such as airports and big brand coffee shops.

Mobile ’phones have achieved massive market penetration [2]. The Internet has been accepted faster than pretty much any other technology [3]. The previous limitations of mobile data rates

[1]Using specifications of 512MB-1GB RAM, 80-120GB HD for 2003 and 20MB HD for 1993.
[2]FAT32, enabling HD addressing above 2GB, was not included until Windows 95 v4.0095b, released 24/8/96.
[3]1200BPS phone modem to 512kbps ADSL connection.

have meant that attempts to combine the two, such as WAP, have been largely unsuccessful [4], and are little more than a gimmick. With the emergence of 3G it remains to be seen whether new applications such as mobile video calling will achieve large scale adoption. It would seem reasonable to assume, however, that mobile data services that match or exceed fixed line data rates at a competitive price would be successful. For business users it would mean that the ability to sustain network performance or maintain a virtual 'telepresence' whether in the office, on the train, or at a client. For other users, services such as high quality video or music on demand and high speed Internet access will be possible, regardless of their location.

1.2 Wireless communications

Contrasting with the apparent demand for high speed mobile communications are the realities of the resources that we currently use for wireless communications. In 1948 Shannon derived the capacity, or information rate, available to us given a specific bandwidth and received signal to interference ratio [5]. The radio frequency bandwidth used for mobile communications has become a scarce and expensive medium[4]. The received signal strength is limited by the distance we need to transmit and the power available, a significant factor in mobile communications. Many researchers have attempted to increase the amount of data we can send given these limits, with complex receiver structures, modulation schemes, error correction and so on. Probably the greatest single advance in bandwidth utilisation is the cellular concept. This means that bandwidth may be re-used. The idea is that simply creating more cells as required creates a separate resource, as long as the cells do not interfere with each other.

The frequency re-use factor is determined by how effectively the available bandwidth may be allocated such that cells do not interfere with each other. The smaller the figure the greater the wasted bandwidth. Early cellular access methods such as frequency division multiple access (FDMA) and time division multiple access (TDMA) at best had re-use factors of 7 for early systems 3 for 2nd Generation systems such as GSM [6] . Code division multiple access (CDMA) promises a frequency re-use-factor of 1, however this potential is limited by co-channel interference. The distance before interference becomes negligible is governed by the susceptibility to interference of the access method and the transmitted signal power, as received power and hence received interference is a function of this power, distance travelled,

[4]UK 3G auction resulted in 5 operators paying over 22 billion UKP for a total of 140 MHz bandwidth

and random fading factors. When CDMA is used within a conventional cellular system the transmitted power is determined by the loss in power between a user and the fixed mast at the centre of the cell and the interference at the receiver.

It is desirable to try and achieve the lowest transmitted power possible. Mobile users rely on a small battery to power the terminal, and a large part of the required power may be used on the signal strength. Even when using a laptop with a larger battery, the power requirements of 802.11 form a significant factor in battery life [7]. For telephony users there is still much debate about the possible health dangers of microwave radiation being generated in close proximity to the brain. It has been desirable from a technical point of view to place mobile telephony masts on top of hills or buildings to ensure coverage in the cell. Whilst this often produces the best signal it may not be the best option for the landscape. A reduction in the required transmitted power will permit greater utilisation of frequency re-use, whether in-cell as an underlay, or in mitigating adjacent cell interference.

1.3 Multi-hop relaying

Relaying of wireless communications signals is not a new idea. It has been used by satellite communications, to boost the signal in fixed microwave links, postulated as a means of extending the range of amateur radio signals [8], and within DARPA was one of the first implementations of packet based communications [9]. The demands of these systems meet some of the requirements for consumer applications, mainly extending coverage and beyond all in DARPA, robustness. They do not address the implications of integrating relaying into a multi-user consumer CDMA context. Further issues that may benefit from relaying are the ability to reduce transmit power and a consequent possibility for an increase in capacity. The reduced transmit power comes from breaking the transmission down from a direct link into a series of smaller hops using other users, or strategically placed seed relays. Not only does each hop require lower power, but the overall transmitted power may be reduced as path loss in non-linear.

The reduction in transmitted power can have several benefits. The battery life of a terminal may be extended, and frequency re-use can be greater due to the reduction in interference, increasing capacity. Alternatively, the reduction in path loss may improve service. High data rates, or even any service, may be unavailable to users near the edge of a conventional cell due to their maximum transmitted power being unable to achieve the required signal to noise ratio. With relaying the only requirement is that users can achieve the required signal strength at the next relay, meaning that coverage and high data rates should be available to more users. Furthermore, with a conventional system if the user has a poor channel directly to the Base Station (BS), they may have no choice but to change location to achieve communication. Relaying means that if that users can transmit to a relay that either has a direct connection with the BS, or an indirect route involving further relays, then a link will be achievable.

1.4 Contributions

This thesis examines multi-hop relaying within the context of TDD-CDMA. Potential benefits of relaying are reduced transmission power and enhanced frequency-reuse. The objective of this work is to identify which situations may be able to benefit from TDD-CDMA relaying, and how to exploit the technique to produce the greatest benefit. The method of constructing the relaying path is though a routing algorithm. Consequently an important objective is the development of a routing algorithm which improves system performance beyond that of previous relaying and non-relaying cellular systems.

Initially this thesis analyses a relaying protocol from the initial draft of UMTS [10], known as Opportunity Driven Multiple Access (ODMA). The interference characteristics of this system are analysed using simulations. The results of this analysis indicate that other topologies may be necessary to exploit some of the benefits of relaying. Consequently, some new topologies are then formulated and analysed. From this novel analysis several novel routing protocols are developed to exploit these topologies. The most successful of these reduces the average required transmission power to far below that of any other examined relaying or non-relaying system. The algorithm is further enhanced by the integration into a novel Dynamic Channel Allocation (DCA) algorithm for multi-hop relaying and TDD-CDMA. This DCA simultaneously allocates routing and time slots to minimise system congestion. If there is any peer-peer traffic, this results in a significant throughput improvement over conventional cellular TDD-CDMA, and the other routing protocols investigated.

1.5 Structure of thesis

This chapter highlights several issues with current wireless communications, and introduces multi-hop relaying as a possible means to contribute to their solution.

Chapter 2 shows how the supported number of users in a CDMA system may be affected by interference and cell size. The Time Division Duplex (TDD) method of duplexing is introduced as a simple and efficient technique for both relaying and meeting current data requirements. Several power control methods are presented. Co-ordination of received power and subsequent minimisation of interference is integral to achieving potential capacity gains and reducing transmitted power in both cellular and relaying CDMA systems. Several existing relaying protocols are discussed, along with their implications regarding power, mobility, and higher level protocols such as TCP/IP.

Chapter 3 examines UTRA-TDD ODMA. Initially an interference analysis is performed using a system level simulation. This shows that, in a single cell, the greatest interference occurs close to the centre. This suggests that, if possible, it may be desirable to route around this area. A further investigation shows that the coverage-capacity trade-off of a relaying system is more flexible than a conventional one.

Chapter 4 develops several new routing algorithms. The algorithms follow from the findings of the previous chapter and a desire to minimise the overall transmitted power and maximise system capacity. The algorithms reflect different requirements including complexity, speed to achieve routing, and required overheads. It is shown that relaying requires a lower overall transmitted power than a conventional system, and when in-cell calls are involved relaying can increase system capacity.

Chapter 5 extends the most successful routing algorithm, congestion based routing, into the time domain as a form of DCA. The results show that this integrated approach can further increase capacity gains over a non-relaying system.

Finally, in chapter 6 overall conclusions are drawn and suggestions for future work made.

Chapter 2
Multi-hop communications and TDD-CDMA

2.1 Introduction

With the wide scale adoption of mobile technology and the continually increasing utilization of networking for productivity, it is likely that future generations of mobile communications devices will be expected to form networks in both local and wide area environments. Many air-interfaces for current mobile communication systems are based on CDMA, which inherently is interference limited. Consequently, to reduce the level of interference, it may be preferable for users to be able to achieve peer-to-peer communications, offloading BS resources and thus achieve better performance than that offered by a direct link to the BS.

In conventional CDMA systems, the reverse-link, or uplink is power controlled to a single BS in a cell, generally giving the best performance when all users are received at the same power, and the downlink is power controlled to the user with the weakest reception. For mixed traffic, with some users transmitting to receivers in-cell and others via a BS to non-local equipment, perfect power control becomes impossible for all receivers and system performance may be severely degraded. Hence, the analysis of power control may be a useful method to ensure that the resulting power solutions are favourable when peer-peer communication is implemented.

Multi-hop communications blur the distinction between uplink and downlink, as a user may be receiving from one mobile station (MS), then transmitting to another. An efficient method that allows users to change their role simply and transparently is TDD. The link is determined by TS allocation, requiring no extra hardware complexity. There is the added bonus that this allocation may be employed to enable data rate asymmetry.

The concept of relaying signals in a dynamic environment has existed for over 30 years [9]. In this period many routing protocols have been developed [11], initially motivated by military requirements. The issues they attempt to address include maintaining routing with a minimum of overhead, robustness in the face of link breakage and mobility, and reducing transmitted power. Until recently, however, little has been offered with regards to increasing the capacity of relaying in the context of civilian CDMA multi-hop communications.

This chapter briefly describes CDMA and TDD. Capacity limitations due to interference are outlined, and the properties of TDD examined. Several power control algorithms are described. Additionally, some existing relaying protocols are included with a basic description of how the algorithm achieves its aims along with their properties.

2.2 Spread spectrum techniques

Spread spectrum communications are those in which a signal occupies many times the bandwidth that is required by the information rate, as determined by the Shannon capacity [5]. The initial motivation for such systems was with military systems where the properties of jamming resistance, and being able make a signal hidden in, or appear like, noise are desirable. The spreading may also make the signal more difficult to decode if it is detected. Spread spectrum techniques, especially CDMA, are now entering the commercial environment as a more efficient method of utilising bandwidth between many users.

2.2.1 CDMA properties and capacity definitions

CDMA users simultaneously share common bandwidth. This bandwidth is greater than the individual users data rate, as every signal is spread with a unique code, or signature sequence, for each user. The ratio of used bandwidth W to information rate R, W/R is known as the processing gain, pg which is proportional the possible number of simultaneously active users. The code allows each user's data to be extracted from the incoming signal at the receiver. The code may be applied directly to each data bit (Direct Sequence (DS) spread spectrum), used to place the signal in one or more of a large number of frequency slots (Frequency Hopping (FH) spread spectrum), select time slots in an interval much larger than the reciprocal of the data rate (time hopping spread spectrum),, or to sweep the carrier frequency over a wide range (chirp or pulse FM modulation). CDMA has also been implemented as a hybrid with Orthogonal Frequency Division Multiplexing (OFDM) called Multi-Carrier CDMA (MC-CDMA) [12]. In OFDM carriers are chosen such that they are mathematically orthogonal. With overlapping carriers the condition for this is spacing of 1/(symbol period). Inter-symbol interference is reduced as the symbol rate is reduced by the number of carriers. With MC-CDMA the spreading code is applied in the frequency domain on a carrier by carrier basis. It has been shown that the maximum capacity of an MC-CDMA system is the same as for a single carrier DS-CDMA system [13]. For the purposes of this thesis CDMA relates to DS-CDMA.

With previous cellular systems, such as FDMA or TDMA, complete frequency reuse has not been possible due to co-channel interference, greatly reducing the spectral efficiency of these systems. Such systems require that each resource division, such as frequency or time slots, may only be used by one user at a time within a certain re-use distance. With CDMA the system is designed to cope with other users sharing the same resource and hence a frequency re-use factor of one is used. CDMA uses pseudo noise (PN) codes to spread the signal and is primarily interference limited. This means that with common frequencies used by adjacent cells, the capacity may be reduced by other cell interference. In order to mitigate this and minimise reductions in capacity due to in-cell interference it is essential to use power control. Unfortunately it is unrealistic to expect perfect power control due to the variation with time of the path loss values. This problem means that according to level of mobility, and system fading parameters, CDMA capacity may suffer due to imperfect power control. Other cell interference may also be significantly increased if cell selection is based upon geographic criteria. System capacity will be improved if the BS is selected by allocating according to minimum path loss instead of minimum physical distance [14].

2.2.1.1 Theoretical capacity

In a conventional CDMA system the the bit energy to interference ratio, ϵ_j, in the presence of Gaussian interference may be denoted as

$$\epsilon_j = \frac{pgP_{u_j}}{\sum_{i:i\neq j}^{M} P_{u_i} + I + N} \tag{2.1}$$

where pg is the processing gain, P_{u_j} is the received strength of the desired signal, M is the number of calls in the cell, I other cell interference and N thermal noise, P_{u_j} the unwanted own-cell interference.

Assuming ideal power control, and a single user detector so that all users are received at the same power, to minimise interference for all users, (2.1) becomes

$$\epsilon_j = \frac{pgP_{u_j}}{P_{rx}(M-1)+I+N} \tag{2.2}$$

where P_{rx} is the common received power. To determine the maximum capacity for a single cell, I is set to 0, and rearranging for M_0, the capacity without external interference

$$M_0 = \frac{pg}{\epsilon_j} - \frac{N}{P_{rx}} + 1 \tag{2.3}$$

therefore, disregarding any upper limit on transmitted power, gives

$$M_0 = \frac{pg}{\epsilon_j} + 1 \tag{2.4}$$

In reality there is an upper limit on transmitted power which will restrict the coverage of a cell. The relationship between the cell radius, S_{cell}, and the number of users has been derived in [15]

$$\log S_{cell} = \frac{1}{k_2}[pgP_{max} - k_1 - MP_{rx}] \tag{2.5}$$

Introducing variance in received power due to multipath, imperfect power control and shadow fading, σ_P, with a log-normal approximation, gives the relationship

$$\log S_{cell} = \frac{1}{k_2}\left[pgP_{max} - k_1 - m_P(M) - \sigma_P U^{-1}\left(\frac{p_m - O(M)}{1-O(M)}\right)\right] \tag{2.6}$$

where $m_P(M)$ is the mean received power for M users, $U(.)$ is the complementary cdf of a zero-mean, unit-variance Gaussian random variable, p_m an acceptable probability of outage, and $O(M)$ the probability of outage due to an infeasible set of power control equations for M users. These equations show that capacity may be reduced as the cell radius increases.

2.2.2 TDD properties

Until recently, consumer mobile communications have been characterised by voice usage, and hence symmetric uplink and downlink data rates. With the growth of mobile Internet, video and data services data rates are becoming more asymmetrical. TDD uses the same bandwidth for both uplink and downlink, performing duplexing by the allocation of time slots, potentially according to the required data rates.

2.2.2.1 TDD bandwidth efficiency

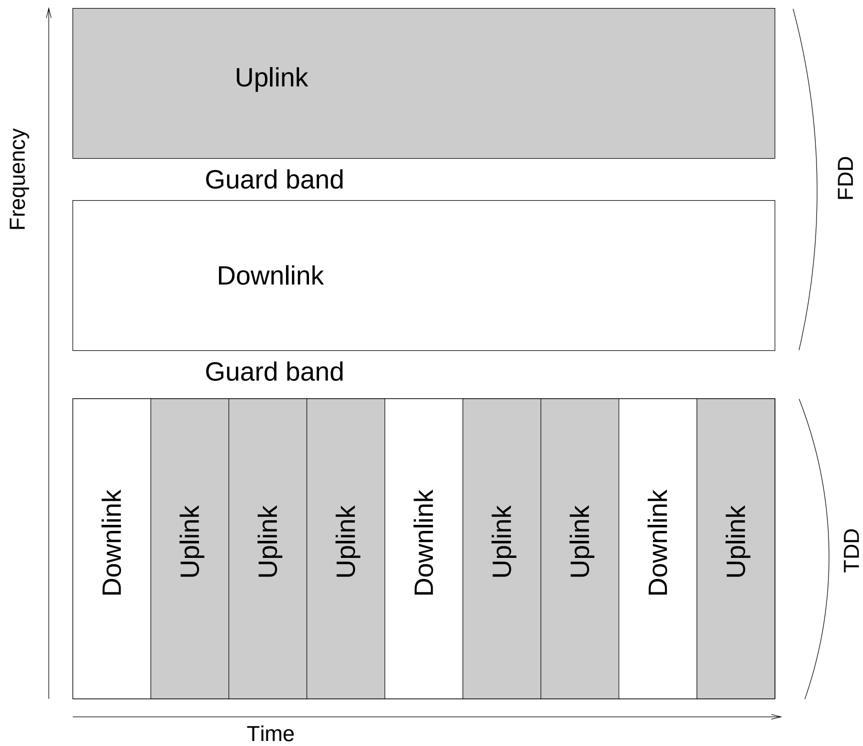

Figure 2.1: *Comparison of FDD and TDD duplexing methods in the frequency and time domains*

Figure 2.1 shows the duplexing methods employed in Frequency Division Duplex (FDD) and TDD. FDD uses separate frequency bands for the uplink and downlink, with a guard band between them to try and accommodate imperfections in baseband filtering and RF non-linearities that would otherwise cause self-interference. With an inherently symmetrical voice network this arrangement is reasonably efficient. Asymmetric data rates may be supported by varying the proportion of bandwidth allocated to each transmission direction. Unfortunately with current systems this allocation is predetermined by the duplex filter, and hence is not dynamically variable. Any mismatching or variability in the asymmetry of actual traffic compared to the bandwidth allocation will result in inefficient usage of the bandwidth. To try and reduce this inefficiency the use of a TDD underlay in the FDD downlink has been proposed [16].

TDD supports duplexing by allocating time slots in a common frequency band. This may support symmetric traffic, through an alternating allocation of uplink and downlink slots. The time slots are imperceptible to the user due to the short length of the time slots. As the time slot length is reduced, however, the spectral efficiency is decreased. This is because a guard time band, where no information may be sent, is required between each uplink and downlink slot to cope with the round trip delay and imperfect synchronization between MSs. An upper limit on the time slot length is imposed by the maximum acceptable latency and requirements for channel reciprocity, as discussed in the next section.

As uplink and downlink slots may be dynamically allocated, not only will TDD support asymmetric traffic, it may be able to exactly match the required data rates for each stream on demand. Unfortunately the situation is not quite this simple when combined with a simultaneous resource sharing multiple access method, such as CDMA, as shown in Section 2.2.3. A limit on levels of asymmetry comes about by the same means governing the maximum time slot length, as several consecutive slots for the same stream are effectively one, longer time slot.

2.2.2.2 Channel reciprocity

The same bandwidth is used in TDD for the uplink and downlink. This means that parameters measured at the receiver may be employed to adapt the subsequent transmission to the channel. This use of channel reciprocity relies upon the channel remaining reasonably constant over the length of a time slot. Hence, any benefits gained through channel reciprocity may only be maintained in higher mobility / fast fading systems by shortening time slot length, or limiting levels of asymmetry.

One useful parameter that is easily obtained is the path loss. As long as the initial transmit power is known, the received power level is all that is required. In FDD a frequency dependent fading between the different bands requires that a feedback loop is necessary, causing signalling overheads and possible delays. Knowledge of the path loss allows open loop power control, described in 2.3.4. Not only does path loss knowledge allow for optimisation of received signal levels, it may be used to more effectively perform BS hand-over, as described in Section 2.3.3, or determine routing in relaying networks, as described in Chapters 3, 4, and 5.

A more advanced use of channel knowledge may be used to remove complexity from the MS, significantly reducing power consumption. The estimate of the channel may be used in a receiver to equalise the signal by convolution with the estimated impulse response. If, however, the channel does not vary during transmission it is possible to gain the benefits of equalisation

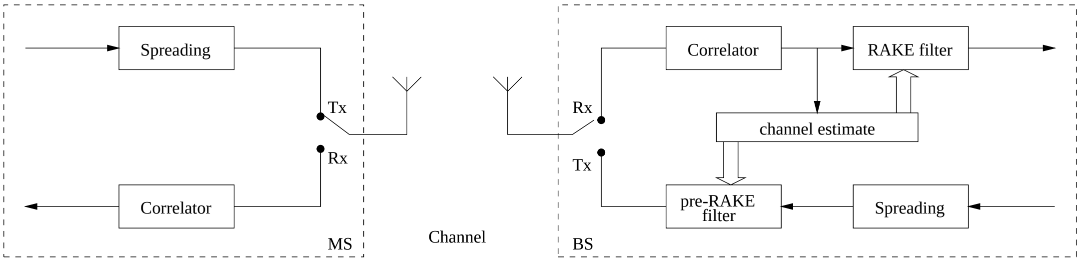

Figure 2.2: *Simplified implementation of pre-RAKE*

in the MS without the need for convolution or channel estimation. Instead of equalising at the MS receiver, the BS applies pre-transmission filtering by convolution with the time reversed impulse response as shown in Figure 2.2. This means that the signal received at the MS is equalised by the channel itself.

2.2.2.3 RF hardware implications

With an FDD system the uplink and downlink channels need to be simultaneously active. Without careful design, the transmitted power is likely to overpower the far smaller received signal. To mitigate this self-interference, duplex filters, as shown in Figure 2.3, as well as tight requirements on layout and shielding need to be incorporated. The cost of implementation increases as the guard band separation, Figure 2.1, decreases. It is also necessary to use two separate synthesizers, low pass filters, and mixers for the up / down-conversion.

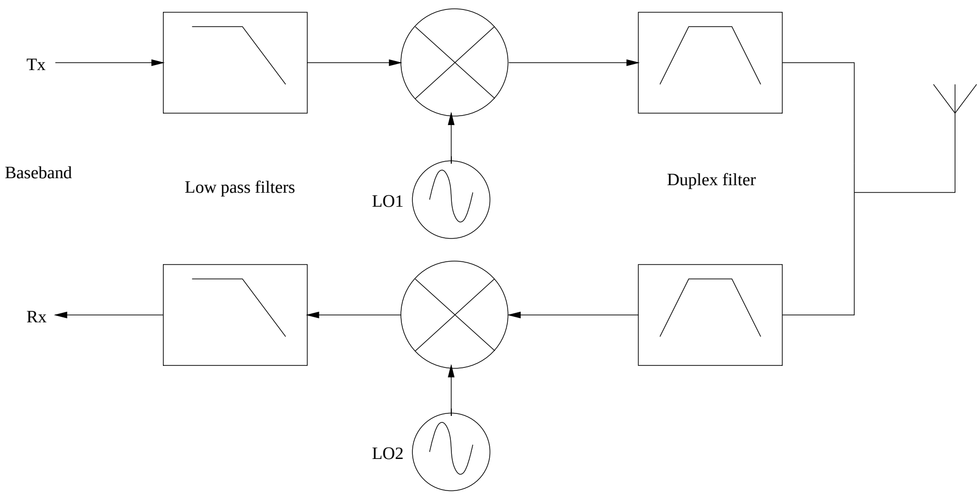

Figure 2.3: *Simplified FDD up / down conversion*

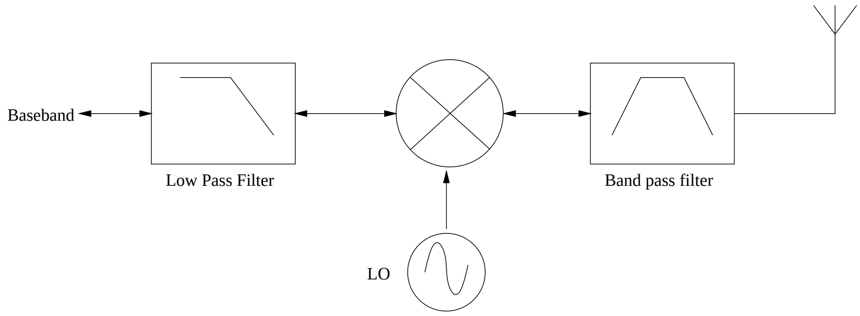

Figure 2.4: *Simplified TDD up / down conversion*

By comparison TDD cannot interfere with itself through simultaneous uplink and downlink as they are exclusive in time. As a single frequency is used, only one synthesizer, mixer and low pass filter is required. Instead of a duplex filter, a simple bandpass filter is sufficient. This has greatly relaxed out of band suppression requirements as it will never be required to attenuate a signal as powerful as the Tx band in FDD.

When considering relaying, the hardware implications for FDD are even greater. With a conventional system the transmit and receive channels are clearly defined by the classification as BS or MS, i.e. BS transmits on downlink and receives on uplink, vice versa for MS. For a relaying system this clarity disappears. A relay may be receiving on an uplink channel one time slot, they relaying on to the BS by uplink transmission on the next slot. This requires additional hardware modifications if a MS will be able to be used as a relay. The TDD hardware, with its single channel requires no modification as it is already able to transmit and receive on the same channel.

2.2.3 TDD-CDMA

The combination of TDD and CDMA allows for efficient bandwidth utilisation, primarily through uplink / downlink asymmetry and frequency re-use respectively. Unfortunately the situation is complicated by additional interference mechanisms that are introduced by this unification when viewed in a multi-cell environment. In FDD-CDMA, where the uplink and downlink are separate frequency bands, the only interference mechanism is MS-BS and BS-MS. This is the situation in TDD if all cells are synchronised and use identical uplink / downlink slot allocations.

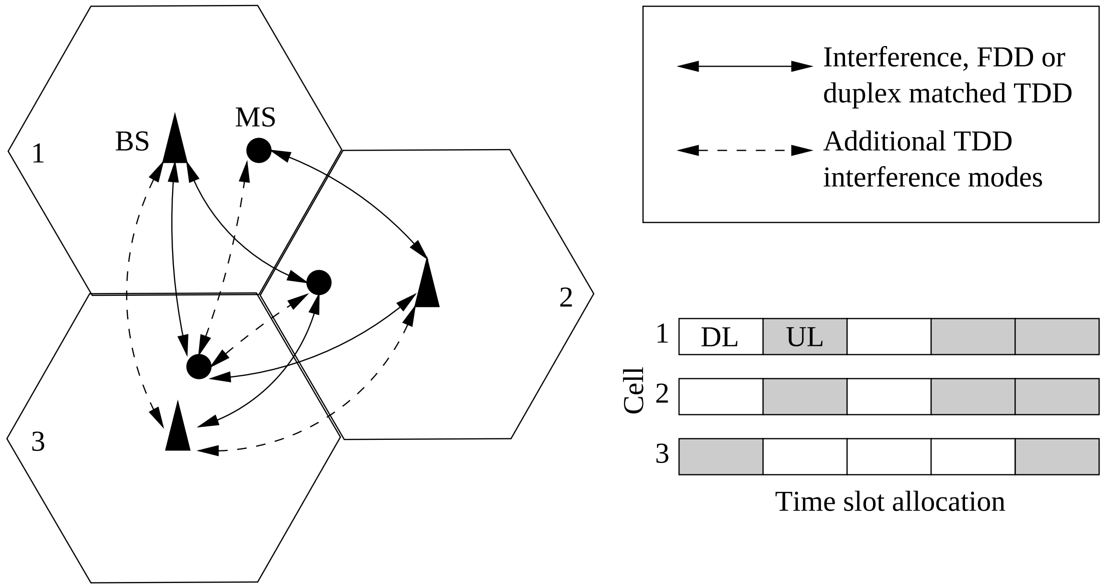

Figure 2.5: *Interference modes of TDD with and without synchronization and uplink / downlink co-ordination*

Figure 2.5 shows the interference mechanisms that result if duplexing slot allocations are not the same between cells. These mechanisms will also occur if the time slots are not synchronised between cells. This is because the lack of synchronisation will cause uplink and downlink slots from neighbouring cells to overlap. Cells 1 and 2 have identical time slot allocation, and hence only suffer from BS-MS and MS-BS interference. Cell 3, however, is using a different level of asymmetry and as well as the BS-MS and MS-BS interference, also suffers from, and inflicts MS-MS and BS-BS interference with cells 1 and 2. MSs in different cells may be close together, and hence serious interference problems may result.

2.3 Power control methods

The capacity of a CDMA system can be dependent on the received signal to noise ratio as shown in (2.1)-(2.4). Meaning that if users are not power controlled to this level there may be an impact on the number of supported users. Therefore it is essential power control systems are an integral part of system design, and hence must be capable of reacting to the rate of system fading. This factor limits the level of system mobility by the update rate of the power control.

With any CDMA system the actual transmitted power is determined by the power control solution. The path loss between transmitter and receiver is an important factor in the required power, but, in a system with more than one user, the power cannot be determined from this single path loss. Hence, when considering how to relay with minimum power, it may be more beneficial to attempt to minimise the resulting solution to the power control instead of just minimising path loss.

2.3.1 Centralised power control

With a centralised power control system it is assumed that all the path gains in the system are known. This includes unwanted interference paths, as well as the wanted MS-BS paths. In many systems this may not be a feasible approach, but does serve to derive upper performance bounds. Early power control systems attempted to achieve a constant received power. This has a limited ability to reduce co-channel interference. A better approach is to construct power control that is optimal in the sense that it minimises interference probability. This is the probability that too low a C/I ratio is achieved at the receiver. In the downlink, ignoring noise due to thermal noise, the C/I ratio at mobile i can be considered as

$$\epsilon_i = \frac{pg\Gamma[c_i,i]P_i}{\sum\limits_{j\neq i}\Gamma[c_i,j]P_j} = \frac{pgP_i}{\sum\limits_{j\neq i}P_j\frac{\Gamma[c_i,j]}{\Gamma[c_i,i]}} = \frac{P_i}{\sum\limits_{j=1}^{Q}P_jZ_{ij} - P_i} \tag{2.7}$$

where Q is the number of active links that experience co-channel interference, $\Gamma[c_i,i]$ path gain from BS in i's cell to i, and Z_{ij} is the path gain matrix

$$Z_{ij} = \frac{\Gamma[c_i,j]}{pg\Gamma[c_i,i]} \tag{2.8}$$

Since $\Gamma[i,j]$ and hence Z, are random variables, ϵ_i will also be a random variable. The outage probability, due to not achieving the minimum C/I ratio, can be defined as

$$O(\epsilon_{min}) = \frac{1}{Q}\sum_{j=1}^{Q}Pr(\epsilon_j \leq \epsilon_{min}) \tag{2.9}$$

This can be considered as the probability that a power vector cannot be found to achieve this minimum C/I ratio. The largest achievable C/I ratio, ϵ_{max}, is related to the spectral properties of the matrix Z [17]

$$\epsilon_{max} = \frac{1}{\lambda - 1} \tag{2.10}$$

where λ is the largest real eigenvalue, or Perron-Frobenious eigenvalue [18], of matrix Z. The power vector required to achieve this is the eigenvector corresponding to λ. One way of minimising the outage probability is shown in [17] by removing cells to form the largest sub-matrix of Z where the maximum possible C/I ratio is larger than the minimum required C/I ratio.

Another approach [19] is to formulate the problem as a geometric problem [20].

$$\begin{array}{lll} \text{minimize} & \alpha & \\ \text{subject to} & \frac{P_i^{min}}{P_i} \leq 1 & i = 1, ..., n \\ & \frac{P_i}{P_i^{max}} & i = 1, ..., n \\ & \left(\frac{1}{\alpha}\right) \prod\limits_{j \neq i} \left(1 + \frac{\epsilon_{min} Z_{ij} P_j}{P_i}\right) \leq 1 & \end{array} \tag{2.11}$$

where α is an upper bound on $1/(1 - O_i^{max})$, O_i^{max} being the maximum outage probability for user i. Geometric problems may be solved globally and efficiently with interior-point methods for geometric programming [21]. Hence minimising α will allocate powers such that there is a minimum value for the maximum outage probability. Although the above methods are for the downlink, they are equally applicable to the uplink [22].

2.3.2 Distributed power control

To measure all the path gains in many cellular systems may require prohibitively large overheads, especially if there are many, highly mobile users. In this situation it is desirable to perform power control with only local information. Most distributed power control systems use only the C/I ratio at the receiver to control the transmitter's power for each link, on an iterative basis. One of the simplest of these, proposed by Zander [23], is shown to converge to the eigenvector corresponding to the dominant eigenvalue of Z. Hence, there will always be a solution, but not necessarily one that achieves ϵ_{min}. The algorithm takes the form of distributed C/I balancing

$$\begin{aligned} P^{(0)} &= P_0, & P_0 > 0 \\ P_i^{(\nu+1)} &= \beta P_i^{(\nu)} \left(1 + \tfrac{1}{\epsilon_i^{(\nu)}}\right), & \beta > 0. \end{aligned} \tag{2.12}$$

where ν denotes iteration, and β needs to be chosen so that the powers are not constantly increasing. It is suggested that selecting

$$\beta = \beta(\nu) = \frac{1}{[P^{(\nu)}]} \tag{2.13}$$

will give a "constant" average power level. Using this, however, means that the algorithm is no longer completely decentralised. This issue is addressed in [22] by including receiver noise in a differential equation, with proven convergence if feasible, from which the algorithm is derived.

$$P_i^{(\nu+1)} = P_i^{(\nu)} \left[1 - \beta + \beta \frac{\epsilon_{min}}{\epsilon_i^{(\nu)}}\right] \tag{2.14}$$

This formulation also allows for the desired C/I ratio to be specified. Hence, it is now possible to achieve a minimum power vector. This reduces power consumption and other cell interference. The selection of β now becomes one of optimal speed of convergence according to system tracking requirements. As this approach is only successful if there is a feasible power solution for every user to achieve ϵ_{min}, additional admission controls are necessary. It has been shown that distributed power control approaches may be applicable to various QoS requirements by slightly increasing the required ϵ through Markovian properties of traffic statistics [24]. As with the centralised methods the algorithms are equally applicable to uplink and downlink [22].

2.3.3 Combined cell site selection and power control

The power control algorithms outlined in the previous sections assume that users are already assigned a BS. This assignment may be through choosing the BS with the minimum path loss from the MS. This approach may mean that the required power for the link is greater than is necessary. For instance if a MS is near the edge of a heavily loaded cell, or in one suffering from a great deal of inter-cell interference, transmitting to a neighbouring BS may reduce both that MS's required transmit power and that the MSs in the first cell.

To try and minimise transmitted powers, two authors independently developed a combined power control and base station assignment algorithm [25, 26]. Both algorithms are decentralised, and are similar to (2.14) except for the power control adaptation being directly from the path loss, and the addition of minimisation though cell site selection of BS, k, from the set of BSs available to i, D_i . Both may take the form

$$P_i^{(\nu+1)} = \min_{k \in D_i} \left[\left(\frac{1}{pg} \sum_{u \neq i} P_u^{(\nu)} \Gamma[u,k] + N \right) \frac{\epsilon_{min}}{\Gamma[i,k]} \right] \tag{2.15}$$

The above algorithm is a synchronous one, and is convergent if the system is feasible [26]. The algorithm may also be formulated to converge asynchronously [25]. Even though the algorithm is formulated as cell-site selection, other BSs are able to receive the signal, and hence form a macro-diversity system. A similar form to (2.15) may be used to further minimise transmitted powers using macro-diversity [27].

2.3.4 TDD and power control

The reciprocal channel of TDD allows for an open loop power control. This means that the link gain does not need to be sent back to the transmitter, merely measured from the received signal. The update rate translates as the time before an uplink packet is received after a downlink packet is transmitted, or vice versa, for the downlink and uplink packet respectively. For a system with symmetric data rates this time is the TDD slot length. When the asymmetric abilities of TDD are exploited, however, this time depends on the level of asymmetry in the data rates, hence the average update rate of the power control is

$$\text{power control update rate} = \frac{1}{\text{asymmetry ratio} \times \text{slot length}} \tag{2.16}$$

though it must be considered that this is an average rate and will vary according to uplink / downlink slot assignment. This puts a constraint upon slot assignment to be as consistent as possible in order to provide a predictable QoS appropriate for the environment and required data rates. Hence, highly mobile systems may limit the supported level of asymmetry.

The interference mechanisms outlined in Section 2.2.3 mean that is may be beneficial to modify target $\epsilon_m in$ values in order to maximise throughput. Under the assumption that the downlink suffers most from the extra interference mechanisms introduced by varying levels of asymmetry [28] downlink throughput may be increased without reducing uplink throughput by increasing downlink transmit power [29]. It has been found, however, that uplink interference may be more significant [30], though downlink power control was not used in this study.

2.4 Dynamic Channel Allocation (DCA)

The power control algorithms outlined in the previous sections, apart from C/I balancing, rely on a feasible solution of the power vector for convergence. One approach to this problem is to have a fixed number of supported users per cell or per channel which will guarantee a feasible solution. This approach provides predictable cellular capacity. Fixed assignment may mean, however, that calls are blocked in a highly loaded cell that may be possible if feasibility conditions were based on actual traffic requirements. With a dynamic topology such as ad-hoc networks, fixed assignment is not possible, due to unpredictable interference. Hence, some form of dynamic admission control is necessary for such systems to ensure a feasible power control solution.

DCA algorithms for CDMA have mainly taken the form of interference-based DCA [31] or combined power control and interference-based DCA [32] which may be implemented in a simple and distributed fashion. Due to the frequency re-use factor of 1 employed by cellular CDMA, frequency re-use DCA such as [33] are not particularly suitable, although they may be applied to ad-hoc systems to try and reduce interference. Considering TDD-CDMA means that DCA can be applied to time slot allocation as a means to improve system capacity through interference reduction [34] or traffic scheduling [35].

2.5 Existing relaying techniques

Research into relaying has generally covered two aspects, route discovery and metrics to determine the route chosen.

2.5.1 Path loss routing

Possibly the simplest routing metric is to minimise path loss, or use the shortest path [11]. Without co-channel interference, this should require the minimum overall transmitted power. For in-cell calls, the user probes to find the path loss to other nodes, and their path loss to the target. The routing is determined by choosing the route with the minimum path loss overall. For out of cell calls a similar probing is performed, but the target may be any BS. This means that the user may be outside the hand-over region of the BS that it linked with. The basic routing structure may be performed in a trellis as will be presented in Section 4.3.1.1. This reduces the number of calculations required, with a path loss based system this causes no degradation in performance as the minimum path loss route is selected at each node in the trellis.

2.5.1.1 DARPA

To try and capitalise in a mobile environment on the dynamically adaptive advantage of packet switching, in 1972 DARPA initiated a research effort into a packet radio network (PRNet). The intention was that not only could the broadcast channel be used more efficiently, it could cope with changing or even incomplete connectivity [9]. In order to communicate with other military networks PRNet became the first “Internet aware” network [36]

2.5.1.2 Destination-Sequenced Distance-Vector Routing (DSDV)

DSDV [11, 37, 38] is a table driven routing protocol, the basic premise being to determine the shortest number of hops to a destination. The protocol requires each node to advertise its routing table. This table contains all the possible destinations in the network, the number of hops to each destination and a sequence number of the information received from the destination. The sequence number allows routes to be chosen with a preference for more recent information, removing the possibility of loops due to stale routes. In order to avoid large amounts of routing information flowing through the network incremental changes are used to relay only the changes that have occurred since the last dump. The only situation where a node other than the destination may broadcast information about the route is if it is discovered that the route is broken. In this case a route update is triggered with an ∞ metric with a sequence number one greater than the last one received from that destination. If a node receives this ∞ metric and it has an equal or later sequence number with a valid metric, then it will send this information to supersede the ∞ metric.

Route selection criteria are dependent on timing and variation of the received tables. Upon receipt of new information more recent sequence numbers replace the older ones, equal numbers are chosen for the best metric. Metrics are incremented by one hop and scheduled for immediate advertisement if new, or may be subject to a settling time if the destination is already held. This settling time is to try and avoid rapid changes in routing before much of the information is gathered and there is a likelihood that a better route will be received soon. It is performed by keeping a weighted average of the time that routes fluctuate before the best metric is received, excluding ∞ metrics.

2.5.1.3 Cluster based networks

In order to try and reduce the overhead of signalling information, and to manage system resources effectively clustering of nodes according to specific parameters has been proposed by several authors [39–44]. From examining the pole capacity of a CDMA system (3.11), it can be seen that halving the processing gain not only doubles the each user's possible data rate for a given bandwidth, but due to the lack of interference from the desired signal, increases the throughput of the system. As the data rate is proportional to $1/pg$ and the throughput at a receiver is $data\_rate \times no\_users$ we get

$$throughput_{max} \propto \frac{1}{\epsilon_i} + \frac{1}{pg} \tag{2.17}$$

hence for a CDMA based relaying system we may be able to see an increase in throughput by clustering to a common link by combining the data streams via processing gain reduction, though this phenomenon has not been fully investigated. It should be noted that this potential benefit becomes negligible where large processing gains are in use.

Clustering algorithms with an unspecified MAC layer are more concerned with reducing the possibility of flooding of routing messages and possible infrastructure assignment, with possibilities such as bandwidth re-use and backbone allocation [39]. In most cases the routing protocol is separate from the cluster formation; both table driven [40] and on-demand [41] algorithms have been applied to clustered systems. The benefit of clustering clearly depends on the sensitivity to flooding with scalability of the protocol. Certain nodes, called clusterheads, are responsible for the formation of clusters [42–44]. This can be considered as analogous to cells and hand-over in conventional cellular systems.

2.5.1.4 Dynamic Source Routing (DSR)

DSR is an on demand source routing protocol, in that no periodic packets are required of any kind. This means that the number of overhead packets is scaled according to the mobility of the nodes once routes are established. The protocol consists of two stages; route discovery and route maintenance. Route discovery only takes place if a node's route cache does not hold a route to the desired destination. The discovery takes place, on demand, by broadcasting a route request packet. This packet contains the initiating and target node addresses as well as a unique request identification number. When a node receives a route request and it is either the target node, or holds a current route to the destination a route reply is generated. If this is not the case the node adds its address to the route request and retransmits it, both forming a record of the route and allowing the node to ignore the route request if it has already encountered it, reducing flooding. This tagging of the route request, plus in the case of intermediate nodes, their route cache, is the basis of the route reply message and hence routing information. The route reply is returned to the initiator using the replying nodes route cache, if this exists, otherwise for symmetric links the route is simply reversed, for non-symmetric links the node may initiate its own route request, piggybacking the route reply on top.

Route maintenance is shared by all users involved in the routing through receipt confirmation. This may be performed as part of the link level protocol or through setting a bit in the packet header requesting confirmation through whatever means are suitable. If this confirmation is not received then the packet will be retransmitted up to a certain number of times. If there is still no confirmation then a route error packet is sent to the initiating node, identifying the broken link. As many routes may have been received in response to the initial route request, the initiating node may be immediately able to try a new route, otherwise a new route discovery phase is entered.

2.5.1.5 Zone Routing Protocol

The Zone Routing Protocol (ZRP) [11, 45, 46] is a hybrid (table / on-demand) protocol for a special class of ad-hoc networks known as reconfigurable wireless networks (RWNs). This kind of system has features such as high mobility, a large network span, and a larger number of nodes. ZRP adjusts to network conditions through a single parameter, the zone radius, reducing the cost of updates for topology changes.

The routing zone is defined at each node by including nodes whose distance is equal to or less than a maximum number of hops. Those at a distance equal to the maximum number of hops are known as peripheral nodes, the others interior nodes. Even though the distance is measured in number of hops, it should be noted that increased transmit power will result in a larger radius as more nodes will be within one hop. A node only maintains routing information on those nodes within its routing zone, meaning that the amount of update traffic does not depend on the number of nodes within the network. The zone is discovered through a table driven protocol, the Intrazone Routing Protocol (IARP), which may be any pro-active technique.

To establish communication beyond the node's routing zone, an on-demand protocol, the Interzone Routing Protocol (IERP) is used. This selectively delivers queries from one node to its peripheral nodes, termed bordercasting. The route discovery for IERP first checks that the destination is not in the zone. If not, the node bordercasts, the peripheral nodes checking if the destination is within their zone, if still not found they transmit to their peripheral nodes and so on. If the destination is found, the accumulated routing information is used to send the route back to the originating node. It is likely that multiple routes will be discovered using this method, allowing the node to choose the route based on a metric. The overhead for route discovery is reduced by only performing global searches when a major topology change takes place, overcoming link breakage on a local level. To reduce flooding, zones may check if a query has previously reached that zone, discarding it if that is the case.

2.5.1.6 Link reversal routing

The motivation for link reversal routing is quite different from other routing protocols mentioned in this chapter. It is intended for high mobility networks, or those with dynamic, rapidly changing topologies. The algorithm is not intended to produce shortest distance routing, but instead to maintain a connected graph with a minimum of overhead. This is achieved by localising the interaction when a change occurs to a single hop, hence a node knows nothing of its position in the graph and the subsequent multi-hop distances once changes have occurred. The graph for each destination is a directed acyclic graph (DAG) routed at the destination, meaning that just the destination may have incoming links only, and acyclic as it contains no loops. A node only reacts to changes when it loses its last downstream neighbour, i.e. it cannot relay a packet onwards. The response is to inform the upstream neighbours that it cannot relay a packet and find a new downstream neighbour if required.

This means that route change information is not only transmitted less frequently, but is not transmitted on a network wide basis like other protocols.

An example of link reversal routing is Temporally Ordered Routing Algorithm (TORA) [47]. The protocol contains three functions; route creation, route maintenance and route erasure. During the creation phase the graph is built according to a metric based upon “height”. The direction of a link, upstream or downstream, is assigned according to height, i.e. up or down. Links to nodes with unknown, or “null” height are not considered. This forms a directed path. If the network changes then these directions may be incorrect link direction may need to be reversed so that all paths lead to the destination. This is achieved by reassignment of node heights. In route erasure a node sets its height to null, causing no links to be directed to it.

When a node re-evaluates its height, timing is an important factor. Simplified, TORA assumes that all nodes have a synchronised clock used to measure the logical time of the failure, though this need not be the case. The metric used by TORA consists of five elements, the first three define a reference level; logical failure time, unique identity of defining node, and a reflection indicator bit, used to separate the original from the “reflected”, higher reference level. The last two elements; a propagation ordering parameter, and the identity of the node, define an offset.

2.5.2 Power aware routing

One of the potential benefits of a relaying system is reduced overall power consumption through the non-linear nature of path loss. There are several issues that may cause concern to planners, both real and perceived, which need to be addressed with regard to the power consumption of users participating in a relaying system. A major factor in the removal of ODMA from UMTS was the perception that users would see a reduced battery life. This will be the case if users in stand-by mode are freely available as relays [48], as they will be transmitting and receiving when in a non-relaying system they would not. This need not be the case, as the benefits of a relaying system may be realised without the involvement of these inactive units; all the results presented in this thesis are on this basis. It may be the case, however, that the use of transceivers purely on path loss will not result in optimal power usage. Some users may have limited battery capacity or low charge. In an interference limited system the required transmitted power may be higher than is possible if the routing is based on required transmitted power instead of path loss, as will be shown in Chapter 4.

Several studies and algorithms have been presented with regard to maximizing the battery life of users within an ad-hoc network [48–64]. Most of these do not consider interference limited systems, though the results are equally applicable to extending the up-time of these systems in conjunction with the consideration for actual transmitted power. The issue of who should be available for relaying has been considered holistically in systems where stand-by users are available for routing [48]. An algorithm is presented that can increase the time for all users remaining by 250% by electing users for participation based on energy consumption, and by checking for potential partitioning of the network, increasing the session time of such systems by over 50%. A similar approach is taken in [49] where backbone nodes in a totally ad-hoc system are selected in a co-ordinated fashion so as to reduce power consumption. This approach shows a 15% reduction in power consumption for a negligible reduction in throughput and small increase in delay. Analogously the master role in Bluetooth scatternets may be swapped according to available battery power [50], again increasing network lifetime by over 50%. The clustering of sensor networks with regard to energy consumption is analysed in [51] with the result that there is an optimal, relatively small, number of clusters regardless of whether the network is homogeneous or heterogeneous. The heterogeneous network corresponds to an overlay of more powerful sensors, effectively backbone nodes. Scheduled rendezvous, where users are powered down until a pre-arranged time, and radio frequency identification (RFID) used as a low power wake up technique is analysed in [52]. The rendezvous is the most power efficient, whilst the low power wake up is the most responsive. A hybrid technique is presented to adapt to system requirements. Connected dominating sets, as mentioned previously, may reduce computation, but also put higher energy requirements upon nodes within the set. The adaptation of this method by alternating available nodes is proposed in [53], and is shown to improve network lifespan.

Another approach considered is to consider the bits / joule capacity of a network. Power control in a non-interference limited system according to throughput and bits / joule are presented in [54] on a local and centralised basis. It is shown that the optimal transmission distance is a function of the load on the network, and the power is adjusted according to this load. Common power and independent power algorithms are investigated, with the independent power adjustment giving the best throughput per unit energy compared with common, min, and max power allocation strategies. The bits / joule capacity of energy limited multi-hop networks is analysed in [55]. It is shown that bits / joule increases with the number of nodes, and that for a network with a fixed number of nodes, the number of bits / joule increases as the ratio of ad-hoc to conventional cellular nodes increases. There may be scheduling variable-rate data to achieve reduced energy per packet at the expense of an increased, but more consistent packet delay [56], which would be advantageous in streaming media applications. This is achieved though on-line look ahead power adaptation to attempt to minimize the required energy and is shown to be close to the optimal off-line approach.

These approaches may be considered as an overlay to reduce the power consumption of the relaying network. Another approach has been to integrate the reduced power consumption or increased battery life by means of a weighted metric. An example of this modified distance is presented in [57]

$$D_{ij} = \begin{cases} W_p \frac{P_{ij}}{P_{max}} + W_e \frac{E_j^O}{E_j^R} & R_i, R_j, E_i^R, E_j^R \neq 0 \\ \infty & \text{otherwise} \end{cases} \tag{2.18}$$

where E_i^O is the initial energy available to node i and E_i^R is the residual energy at node i, and R_i the residual capacity at node i. The weights W_p and W_e may be adjusted to favour either of the two terms, biasing the routing towards minimum power and battery life respectively. This approach attempts to ensure that energy consumption is evenly distributed across the network. It has been extended to frequency allocation [58] but may equally be adapted to different radio access methods. Equivalently the integrated problem has been addressed by constructing spanning trees [59] or connected dominating sets [53] that are power aware. In [59] the trees may be constructed with regard to global or local efficiency, especially with regard to multicast. For a global approach, less overall power is consumed in multicast with fewer, higher power transmissions. This causes reduced battery life for these users, compared to the local, individual battery approach. A weighted compromise, similar to (2.18), is developed to address this issue.

Several methods have been presented that use maximum battery life as the sole metric [60, 61]. In [61], where an actual 802.11 energy consumption model is used, the minimum battery cost metric actually results in far higher power consumption than a minimum hop routing. More intelligent battery based metrics, however, do result in reduced power consumption. In [60] the power consumption of the node is further broken down into processing power and transceiver power, and it is pointed out that the minimum battery routing tends to favour longer paths. For the purpose of this thesis it is considered that while processing power currently forms a considerable part of the overall consumption, with advances in semiconductor feature size reduction, and commensurate square power reduction, this factor will be a negligible fraction in the future. Thermal noise dominates the minimum detectable power, hence with current access methods, it is unlikely that required transceiver power will be reduced by similar technological advances.

The above methods have not been solely concerned with CDMA. An interference based technique [62] similar to that presented in this thesis and published after [63] points out that this approach approach reduces power and hence energy consumption. It is shown in [64] that minimum consumed energy routing reduces latency and power consumption when compared to using the shortest path for CDMA.

2.5.3 Novel routing methods

As well as the routing protocols outlined in sections 2.5.1-2.5.2, several techniques have been proposed that go beyond the current paradigms for wireless ad hoc networks. One of the basic preconceptions for wireless ad hoc networks is that the data is sent over a single route. One of the simplest advances that transcends this approach is multipath routing [65] or multipath source routing [66, 67]. Single path routing may under utilize resources and is susceptible to link breakage and possible congestion problems. The idea underlying multipath routing is that by distributing the data over several paths load balancing, reducing congestion and unfair relay power consumption, and route failure protection becomes possible. The problem with this approach becomes how to find the most effective allocation of data between the paths. This has been achieved by modifying DSR, which already discovers multiple routes without exploiting them simultaneously, by applying an heuristic algorithm. An important criterion in selecting the multiple paths is to find node disjoint or independent paths, resulting in a greater aggregation of resources and the likelihood that performance change in one route will not affect the others. As well as the intended benefits it has been shown that mulitpath routing can reduce end-to-end delay [67] and reduce control overheads [65].

A more advanced approach that utilizes multiple paths is multiuser diversity[68] for single hop networks or co-operative / user co-operation diversity [69–72] for multiple hops. With this technique the multiple paths are used in a similar way to multiple antennas in multiple input multiple output (MIMO) or variant systems [73] without the need for physical arrays. Cooperative diversity expects to achieve comparable diversity gains in aspects such as capacity and resilience to multipath fading. As with multipath routing, the system attempts to select independent, uncorrelated channels but utilizes space-time coding to exploit the diversity.

2.5.4 Mobility issues

When the topology of a network changes rapidly due to node mobility, it is necessary to reconfigure the network according to the changes. If this update is not performed rapidly then performance may be severely compromised though additional interference or link breakage. If the routing overhead has been reduced by updating link information only when there is a change, then a consequence of sudden high mobility can be that the network is flooded with routing information. This will have the effect of reducing capacity as a large proportion, if not all, of the communications resources may be used for signalling instead of the desired data. An interesting counterpoint to this argument is found if the delay constraints are considerably relaxed. It is shown in [74] that mobility may be exploited to increase the capacity of ad-hoc wireless networks. The idea is that if users are mobile, it is likely that a better link will become available. This may be exploited if there is time to wait for it. This mechanism is that data travels by being split off to many relays, physically carried (in electronic form), and then relayed when one of them is close to the destination.

Several of the routing protocols described previously, such as ZRP and link reversal routing attempt to reduce the degree of flooding due to mobility. Another approach is to attempt to route using the least mobile relays. Signal Stability-Based Adaptive Routing (SSA) [75] routes on the basis of the signal strength between nodes and the node's location stability, choosing long existent channels with strong signals. To achieve this the protocol breaks down into the Dynamic Routing Protocol (DRP), which maintains the routing table, and the Forwarding Protocol (FP) to look up the next hop. Within the DRP each node sends out a periodic beacon which allows other users to measure the signal strength. Nodes are classified as strongly connected if the signal has been received previously for a set number of times, weakly connected otherwise. Strongly connected nodes appear in the routing table, along with the next hop for each route. The FP first looks up a destination in the routing table, if there is no entry it initiates a route search in a similar manner to other on-demand protocols, except that a request is only processed if it has arrived over a strong channel, unless, after a time out period, no route is found. The first returning route packet is chosen as it has probably travelled the shortest or least congested path. Associativity-Based Routing (ABR) [76] uses a similar notion of users sending a periodic beacon in order to measure node associativity. An associativity counter is incremented each time the beacon is received and the route chosen for the greatest degree of association.

2.5.5 TCP/IP applications and ad hoc networks

We rely on TCP/IP for the vast majority of wired computer networks and as the facilitating engine for the Internet. Its design, although it has ancestral relations with DARPA PRNet, IP was not designed for, and until recently had not been tested with civilian wireless networks to any great extent. This is especially true for the unique challenges of multi-hop wireless networks, although IP routing technology does provide support for multi hop relaying and dynamic internetwork connections [77]. The emergence of IEEE 802.11 [1] for wireless networks and other systems such as HiperLAN [78] not only make mobile IP an issue, as WAP, GPRS, and 3G do, but also provides a test bed for multi-hop IP networking.

Several investigations have been made into measuring actual TCP system behaviour over multi-hop networks with MAC protocols such as 802.11 [79], HiperLAN/2 [80] and WaveLAN [81]. It is shown in [79] that the performance of the 802.11 network is greatly affected by its interaction with the wired network. Without the wired network a small TCP window is desirable, however this becomes untenable with the wired network. This is shown to be increasingly problematic for the multi-hop system as the large window leads to accumulation of packets in the wireless section. The authors suggest that the network needs to be able to distinguish between channel loss and congestion loss to respond appropriately as well as intelligent bandwidth control to support optimal spatial reuse. Problems have also been unearthed between TCP, 802.11, and multi hop networks in simulated studies [82, 83]. For example the need to distinguish between congestion and packet loss is echoed in [82]. It is shown that due to this mechanism the performance deteriorates dramatically when mobility causes route breakage, and it is suggested that interaction between routing, TCP, and the MAC is necessary to alleviate this situation. In [83] it is shown that interference, preventing the reception of a request to send (RTS) signal, results in a TCP session being shut down after a second session is initiated. It is suggested that this problem lies in the 802.11 MAC, as it is not designed for multi hop communications.

A routing protocol has been presented with specific application to the Internet [84]. Specific nodes are allocated to perform specific network tasks or as a connection to the Internet. These nodes use table based routing, while peer-peer communications are via on-demand routing. This system is shown to have better data delivery rates and a lower control overhead than a purely on-demand system. A similar approach is taken for multicast in [85], except that the table for connection between the Internet and the users is implemented as a modification of the IP. Application based frameworks have been proposed [86, 87] in the context of ad hoc networks. The intention is not just routing information through interfaces such as Bluetooth and 802.11 with throughput, delay, mobility support and predictability appropriate for the application, such as streaming media, but also as a technique to break operations into sub-tasks suitable for the devices in the network. The capacity of multi-hop networks has been analysed using TCP traffic and an 802.11 MAC layer for different applications [88]. With persistent connections such as file transfer protocol (FTP), the capacity is shown to decrease after a certain radius as shown in Chapter 3, and the capacity is greater for a high number of connections at lower transmission radius and for fewer connections at larger radii. For intermittent connections such as Telnet, however, this capacity loss is not present due to reduced interference, though an overall reduced capacity is shown due to not gaining any capacity through frequency re-use, the capacity consistently lower as the number of connections increases for all radii.

2.6 Summary

CDMA enables bandwidth to be simultaneously shared between several users, by spreading the signal with a code. The degree to which the signal bandwidth is increased is measured by the processing gain. CDMA promises complete frequency re-use in a cellular environment. When interference is considered as Gaussian, CDMA is primarily interference limited. If a maximum transmit power is considered the required cell coverage may also compromise capacity.

TDD is a duplexing technique that efficiently accommodates asymmetric data rates, and is suitable for relaying. Duplexing is performed by allocation of time slots. As the same channel is used for both directions, techniques such as pre-RAKE, and open loop power control are possible. TDD requires a simpler RF architecture than duplexing with separate frequency bands. When time slot allocation is not synchronised between cells, additional interference mechanisms occur.

In order to reduce interference, and to improve the frequency re-use ability it is necessary to use power control. Power control may be implemented in a central or distributed fashion without compromising performance. Combining power control with hand-over is a means of coping with the prevalent conditions of each cell.

Relaying of mobile signals began in 1972 with PRNet. Since then several routing algorithms have been developed using table driven or on-demand approaches. These may be combined to achieve a compromise between signalling overhead, mobility levels, robustness and routing latency. The metric to determine routing may be determined choosing the shortest path, minimising transmitted power, maximising battery life, robustness, information-theoretic capacity, or a combination of these.

Chapter 3
UTRA-TDD Opportunity Driven Multiple Access (ODMA)

ODMA is an ad-hoc multi-hop relaying protocol first proposed by Salbu Pty [8], and then considered in a modified form by a concept group for the 3rd Generation Partnership Project (3GPP). Provision was made in early revisions of the standard [10], although it now appears to have been dropped in order to achieve a finalised standard as a result of concerns over complexity, battery life of users on stand-by, and signalling overhead issues. However, ODMA remains an attractive prospect for future mobile communication systems, due to advantages offered by a reduction in transmission power [89], potentially enhanced coverage and with a greater trade-off possible between Quality of Service (QoS) and capacity in the extended coverage region [90], and under certain circumstances may show increased capacity [91].

Multi-hop wireless networks like ODMA will be shown in this thesis to reduce overall transmission power, be resilient to shadowing and potentially increase coverage compared with single hop transmission, however, for simple receivers and low user density, the actual capacity of UTRA TDD may be marginally reduced from the maximum non-relaying capacity. This chapter analyses the implications of relaying in a cellular scenario as compared to a conventional non-relaying system. Initially the interference is analysed by investigating the effect of reduced transmitted power resulting from reduced path loss for a link. The effect of shadowing is considered and it is shown that a relaying system is able to benefit from increased zero mean log-normal shadowing by utilising the diversity of paths available. A correlated shadowing model is developed from a previous model considering both distance and angle of arrival [92] to include the shadowing correlation between all transceivers, as they may all be available to receive in a relaying environment. It is shown that while this affects the interference pattern the perturbation is not significant.

Further analysis is made of the impact upon the capacity of ODMA in relation to the coverage of a cell comparing relaying performance to the analysis made for a non-relaying system by Veervalli [15]. It is shown that after the coverage limit of non-ODMA UTRA TDD has been reached, ODMA will provide enhanced coverage. As the number of calls and/or quality of service is decreased the cell coverage can be increased beyond conventional coverage-capacity trade-offs, allowing operators a far greater degree of flexibility.

3.1 Introduction

ODMA is a misnomer as it is not a true multiple access technique. It is a relaying protocol potentially providing benefits such as reduction of transmission power, overcoming dead spots, and a more even distribution of interference with reduced mean received power.

The basic principle of ODMA is that compared to the conventional approach, where a MS in a cell communicates directly with the BS, or vice versa, in a single line of sight transmission, it is more efficient to break the path into smaller hops, as shown in Figure 3.1. This is achieved by making use of other MS in the cell to relay the signal. The optimal routing is calculated using intelligence in the MS and BS to try and achieve the minimum total path loss for the transmission.

The UTRA-TDD standard did include provision for ODMA [10], as a modification of a Patent by Salbu Pty. Ltd. [8] although the implementation was far from finalised. The main features of the standard covered signalling slot allocation and methods for building neighbour lists, but a routing protocol was noticeably absent. ODMA has now been removed from UTRA-TDD, heresay suggesting concerns of increased power consumption, especially from users not involved in calls being used as relays, and the unfinished state of the protocol exacerbated by a lack of resources available within companies desperate to recoup the expenditure of 3G. This thesis will show that the issue of increased battery drain for non-calling users is not a problem as all scenarios examined only consider relays available if they are already using one or more of the TDD time slots. For those involved in calls an increase in battery life will result on average for all users if only the transmitted power is considered. Users close to the BS may lose out, but for non-relaying they benefited from the lowest required power, MSs at the edge of cells will see the greatest benefit, the result being battery life is more consistent and longer on average. Several papers cover the overall power consumption of a MS, additional factors to transmit power being mainly attributable to CPU cycles. For this thesis it is considered that because of the general trend in reducing feature size in ICs consistent with Moore's law [93], and the commensurate reduction in voltage, hence power, that transmitted power will be the dominant factor on battery life by the time any 3G evolution system may be released.

It has been shown by Harrold and Nix [89, 91] that a relaying system with distributed intelligence can show an average reduction of 21dB in required transmission power or increased coverage [89], and that under certain circumstances, with a sufficient density of relaying users there may be a capacity enhancement over conventional TDD [91].

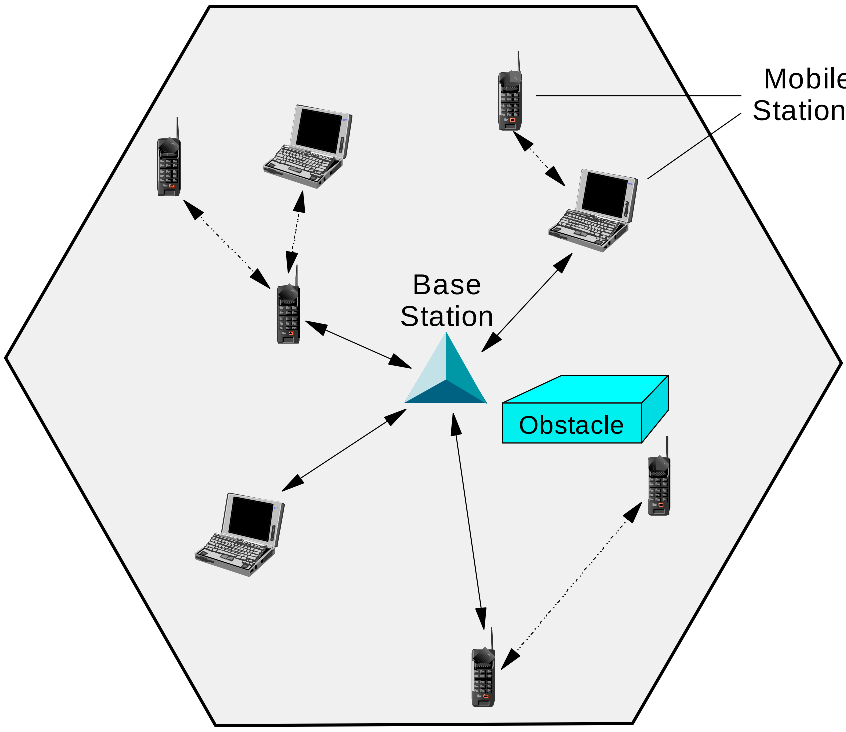

Figure 3.1: *ODMA scenario showing routing with path broken into shorter links, and avoiding shadowing*

This chapter begins with a background to UTRA-TDD ODMA and follows its evolution to the point where ODMA was dropped from the UTRA-TDD standard. The structure then follows the progress of investigations into path loss, shadowing, and finally coverage-capacity tradeoffs. In the former path losses are examined in the context of a simple two hop routing algorithm to minimise the path loss. The resulting interference pattern throughout the cell is then compared with a non-relaying system and theoretical maximum gains. The interference pattern is analysed for different values of shadowing variance. It is shown that whilst in the conventional system shadowing increases overall interference, a relaying system is able to exploit paths improved by zero mean log-normal shadowing, as it selects the minimum path loss route, hence choosing those benefitting from reduced path loss due to shadowing.

The second half of the chapter analyses the capacity-coverage trade-off within ODMA in comparison to a conventional TDD system. The connectivity of ODMA is sufficiently different to traditional CDMA MS-BS communication that it is not reasonable to use the conclusion of Veeravalli and Sendonaris [15] that for a maximum transmission power the coverage of a cell is inversely proportional to the number of users. This information may allow for a coverage based admission control. As it is likely that the greatest bottleneck in an ODMA relay link will be the final MS-BS hop, it may be advantageous to allow cell breathing, or dynamic cell geometry through BS assignment. This would provide for a more even loading of BSs, optimising system requirements.

3.2 UTRA-TDD ODMA Background

ODMA was first proposed by the small South African company Salbu Research in a 1978 patent [8]. In its initial form the motivation was for a packet based radio system using TDMA principles. Together with Vodafone, and to a lesser extent Siemens, Salbu introduced ODMA to ETSI SMG2 in 1996 as a proposition for the 3G mobile system [94–98]. The idea on its own was a poor contender compared to the several CDMA variants and was never going to succeed in its own right. The epsilon group, however, carried out investigations into its feasibility with the outcome that ODMA was proposed to other working groups as an extension or enhancement to their existing access methods [99–101]. The proposal only required hooks to be put in and ODMA could be enabled or disabled by the operator, hence implementation was not required in the initial hardware, delaying roll out. General opinion was that ODMA may as well be included even though many issues were still unresolved.

Since integration into the main UMTS standard little appeared apart from recommendations for the standard [102, 103], the standard itself [104–106], and some notes on security [107] before it was eventually deleted from the standard.

3.2.1 Features

The original patent [8] describes a basic routing strategy. First a neighbour list is built up, this can be either from listening to other mobiles or by probing. The latter is a request for information from surrounding mobiles. A request is sent out for identity and quality of received signal (path loss, noise level). There is no ability to tell if the transmission is going in the optimal direction, the strategy is to transmit to the MS with the best signal quality that has communicated with the BS. Some power reduction seems to be the only requirement, but it is suggested that the route will be known up to three hops ahead.

The proposals to Delta concept group [101] add to this basic idea in relation to UMTS. The neighbour list is required to contain at least five entries. If this is not met after transmitting at the lowest power and highest data rate the power is increased. If the condition is still not met at maximum power, the next lowest data rate is used and the power reset to a minimum, and so on. This adaptation also works if the neighbour list is too large. Two connectivity types address the routing. Local connectivity is available up to two hops away, with all path loss and noise information available to the MS, and a link budget analysis is made to minimise path loss. End to end connectivity is used for more than two hops, using an origin and destination ID. There is a 'time to die' criterion after which the packet is deleted, so delay time is considered in the routing algorithm for this mode. There an interesting comment in the standard concerning delay and number of hops. Considering an increase in hops, one would assume that the delay would increase, however it is pointed out that the lower power allows a higher data rate, which will balance the hop based delay.

The basic intention of all previous routing algorithms is to minimise the mean transmitted power along the route, although this is often implemented by minimising path loss. The main difficulty is to make the correct decision whilst achieving a minimum of network overhead.

UTRA TDD uses only short orthogonal spreading codes, the longest being length 16, corresponding to 16 kbps [104]. From the limit of the pole capacity [15], the small processing gain limits the number of users that may be routed through a node, and ultimately to the BS. There is no explicit routing algorithm in [105]. The routing strategies discussed previously in combination with the ODMA principles indicates the following requirements:

(1) optimise node loading according to pole capacity,

(2) minimise overall path loss,

(3) minimise interference at nodes.

TDD allows diversity in time, however, optimising this allocation is beyond the scope of this chapter. The initial step for routing is to assess the path loss to and interference at other MS. This is achieved by probing neighbours. The description of probing is probably the most complete part of the standard [105], it consists of several modes designed to get an initial neighbour list and then keep updated with a minimum of interference.

UTRA-TDD supports only low mobility due to the open loop power control's time constant being governed by the slot length. Its advantages include terminal simplicity, channel reciprocity, and asymmetric uplink and downlink bandwidth through time slot allocation. This indicates possible uses for LANs, or other data transfer such as mobile IP.

3.2.2 Gathering ODMA network parameters

In order to implement routing protocols it is necessary to build an information database that contains details of nodes available for routing, and the parameters required to calculate the routing metric (path loss from calling MS and to BS, interference, etc.). The scope of the information requirement is dependant upon the nature of the routing protocol, and this overhead is described in more detail in Section 4.6. The option exists to perform the routing either at a central system such as a BS, or in a distributed or local fashion where each MS holds a list and performs the metric calculation itself.

3.2.2.1 Centralised network lists

With a centralised list system all the routing is determined on a local cellular group basis with information gathered at the BSs using a dedicated signalling slot. Much of the information still needs to be gathered by the mobiles, such as MS-MS path loss. This list inherently includes all the users in the local cellular group, i.e. central cell and bordering neighbour cells. The routing information is processed at a central processor and then sent to the appropriate MSs though another dedicated time slot.

Advantages of centrally processed network lists include the ability to assess the entire system, potentially resulting in the optimal routing for a particular algorithm. This is because all the required parameters are held simultaneously. The algorithm will not be required to make any assumptions of redundancy or approximation. In addition algorithms such as [22, 23, 108] may be used which simultaneously solve a system of local requirements in order to obtain a globally minimal solution through linear algebrabraic techniques [109].

The central solution allows for the possibility of integrating admission control and routing in a way analagous to that used by several proposed power control systems [25, 26]. The motivation for this approach is that, as opposed to the idealised scenario of a single receiver for the uplink (considered the limiting factor on capacity by many investigations [15, 110, 111]), the maximum capacity for a scenario involving multiple receivers is dependent on the interaction of parameters such as transmitted power and the path gain matrix, even when every user is perfectly power controlled to its receiver [15, 111]. Using this technique, allocation of a resource (such as a time slot) may be made in order to provide the maximum capacity at a particular instance instead of the more usual first come first served approach [33, 112].

As the information needs to be centrally collected, a likely mechanism is through the messaging slot / channel such as for the proposed UMTS system [106] where coverage allows [15]. This has the benefit of allowing for system wide synchronisation thus improving overall thoughput.

Disadvantages of such “all knowing” include a delay from information gathering to informing the MS though messaging propagation. This occurs through one or both of two mechanisms. Firstly, after the parameters have been obtained, the resulting connectivity information needs to be imparted to the relavant MS, secondly if the MS and BS lie beyond the others non-relaying range, the system may experience relaying delay, though this may depend on the system architecture, see Section 4.6. Either of these factors will introduce errors due to differences between data used in the computation and the current parameters. The result being a degradation in system performance especially in a fast fading or highly mobile environment. Indeed this situation is not the worst case. It is possible that mobiles wishing to communicate solely on a LAN basis, but out of range of a BS, or those out of range with a single hop but in range with two or more hops, may be unable to establish any routing information whatever.

3.2.2.2 Local network lists

A local list system is based on the idea of distributed intelligence, such that the MSs are self organising, utilising the BS purely as a sink for information that needs to travel beyond the scope of the local network. The list is established by probe signals in a dedicated time slot, as shown in Figure 3.2 [10], and routing formed as follows. In this investigation an initial minimum list size of 5 per MS is used and as suggested in the initial protocols for ODMA this is increased in certain circumstances [10]. Scenarios where this minimum list size is exceeded may be more users coming within the current quanta of path loss threshold, after

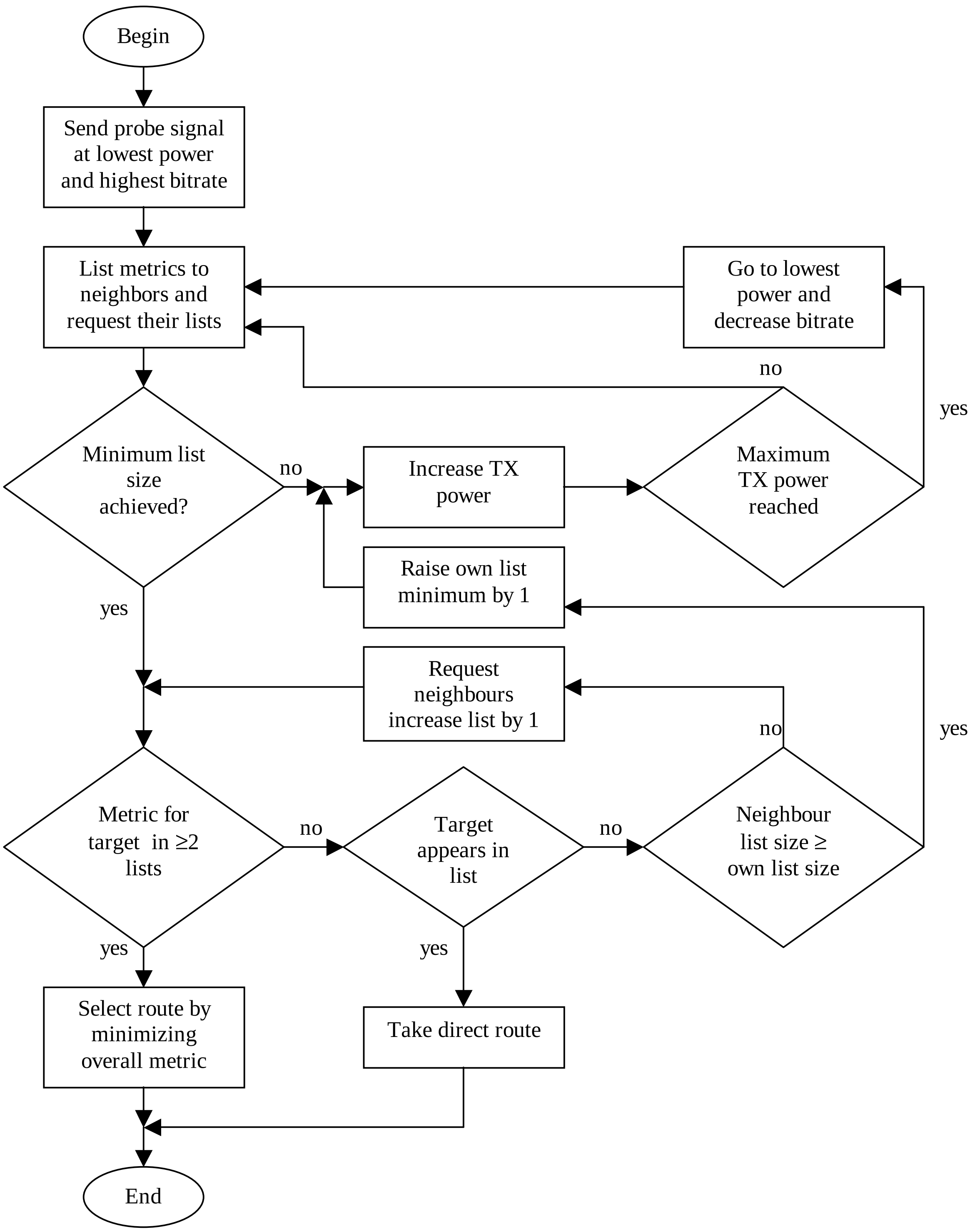

Figure 3.2: *Flow diagram for local list routing*

minimum list size was not met for the previous probe level, or where a practicable target is not contained in the lists of the members of a list with minimum size. The implications of locally organised networks mean that this type of protocol may fulfill different requirements, and hence applications to the central system.

One positive aspect of local organisation the ability to establish networks in areas with poor or no BS coverage. This was the original and purest meaning and motivation for 'ad-hoc' networks [11]. As it is not neccesary for a central organising node to facilitate network operation, a BS need neither be within range or even communicated with. Initial applications were mainly military [9] though it is rapidly being found to benefit requirements as diverse as wireless LANs, 'smart' homes [113] and self-organising sensor arrays. For MSs with restricted power resources or systems where bandwidth is precious a reduction will be seen in peak transmitted power and hence potentially damaging interference. This comes from restricing messaging overheads to communication only with the closest MSs and thus requiring the lowest power transmissions. In scenarios where a limitation of routing information latency is desirable, due to rapid changes in the path matrix, or where a high degree sensitivity is evident e.g low processing gain local routing may be advantageous. This is because the lag can be made to be dependant only on the time difference between Tx & Rx slots in a TDD system, i.e on length of slot and allocation of transmit slots between users. This is possible because path loss and other channel paramaters are available from the reciprocal channel as shown in section 2.2.2.2, this may be further simplified with a header containing information such as initial transmit power.

A locally routed system may be less desirable where the sub-optimal routing for a particular algorithm due to an incomplete path gain matrix may make substantial impacts on the power requirements or available capacity. Such an instance is where a high processing gain is used with the system operating close to theoretical capacity. This results from the minimised database of the local lists, hence possibly not producing the same routing as if the algoritm was able to use all users. As there is no shared slot contaning metric data, and indeed one network of users may be completely unconnected to another save though the impact of interference, imperfect synchronisation is a potential result within the network and a near certainty for inter-cell/network. The former resulting in a required increase in guard bands between time slots, and both in a likely reduction in the potential benefit available from multi-user detection. Any system with distributed intelligence requires a like dissemination of processing power to the MS requiring increased MS complexity. Whilst the requirement per MS will be less than that for the central processing model, simply being required to calculate its own route not everyone else's, the reduction cannot be expected to be linear with number of users. This is due to calculations being replicated by different MSs, e.g. reciprocal path gain values and routes. An implication of this requirement for increased processing by each user will be a like increase in power useage, indeed routing algorithms have been proposed that include processing as part of a routing metric [60, 114].

3.2.2.3 Probing methods

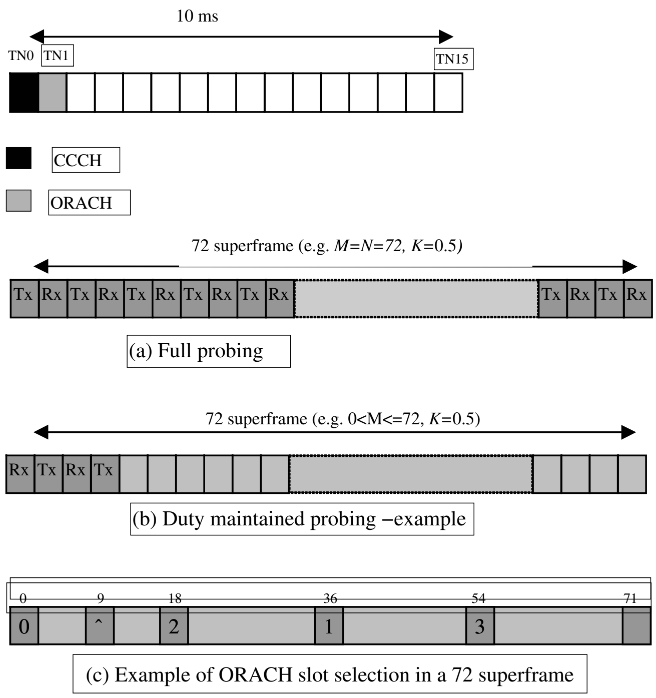

Figure 3.3: *ORACH Superframe Selection*

The ODMA protocols included in early specificationsis of UTRA-TDD mainly concerned the probing cycle and use of the ODMA Random Access Channel (ORACH) [10], Figure 3.3. There are three levels of activity; full probing, where the relay constantly monitors and transmits probes on the ORACH, duty maintained probing, the 'normal' mode, allowing flexibility in scheduling, and relay prohibited where all probing is ceased and normal TDD or FDD operation is resumed. The level of probing activity will be governed by parameters such as number of neighbours, gradient to base of neighbours, terminal speed and battery level. All routing strategy information is still missing, apart from a note that all MS should have at least one gradient to a NodeB, where a gradient is a cost function in terms of propagation conditions, number of hops, and other parameters.

3.2.3 Previous Simulations

Vodafone appear to have produced the majority of the industrial simulation results [95, 97, 98], apart from the work at from Bristol University [89, 91] no other results appeared to have been published directly concerning ODMA at the commencement of this thesis. For the first simulations [97] Vodafone used three propagation models, inverse square law, inverse fourth power law, and a Manhattan model. These all use seeds to relay the signals instead of relaying by MS. There are capacity results, but they are simply the number of supported calls, with no considered access method, calculated by increasing the number of calls until the "resource" usage was 100% at a point in the cell. Later results [95] consider indoor office, outdoor/indoor/pedestrian and vehicular models. The models are more advanced and based upon the path loss models in the UMTS selection procedures [115] incorporating COST 231 path loss and a distance dependent exponential autocorrelation function for the log-normal shadowing. They use MS as relays, however only transmission power is considered, with no capacity calculation.

All these simulation results show that the reduced overall path loss results in a lower overall transmission power, although this is shared by MS not directly involved in the call. This will result in a reduction in interference, and reduced average battery consumption. The papers discuss the situation with shadowing. If there is high shadowing on the LOS path, transmission power will need to be increased to achieve the required C/I ratio. If the maximum transmit power is reached before this condition is attained a dead spot occurs and hence results in a lack of communication. Using ODMA it will be possible to go around the area of high shadowing resulting in a further gain on top of the shadow free example.

It is mentioned that due to the reduced transmission power and the subsequent lower interference, a system can be devised such that the radio resources, be they time slots, frequency bands, etc. can be re-used. This effectively creates many pico-cells within the main cell and should serve to increase capacity.

3.3 Path loss investigation

This section introduces a simple simulation platform and routing algorithm to investigate the interference properties of a relaying system within a direct spread spectrum context. The effect upon path loss is examined by comparing a simple two hop relaying system that attempts to minimise the path loss with a conventional system. The resulting interference pattern throughout the cell is used to show bottlenecks in the system, and hence the limiting factors for potential relaying gains, suggesting the new network topologies proposed in Section 4.2. The interference pattern is analysed for different values of shadowing variance for correlated and uncorrelated shadowing variables. This indicates how consistently relaying will perform moving from environments such as rural to indoor, and whether there may be benefits from using relaying in an interference limited system.

3.3.1 Simulation model

The COST 231 model was used for the indoor office test environment,

$$L(dB) = 37 + 30\log_{10} d + 18.3 f^{((f+2)/(f+1)-0.46)} + \xi \tag{3.1}$$

where d is the transmitter receiver distance in metres and f is the number of floors in the path. The recommendation is to set this to 3. ξ is log-normal shadowing in dB, with a standard deviation of σ and a zero mean, no correlation is applied. The minimum loss is never allowed to be less than free space.

MS were placed randomly, the polar co-ordinates normalised to give a uniform distribution by taking the inverse of the required pdf [116], in this case $1/r^2$. The routing used in the initial simulations is a simple form of ODMA, corresponding to local connectivity only. There is an allowed maximum of two hops, and the metric is calculated using the minimum overall path loss, an example is shown in Figure 3.4. The required transmission power is calculated as shown in equation (3.2).

$$TxPower(dB) = sensitivity(dBm) - gain(dB) + L(dB) + I_{margin}(dB) \tag{3.2}$$

Where $gain$ is the total overall antenna gain and transmitter losses, and I_{margin} is a value based upon the number of users to try and achieve the required C/I ratio. This is derived from

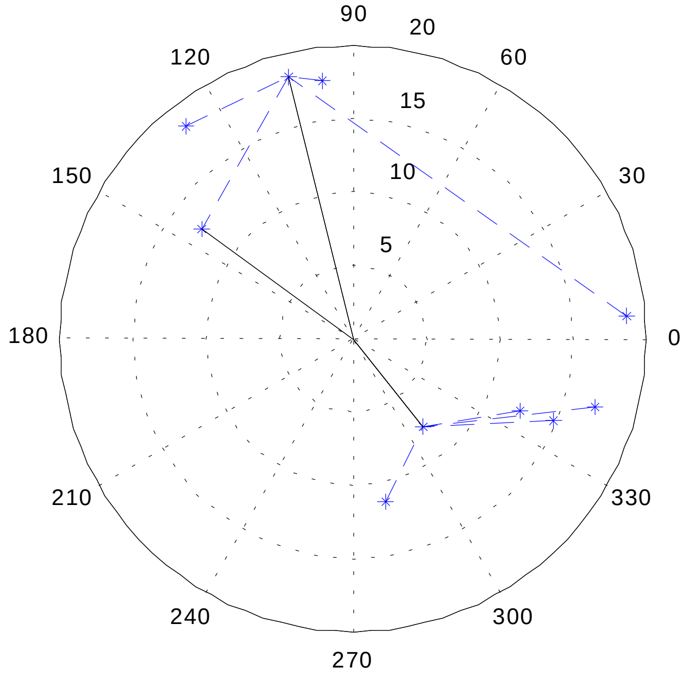

Figure 3.4: *Example of mobile placement and routing*

the perfect power control requirements for a direct transmission signal, i.e. there is no power control system, in fact this means that the ODMA transmissions use a margin that is higher than necessary, so these results are actually worse than could be expected from a real system. No upper limit is applied to the transmission power. The interference power is based on a similar concept.

$$I(dBm) = TxPower + gain - L \tag{3.3}$$

This is used to plot an interference surface for the uplink, with the grid uniformly distributed in the same way as the MS, an example of which is shown in figure. One problem with using this grid, as opposed to simply measuring the received power at nodes is that the power is averaged over the space in the grid, so the values around the base station are higher than the actual received signal, and may not be completely indicative of the interference at the receiver.

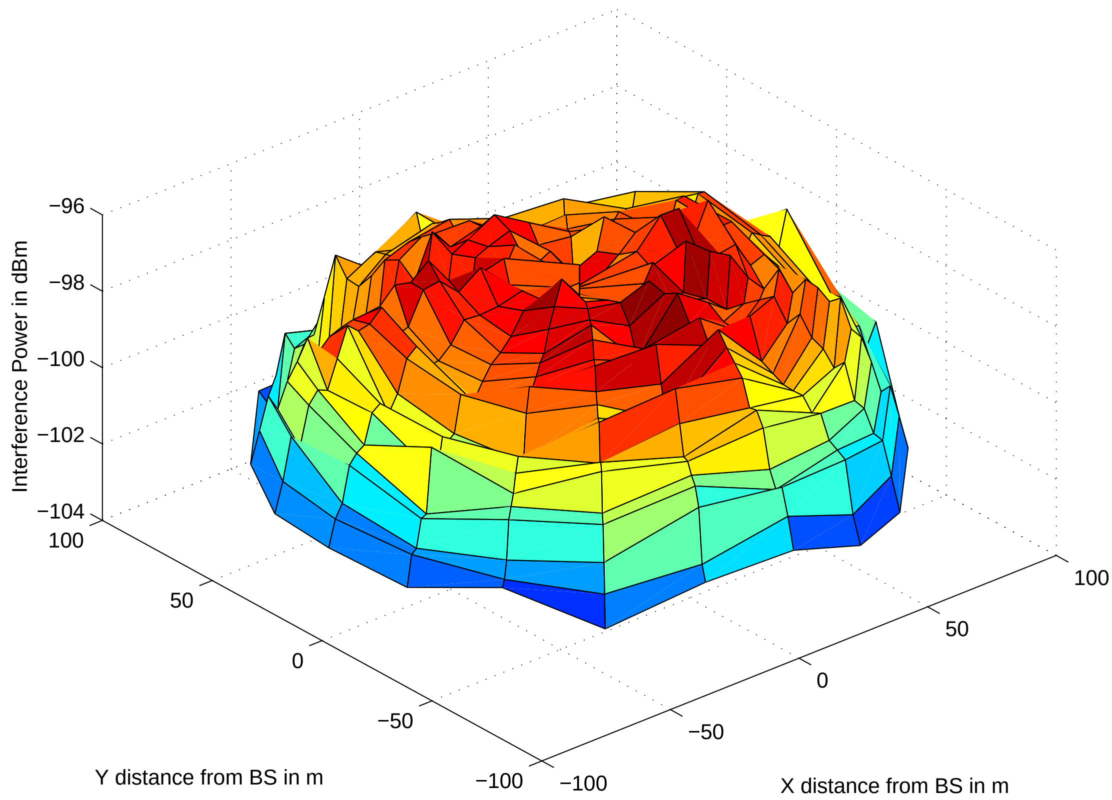

Figure 3.5: *Example of the interference surface experienced by MS*

3.3.2 Characterisation of interference

The interference pattern for the simulation was averaged from the surface plots as shown in Figure 3.5 over equal radii and several hundred runs to produce an interference cross-section for different values of σ in the log-normal shadowing, as shown in Figure 3.6 for a 20m cell size, and Figure 3.7 for a 100m cell size. It can clearly be seen that, as expected, the increase in σ causes the conventional system to require increased transmission power, hence increased interference. The ODMA system, however, is not only resilient to the increase in shadowing, it actually benefits from the increased shadowing deviation. Although it is not completely clear why this occurs, it is hypothesised that this is due to the distribution being zero-mean, resulting in lower path loss. There may also be shielding of some MS by the shadowing, resulting from the increase in average difference of Tx to Rx transmissions and Tx to other MS path losses. This is caused by choosing the lower path for the former and the latter being zero-mean. The general resilience seems to be due to the choice in signal path, hence adaptation, allowed by

ODMA. It is important to note that if more than one cell was considered the conventional

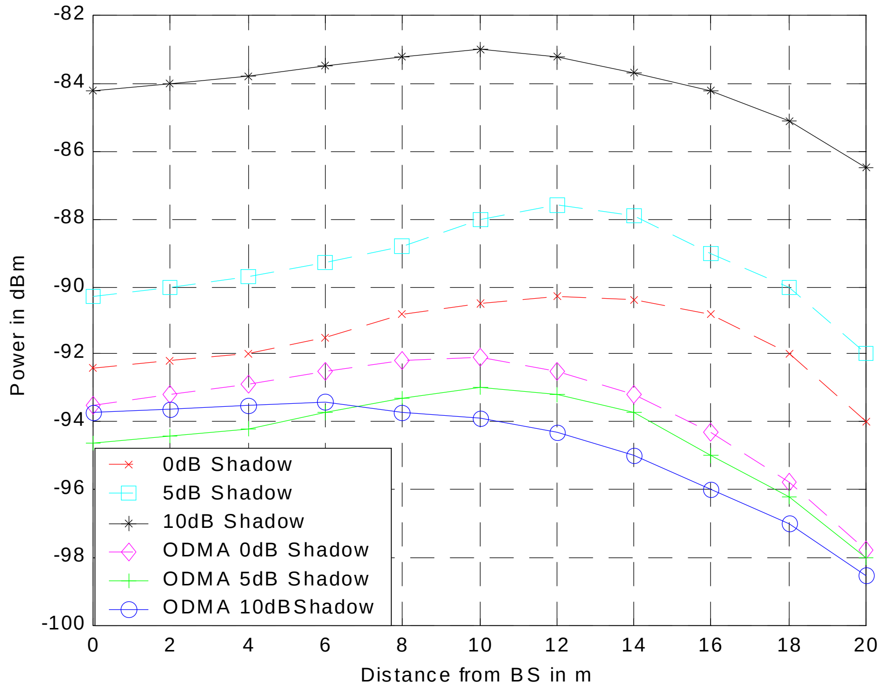

Figure 3.6: *Interference with distance, cell 20m 10 users*

system would continue to have an increase in interference power with distance, instead of tailing off as shown for the single cell case. It is not possible to make capacity calculations purely from the above information as the capacity of an ODMA system is not dependent just on the interference at the receiver, but is limited by the worst link in the system. It may be possible to overcome this by sending data over multiple routes, but even then there is the problem that the weakest link being the last one before the BS, so multiple routes may all suffer equally. As can be seen in Figures 3.6 & 3.7 an effect of ODMA is that the interference slope is almost the opposite of the conventional system, increasing towards the centre of the cell, due to the increased load on the central MSs. This will accentuate the bottleneck on the weak link, as almost all traffic will need to pass through these nodes. This would suggest a possible target for a routing algorithm, to produce a flat interference pattern from centre to edge of the cell. With the bottleneck in mind it would seem prudent to investigate BS diversity techniques such as antenna diversity, and analyse the effects of higher data rates on the central MS, once they become power limited.

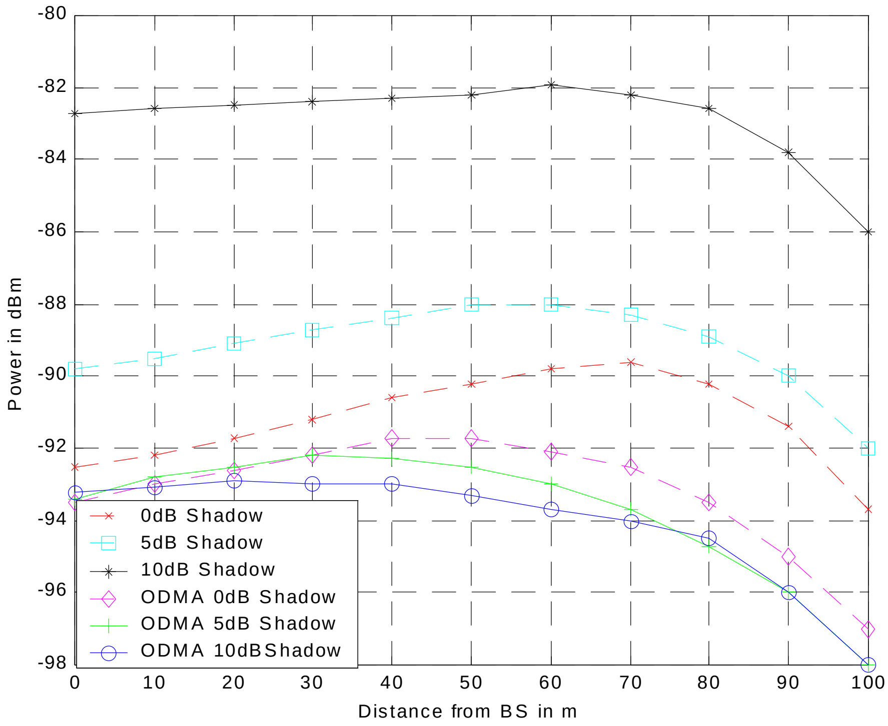

Figure 3.7: *Interference with distance, cell 100m 10 users*

3.3.3 Correlated shadowing

The initial simulation uses uncorrelated shadowing, simply assuming a log-normal distributed random variable can represent the path loss fluctuations due to shadowing. For the case with no available path diversity in the transmission, such as a conventional non-relaying CDMA system, this is a reasonable assumption, however in an ODMA system where there are several choices of path available for routing, ignoring correlation in the shadowing may cause potentially optimistic results. This is due to the low shadowing paths being available in all areas of the cell, e.g. two users in close proximity may be given completely different shadowing values, the high shadow path will not cause any difficulty, as routing can be made through the other user. It is more likely that there will be a correlation between the two users as the reason for the shadowing, building, wall, etc. will probably affect the path of both users. Klingerbrunn & Mogensen [92] proposed a method for modelling cross-correlated shadowing with regard to the base station. Previous models have assigned correlation coefficients according only to the angle of arrival. The method in [92] includes provision for correlation using both angle of arrival and distance correlation, the idea being that the correlation is greater if more of the propagation path is common between the users. The transformation between $\boldsymbol{X}$, uncorrelated, and $\boldsymbol{Y}$, correlated shadowing matrices is provided by a weight matrix $\boldsymbol{C}$, with the form;

$$\mathbf{Y} = \mathbf{CX} \tag{3.4}$$

$\boldsymbol{C}$ is derived by performing Cholesky factorisation on a correlation matrix, Γ, where

$$\Gamma = \begin{bmatrix} 1 & \rho_{12} & \dots & \rho_{1N} \\ \rho_{21} & 1 & \dots & \rho_{2N} \\ \dots & \dots & \dots & \dots \\ \rho_{N1} & \rho_{N2} & \dots & 1 \end{bmatrix} \tag{3.5}$$

this maintains the variance of the data when the correlation is performed. The correlation coefficients, ρ_{ij}, are generated according to the correlation model, of which two are presented for distance and angle of arrival correlation. This model is adapted to ODMA by extending the model from only considering the shadowing on paths to the BS, to applying the correlation to all path losses between transceivers. The operation is performed $n + 1$ times where n is the number of mobiles in the cell. Starting with the base station as receiver, the correlation matrix is calculated with the desired receiver being omitted from the shadowing and weight matrix, then the first mobile station as receiver and so on until the correlation for all transmissions to all users have been calculated.

3.3.3.1 Positive Definite Matrices

In order to perform the Cholesky factorisation it is necessary for Γ to be a positive definite matrix. With large numbers of elements in the matrix, highly related variables such as the result grid and the base station, and rounding errors in computation, it often occurs that the matrix is not positive definite.

Positive definiteness is satisfied if all of a matrix's eigenvalues are positive [117]. This may be qualified to some extent by the determinant of the matrix. For symmetric matrices, such as our correlation matrix, if the matrix and every principle sub-matrix (formed by removing row and column pairs) does not have a positive determinant then the matrix is not positive definite. Rounding errors that create these problems need to be modified. The solution is to add a quantity to the diagonal of the matrix, until it becomes positive definite, or multiply the off-diagonal by a factor as close as close as possible to 1 until the eigenvalue condition is satisfied [118]. This works by attenuating the estimated relations between the variables. It means, however, that it is not always possible to indicate the degree of correlation in the system, e.g. a value of less than 1 is often required on non diagonal positions in order to satisfy positive definiteness in the matrix. It is therefore desirable to perturb the original matrix as little as possible.

The sensitivity of a matrix to rounding errors can be due to the decomposition technique, e.g. pivoting around small numbers as they suffer higher percentage error for a fixed error, or some property of the matrix. Assuming that most decomposition techniques include a sufficient degree of intelligence to choose the optimal starting point, the matrix sensitivity will dominate. Hence it is useful to find a measure of this sensitivity [109]. If we introduce an error vector δb into the original positive definite matrix A, this will be amplified in a resulting eigenvector x by a factor $1/\lambda_1$, the largest eigenvalue of A^{-1}. In order to make this amplification factor invariant to any matrix scaling, it is necessary to normalise by instead using eigenvalue bounds.

$$\frac{\|\delta x\|}{\|x\|} \leq \frac{\lambda_n}{\lambda_1}\frac{\|\delta b\|}{\|b\|} \tag{3.6}$$

The number $c = \lambda_n/\lambda_1 = \lambda_{max}/\lambda_{min}$ is called the condition number of A. Hence, the larger the condition number, the greater the scaling of the error. A matrix with a large condition number is termed ill-conditioned. The condition number of our path loss matrix indicates how succeptible to errors, due to mobility or inserting arbitary values due to incomplete data, routing approaches based upon this matrix will be. The norm of A is defined by

$$\|A\| = \max_{x \neq 0} \frac{\|Ax\|}{\|x\|} \tag{3.7}$$

which bounds the amplifying power of the matrix [109]. It will be shown in Chapters 4 and 5 that the norm may also be used as a routing metric.

3.3.4 Results

Figures 3.8 and 3.9 show a comparison of ODMA using correlated and uncorrelated shadowing models for 20 and 100m cells respectively. It can be seen that in general for the 5dB shadowing case, the correlated model produces slightly higher interference statistics than the equivalent uncorrelated system, however, for the 10 dB case the correlated model gives lower values of interference. It would seem that the correlated model does influence the interference pattern, but

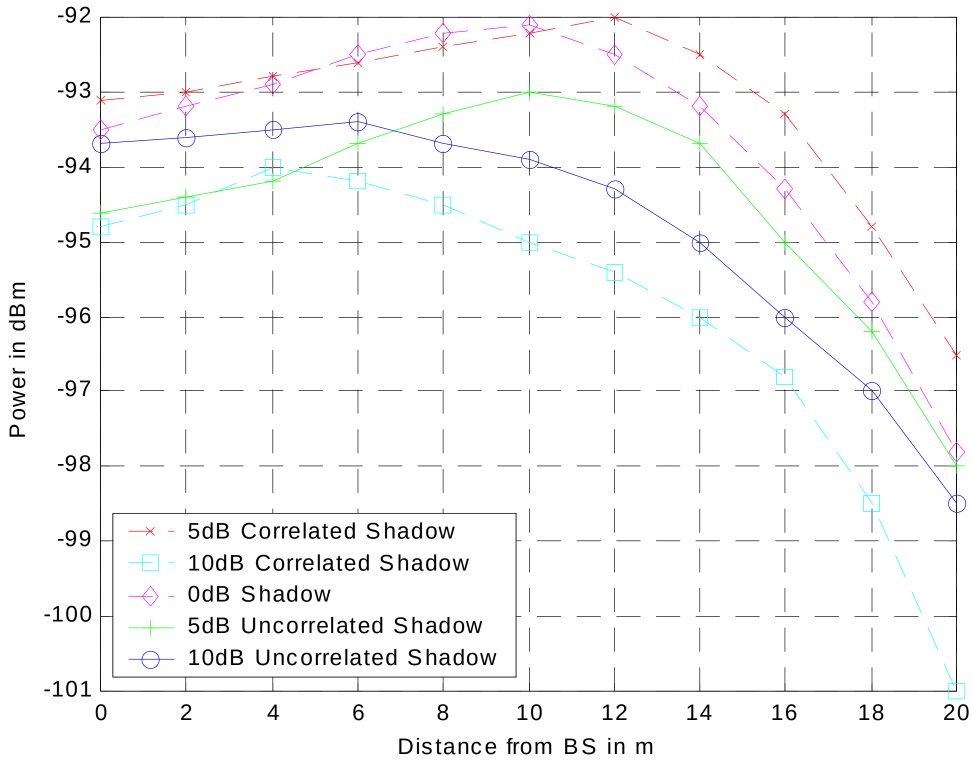

Figure 3.8: *Correlated and uncorrelated shadowing for ODMA, cell 20m*

in all cases the performance is not significantly decreased below the level of the 0dB shadowing case.

3.4 Capacity-coverage analysis

A relaying system is sufficiently different from a conventional CDMA system that it is not reasonable to assume that for a maximum transmission power, the coverage of a cell is inversely proportional to the number of users. This is due to the availability of many paths to the users, i.e. there are many possible receivers, effectively creating hand-offs within the cell. The number of users transmitting to a particular receiver is therefore not fixed.

Analysis of the coverage-capacity trade-of for a relaying system may allow for a coverage based admission control. As shown is Section 3.3 the bottleneck in terms of interference for an ODMA relay link will be the final MS-BS hop, it may be advantageous to allow cell breathing, or dynamic cell geometry through BS assignment. This would provide for a more even loading

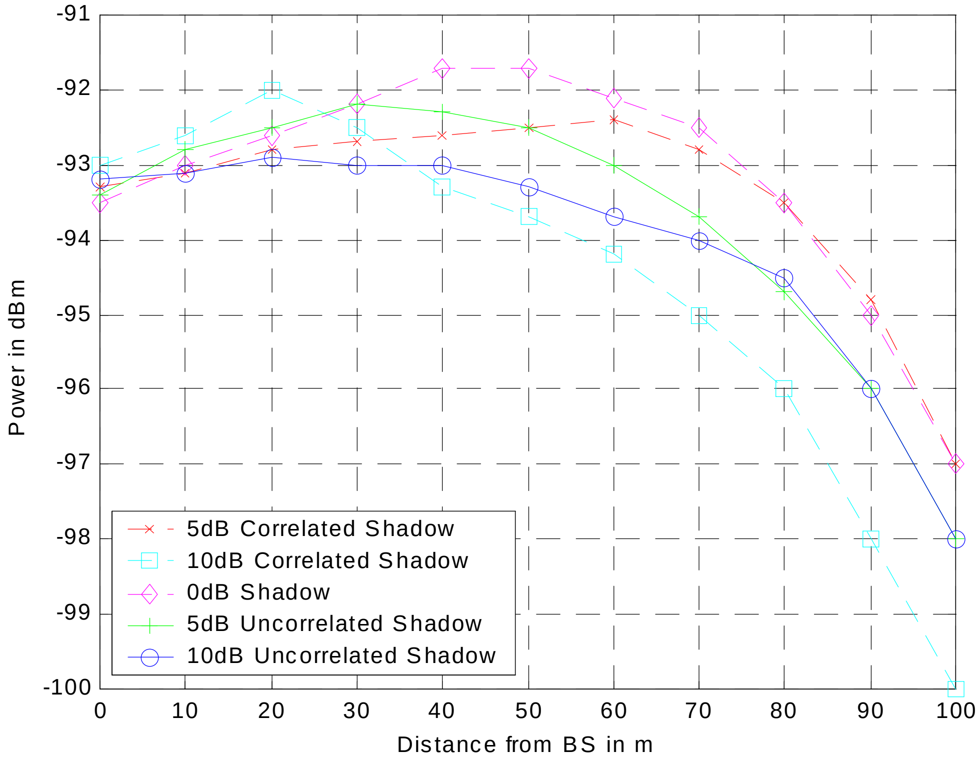

Figure 3.9: *Correlated and uncorrelated shadowing for ODMA, cell 100m*

of BSs, optimising system requirements. Knowledge of the coverage-capacity is also essential for effective cellular planning.

3.4.1 Simulation model

Time slots need to be allocated as part of the routing process. This is because a TDD system is not able to transmit and receive simultaneously. There are only two alternating slots used in this model, A and B. The slots are allocated using the following criterion:

1) The final hop must correspond to the receive slot of the target.

2) The slot allocation must alternate (the relay cannot transmit and receive on the same slot).

3) The uplink and downlink (as opposed the the nomenclature for the slots) are simulated simultaneously. This removes the need for any argument as to which dominates the capacity. Indeed with a relaying system the distinction is blurred as a large proportion of communication is MS-MS.

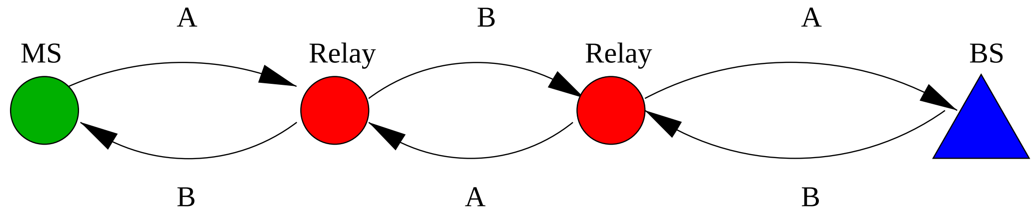

Figure 3.10: *Example allocation of A and B timeslots for a 3-hop route*

Parameter	Value
Maximum transmit power	10 dBm
Target C/I at MS	5 dBm
Target C/I at BS	2 dBm
Logn. Standard deviation, σ	5 dB
Noise figure (receiver)	5 dB
Bit rate	16 kbps

Table 3.1: *UTRA-ODMA-TDD simulation parameters*

An example allocation structure is shown in Figure 3.10. The routing is allocated according to the minimum path loss, and more than 1 call/route is provided by increasing the data rate with a lower processing gain.

Considering UTRA-TDD's suitability for low mobility data use, the path loss model for the indoor office test environment, equation (3.1), is used [115]. A correlated shadowing co-efficient is used, even though the interference pattern is not dramatically affected due to the path diversity available in ODMA. However, non-correlated shadowing could produce over optimistic results with low shadow paths available in all areas of the cell.

The simulation is performed in a single cell with MS distributed in a random fashion with a uniform distribution. It is considered that joint detection is available to the BS but not to the MS due to complexity. This is modelled by different target signal to interference ratios at the respective targets.

3.4.2 Power control

Power control is implemented as a simple-step increment if the desired signal to interference ratio is not achieved at the receiver. A link is in outage if the maximum transmit power is reached at any stage in a link. This is not the optimal method for power control / call admission as capacity may be increased by more selective pruning, however, the intention is to model a simple distributed algorithm. Monte-Carlo analysis is applied to assess the capacity.

3.4.3 Capacity limitations

As a user may relay any other, the ODMA cell can be considered as a network of pico cells, the effective BS in each case being the relaying MS. In a conventional system the the bit energy to interference ratio, ϵ_j, in the presence of Gaussian interference may be denoted as shown in (2.1).

In the multi-hop scenario, where each relay is a receiver, and interference comes from all the hops sharing the same time slot. Ignoring interference that may occur from hops in the same time slot for the same route, the interference at each receiver becomes

$$\epsilon_j = \frac{pgP_{uj}}{\sum_{i:i\neq j}^{M} \sum_{k=1}^{h_{vi}} P_{ij_k} + I + N} \tag{3.8}$$

h_{vi} the number of hops for user i in TS v, P_{ij_k} the power at node j from the route for user i, hop k. This applies to each relay and the receiving node in a link.

Thus the link for each user is limited by the lowest value of ϵ_j on route. This means that interference throughout the cell affects the uplink, not just at the 'real' BS. In the majority of cases, however, the most problematic link is the final hop to the BS. This is due to power warfare occurring when there is heavy cell loading. MS nodes do not suffer too severely from this issue as they will normally only relay a fraction of the total number of users, whereas everyone has to route to the BS, unless the target MS is in the same cell.

By splitting the interference into intra-cell interference, I_{ODMA}, corresponding to interference at the BS due to in-cell MS-MS transmissions, and adjacent cell interference, I_{ad}, the received bit energy to noise for each user with perfect power control at the BS for the uplink can be reformulated from (3.8)

$$\epsilon_j = \frac{pgP_{uj}}{P_{rx}(M-1) + I_{ODMA} + I_{ad} + N} \tag{3.9}$$

where M is the number of users transmitting directly to the BS, and P_u the received power at the BS. If pg is constant for all links, i.e. calls are not aggregated together as two or more calls at a higher data rate and all users are transmitting at the same rate, it can be seen that M is an upper limit on links / time slot for calls involving an uplink to the BS. Rearranging with respect to the number of users, M

$$M = \frac{pg}{\epsilon_j} - \frac{I_{ODMA} + Iad + N}{P_{uj}} + 1 \tag{3.10}$$

In comparison with the pole capacity for a CDMA system from [111]

$$M_{MAX} = \frac{pg}{\epsilon_j} + 1 \tag{3.11}$$

It can be seen that the only variables we have control over that limit the number of users that can route to the BS are I_{ODMA} and P_u. This means that if the limiting interference at the relaying nodes is linearly related to the transmission of the M users. The effects of adjacent-cell interference and receiver noise can be mitigated against, but the reduction in capacity due to I_{ODMA} cannot be minimised by increasing P_u, as this will result in a corresponding increase in I_{ODMA}. There is, however, more scope for optimising P_u as the effective reduction is cell size for MS-BS transmissions mean that the average MS-BS path loss is reduced, hence outage due to maximum transmit power being reached will be lower.

I_{ODMA} is dependent in several factors, including shadowing, routing, power control and call admission. The routing in conjunction with shadowing will determine the relationship between P_u and I_{ODMA}. The number of hops per link is a balance between minimising transmission power, as discussed in the next section, and the number of interferers, albeit at a lower transmit power. Power control in conjunction with call admission is a trade off between the benefit of reduced transmission power, and increasing capacity by increasing power.

It is important to note that the above equations only hold for single user detectors where the interference from other users is Gaussian distributed [119]. Multi-user detection and selective use of spreading codes invalidates the assumption of Gaussian distributed interference. Indeed with a more sophisticated receiver, I_{ODMA} could be used as a form of antenna diversity with MSs not on the original route retransmitting the signal, as shown in Figure 3.11 actually improving system capacity.

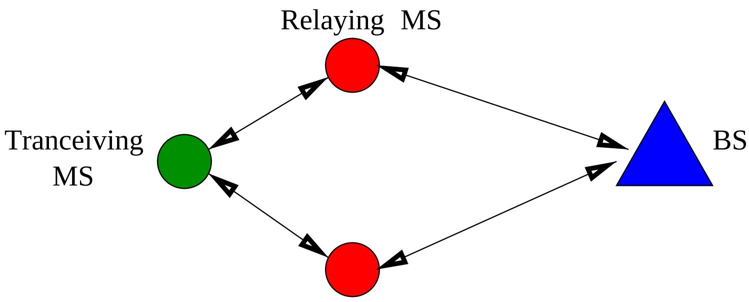

Figure 3.11: *Retransmission of signal over multiple paths to introduce antenna diversity*

3.4.3.1 Transmission Power

One of the main cited benefits for ODMA is the reduction of transmission power for a link. This is achieved by splitting the transmission into a series of hops using other MS as relays. The transmission power is reduced due to the non-linear nature of path loss, as shown in Figure 3.12. The gain shown is the reduction in overall path loss over a single transmission. The path loss model is of the form (without shadowing),

$$L(dB) = k_1 + k_2 \log_{10} d \tag{3.12}$$

where k_1 is a constant loss, and k_2 the path loss exponent, and d the transmission distance in m. The larger the path loss exponent, the greater the potential gains. Linear path loss would not show any gains for relaying. The gains are the maximum available for the non-shadowing scenario, with MS spaced equidistantly along the line of sight path from the MS 100m from the BS.

It can be seen that gains of almost 30 dB can be achieved in the vehicular model, and 15 dB typical for the indoor model. Although the overall transmission power is reduced, this lower burden is shared between users not directly involved in the call. Although it might initially appear that this will be unpopular with these users, this potential issue can be removed by introducing criterion as to which MS are available for relaying. Indeed in all the simulations in this thesis use the approach detailed below, such that the battery life of users on standby will remain unaffected.

In order to achieve this transparent sharing of resources only mobiles that are transmitting in other time slots are allowed to be viable relays, for example in a UTRA-TDD context with

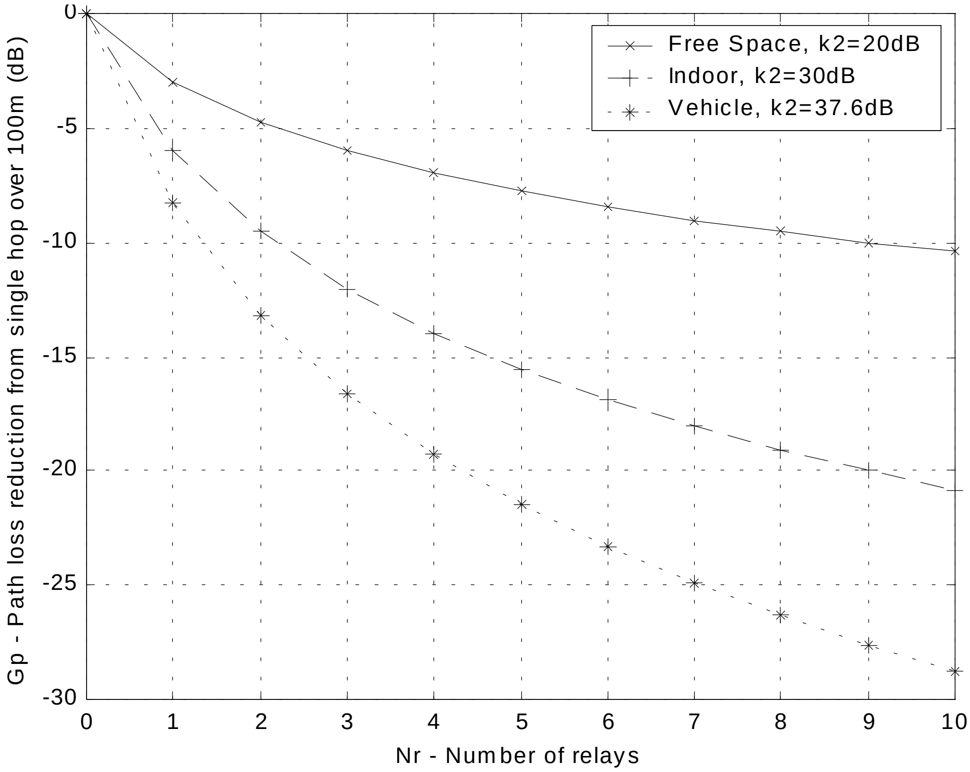

Figure 3.12: *Path loss reduction against number of relays for 100m transmission*

each user transmitting one slot per frame on average. This would allow a routing pool 15 times the size of available calls per slot, and remove the need to run down the batteries of users not making calls. A potential drawback is that users near the BS may experience a higher power requirement than with a conventional system, but this should be contrasted with the overall reduced power / call requirement, and a more predictable and consistent power usage. In fact this arrangement means that battery consumption will have both a lower mean and deviation. Conventionally low Tx power users (near BS) will see an increase in required Tx power, conversely users near the edge of a cell, normally experiencing the highest required Tx power will see a reduced power requirement. Meaning that on average everyone should benefit.

3.4.4 Results and discussion

Figure 3.13 shows the average number of supported calls for each timeslot in the TDD frame. Until the cell size reaches 30m the conventional TDD system achieves greater capacity. This is due to the combination of I_{ODMA} and the simple receiver architecture, where all received signals must be at the same power for optimum capacity. At 30m all systems are equivalent. After this point the non-relaying system quickly loses the ability to reliably support calls, this is due to many of the MS lying in a region where the path loss is too great for the signal to reach the BS with the required signal to interference ratio above the receiver noise.

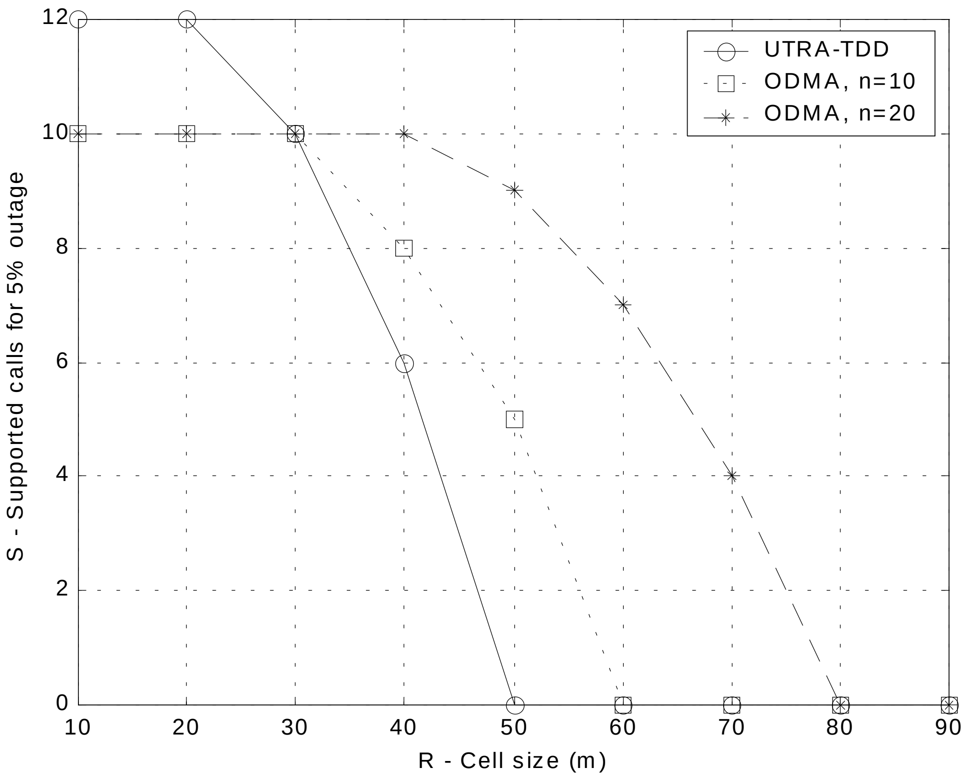

Figure 3.13: *Supported number of users per time slot against the coverage of the cell, for less than 5% outage, n is the number of users available for routing*

Reducing the target number of calls allows for a small increase in the coverage but ultimately the MS cannot increase their power sufficiently.

The ODMA scenario where the number of calls is initially the same as the number of users available for routing offers a gain in capacity of 2 users at 40m and will support 5 users when the conventional system cannot cover that radius. When the number of users available for routing is double the initial limit for call admission the capacity is conserved until 40m and almost full capacity is offered when the conventional system has failed. After this point a reliable system is available for another 30m for an albeit reduced number of users, 3 times the coverage in terms of area than a non-relaying system .

Figure 3.14 shows the probability of outage for different numbers of allowed calls against the coverage of the cell. For the conventional system once outage starts to occur the gradient is such that the number of dropped calls is too great for service to be maintained, this corresponds to users outside a particular radius getting no service. As the number of allowed calls for ODMA is decreased, not only does the coverage increase for a particular probability of outage, the gradient of the curve decreases. For the 4 user case there is a 4% probability of outage in a 70m cell. Coverage is still available, however, at 90m with a 16% probability of outage, much less than the 40% outage for the greater area in the conventional scenario, i.e. in the conventional scenario all MS between 70 and 90m would be in outage.

3.5 Conclusions

Through the use of ODMA relaying to minimise the mean path loss it has been shown that for a simple model, using only a single cell and local connectivity, the relaying system shows a reduced level of interference in the cell compared to a conventional CDMA system. When shadowing is taken into consideration, the conventional system shows an increased level of interference for higher variances in shadowing. An ODMA system may actually exploit the lower path losses made available by zero mean log-normal shadowing, reducing interference in some higher shadowing scenarios.

In order to ensure that the model itself is not responsible for the gain in high shadowing environments, a correlated shadowing model was extended to an ODMA situation. This showed that correlation between shadowing variables for distance and angle of arrival to determine shared paths shows different interference characteristics, but the benefit of path diversity is not significantly diminished in the worst case, and may actually be improved for high shadowing.

Through the use of multi-hop transmissions, ODMA will extend the coverage of a cell, but only after the cell size is large enough to prevent a comparable single hop system from achieving its maximum capacity.

When coverage is a more important criterion than capacity ODMA will provide a reliable service far beyond the coverage of a conventional TDD system.

As the number of users available for relaying increases, the coverage of the ODMA cell increases, and the gradient for coverage-capacity decreases. Reducing the number of allowed

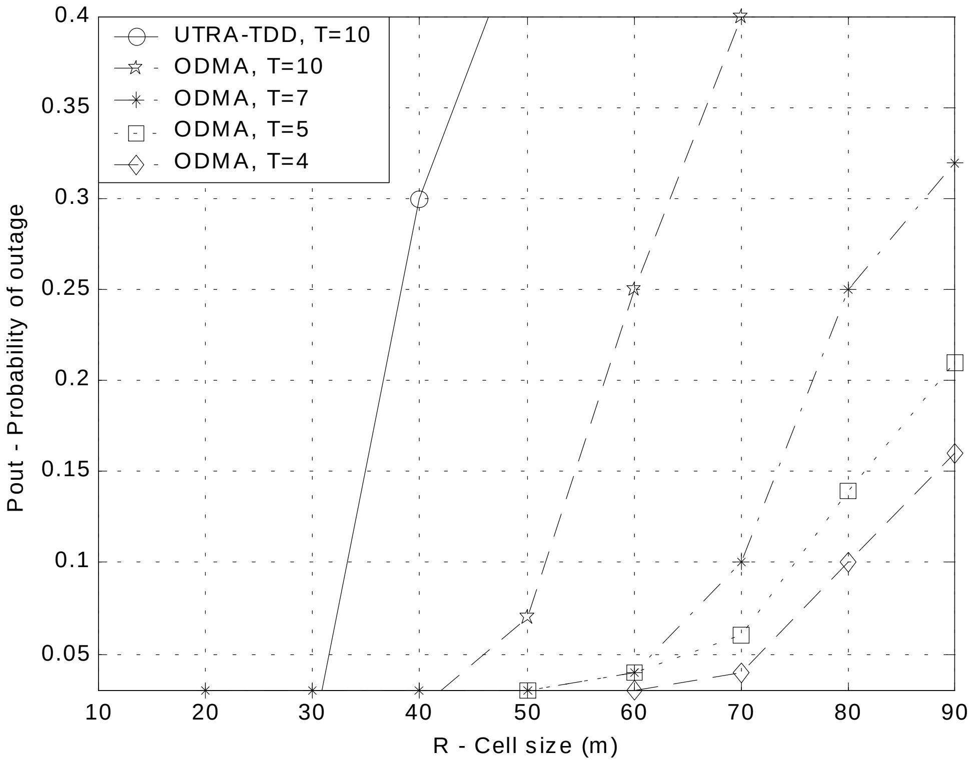

Figure 3.14: *Probability of outage against the coverage of the cell, for different numbers of allowed calls, T, with 20 users available for routing*

calls means that ODMA can provide a reliable service for an area greater than the normal capacity-coverage trade-off. By allowing a reduced quality of service the operator can further extend coverage, the outage being shared between all users, not just those outside the transmission radius limit of the non-relaying system. For unevenly loaded adjoining cells, ODMA could be used to even out the loading by dynamically adjusting the cell size.

The use of ODMA could provide operators with a far greater degree of flexibility in cell planning, and to go beyond the conventional trade-off between coverage and capacity. This comes at the cost of increased complexity and signalling overheads, and relies upon a sufficient user density to maintain available relays.

Chapter 4
Routing strategies in multi-hop CDMA networks

Multi-hop relaying routing protocols have been investigated for CDMA air interfaces in conventional cellular scenarios, as described in Chapter 3, and in [89, 91]. This chapter compares the performance of ODMA with direct transmission for cases where links may be required directly to other nodes, as well as to a controlling (back-bone) node, and presents two new routing algorithms.

For an interference-limited system, it is shown that the topology is not supportable by a conventional (single-hop) system, but that a relayed system is able to provide service. As an enhancement to path loss routing, a new admission control and routing algorithm based on receiver interference is presented which is shown to further enhance performance.

A second new routing algorithm, which considers the interaction between all receivers in the system by means of a ’congestion’ measure is presented. This approach allows for routing that is optimized for the entire system, not just a particular route under arbitrary starting conditions. This is possible under both central and local parameter gathering scenarios. Through formulating this measure into the power control equations it is possible to determine system feasibility, although this is a conservative criterion due to approximations in the formulation. This congestion based routing is shown to outperform non-relaying and any previous routing technique in available capacity for the new network topologies, and has the lowest transmitted power requirement of all investigated methods.

4.1 Introduction

Previous ODMA systems have utilized the path loss between terminals as the metric to determine the routing for the relayed packets [10, 89, 91]. This is suitable for a single user system, or one not interference limited such as frequency or time multiplexing where no simultaneous resource sharing is required. For an interference limited system with multiple users, route selection purely from path loss does not take into account the degradation in performance that will be suffered by other users, either in the form of outage or reduced data rate. The degradation in performance is caused by similar factors discussed previously to networks, Section 3.4.3, not exclusively of a star topology. An ODMA system is effectively the same, even when there is no peer-peer requirement, due to the relaying nodes. Unlike the non-relaying system, however, we have a selection of paths available to us, so it is possible to minimize the interference effects by careful selection of the route. This section investigates several systems for reducing the detrimental effects of interference, with various trade-offs between complexity, transmitted power, latency, signalling overheads and capacity, and the differences between a locally or centrally organized system.

4.2 Multi-hop network architectures

In Chapter 3 it was shown that there may be capacity gains due to relaying when non-relaying systems start to lose system capacity through an extended coverage requirement. Due to the relaying interference I_{ODMA} in Equation (3.10), however, the supported number of users for a conventional cellular network within the non-relaying coverage area is reduced if a relaying system is employed. This section investigates new network topologies that attempt to utilize the features of a relaying system to allow increased capacity over a non-relaying system, especially where there is a high degree of peer-peer communication, e.g. as shown in Figure 4.1

4.2.1 Topologies

The motivation for introducing peer-peer communications is two-fold. First the pole capacity of a receiver, Equation (3.11), limits the number of users that may be received by a single receiver. If all calls go via the BS then this limits the number of calls in a cell. Secondly the interference patterns shown in Section 3.3.2 indicate that the highest levels of interference are towards the centre of the cell. It is therefore considered that it would be advantageous to reduce the number of calls via the BS if possible. The network topologies presented here allow for peer-peer communication if required to try and achieve this, and hence utilize the lower interference and spare capacity experienced by MS towards the edge of a cell.

In this section the allocation of a target from a user attempting a call is considered in two ways, as illustrated in Figure 4.2. The first is in a cellular or BS centred fashion, where if the desired

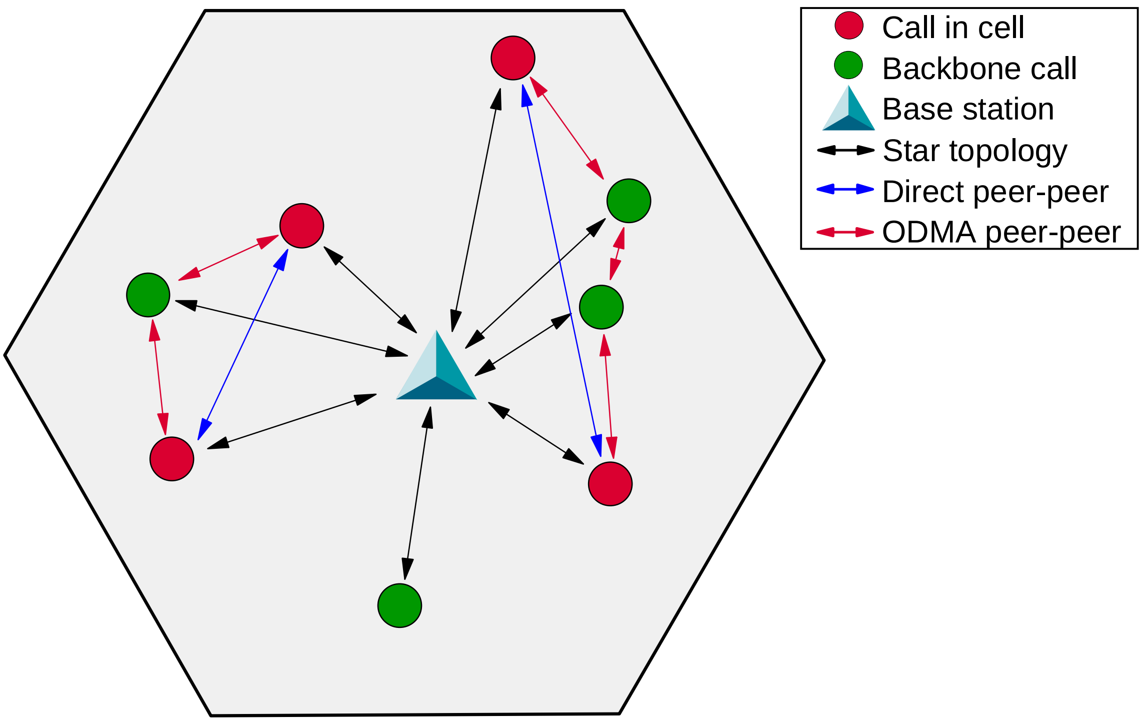

Figure 4.1: *Cellular communication utilizing both BS and peer-peer transmissions, for relaying and non-relaying systems*

recipient is within the cell allocated to a user by hand-over procedures then the user will attempt a direct link without the use of the BS, otherwise the transmission is relayed via the BS to the cell containing the end receiver. A similar topology has been independently presented by Lin and Hsu [120], and routing protocols investigated [121]. The motivation for this architecture is not motivated by interference, as no air interface is considered, hence the routing protocols are not relevant here, and solely concern route discovery and throughput.

The advantage of this BS centred availability region is that no extra signalling is required to establish the end to end terminals, unfortunately the transmission may be from one side of a cell to the other causing additional interference in the critical BS region. The second approach is to centre the selection region on the MS and then use the same criterion detailed above, this reduces the BS interference problem but requires increased signalling. This MS availability region is merely a revision based upon the findings of Section 3.3.2, to attempt to reduce the BS interference, and to optimize transmission distance. This approach is still ignorant of other system parameters, analogous to the path loss routing which will be presented in Section 4.3.1.

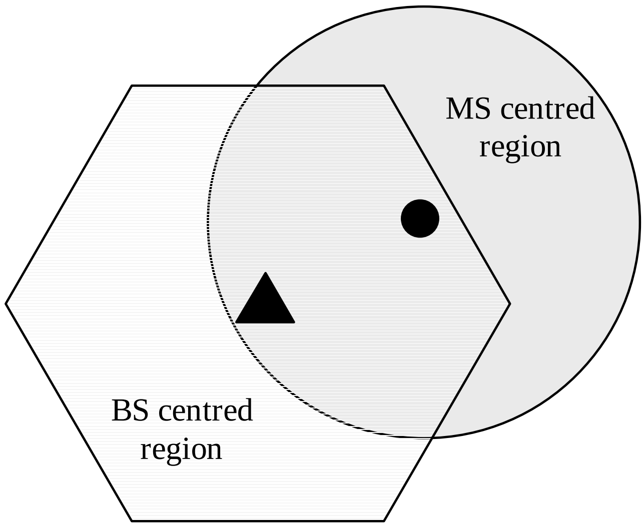

Figure 4.2: *Regions governing local target selection*

It is presented in order to show that for an interference limited system at least, whilst it may be reasonable to centre a cell on the BS for calls via the BS, this is not a reasonable assumption for mixed peer-peer and BS communication. An optimal approach would be to decide upon BS or end recipient to maximize capacity or throughput. Perhaps this could be achieved though comparison of the congestion measure, as will be shown in Section 4.5 for the two possibilities, however, this is beyond the scope of this thesis.

4.2.2 Impact of CDMA

The conventional technique for networking in interference limited systems is a star topology in order to ease the problem of power-control. The topology used in this paper consists of sources and sinks, with communication targeted outside a cell and routed through a BS, while that within cell is targeted at the desired recipient. Whilst this minimizes the number of links for maintaining a cellular paradigm, there is no longer a single point to which the power must be controlled. As there is more than one receiver it is not guaranteed that all the transmissions can be received at the same level by all receivers, and in some cases the interference generated by one user may mean that others close by may not be able to receive the desired signal, no matter how much the source increases power. In these cases it may be better to revert to a star topology, though it must be considered that two calls are now required where one sufficed previously.

4.3 Using path loss and interference based metrics to route

Within the scenarios users are required to communicate either with each other or to achieve a link onto a backbone. The criterion for the local routing is that the target is in the same cell as the transmitter. It is likely that greater capacity would be achieved if the region for local routing were centred instead on the user, however, a simple mechanism for call assignment was selected. Previous work on ODMA [89–91] uses path loss between terminals in the metric to determine the routing. This is a quick and efficient way to establish routing, however it does not take account of bottlenecks in the system due to interference caused by many users routing through a particular area, indeed it will encourage bottlenecks as users will all try to route via low path loss regions. In this chapter three new algorithms are investigated, based on either minimizing interference or a ’congestion measure’ [122], so that in combination with local and central lists seven network topologies may be investigated and compared.

4.3.1 Path Loss Routing

The simplest form of routing is to attempt to minimize the path loss in the system. In non-interference limited systems this can also be considered optimal routing as far as power consumption is concerned, as long as no other power control requirements are imposed other than a minimum received signal power. For the CDMA system considered here, path loss is not an indication of transmitted power. The required C/I ratio is altered as shown in Equation (3.9), the I_{ODMA} term is dependent on the interaction between all path losses for all transmissions in the system. Minimizing the path loss for a route may well reduce required transmission power, and hence I_{ODMA}, but there is no guarantee that this will be the case. This is because of the path loss routing may generate a situation where the required C/I means that a higher transmitted power is required that for the single hop routing due to the lack of power control to a central point.

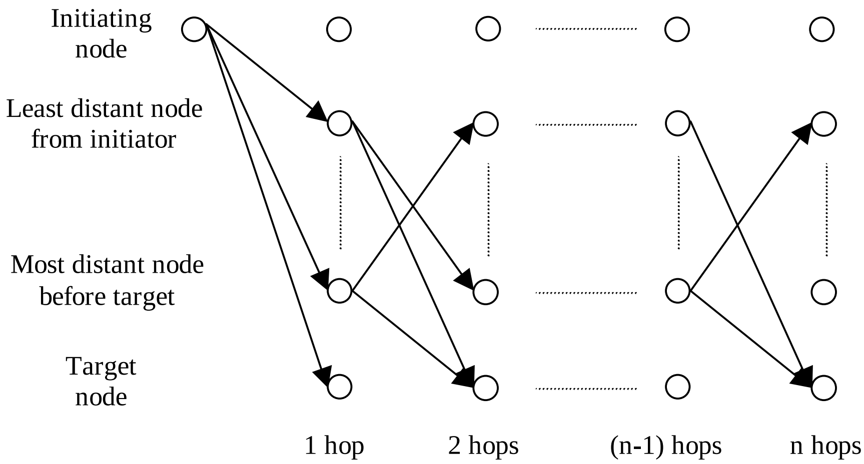

Figure 4.3: *ODMA routing trellis*

4.3.1.1 Central routing calculation

For in-cell calls, the user probes to find the path loss to other nodes, and their path loss to the target. The routing is determined by choosing the route with the minimum path loss overall. For out of cell calls a similar probing is performed, but the target may be any BS. This means that the user may be outside the hand-over region of the BS that it linked with. The basic routing structure is performed in a trellis as shown in Figure 4.3 to reduce the number of calculations required, with a path loss based system this causes no degradation in performance as the minimum path loss route is selected at each node in the trellis. The trellis is formed by ordering the nodes with respect to the path loss from the initiating node. It is truncated at the target distance plus a margin to include 90% of the users within the shadowing distribution of the system. The routing is performed at each stage by storing an array of the current distance and previous nodes visited at each node. A transition is available to any node at the next stage provided that node has not been previously visited, giving a number of paths from each node at stage i of number of nodes $-i-1$, when $i=0$ at the initiating node. The winning entrant to a node is decided by choosing the minimum distance. The routing for i hops is held from the path information of the winning entrant at the target node at stage i. The trellis is truncated at stage n if the distance at the target node stage n is greater than distance at the target node stage $(n-1)+$ *(the shadowing margin used above)*, or if n is equal to a maximum allowed number of hops. The minimum distance at a target node is chosen, and the routing information taken from the path used to reach it. The routing is considered for 2-hop and multi-hop cases.

4.3.1.2 Distributed routing calculation

Local routing is performed using the trellis structure as described in Section 4.3.1.1. The difference is the method of discovery and the subsequent reduced availability of path loss information. The basic methodology for gathering the path loss data is as described in Section 3.2.2.2. The parameters are a minimum list size of 5, with a maximum of 2 allowed hops.

4.3.2 Interference based routing

Routing using path loss is non-optimal due to multiple access interference. This section describes a routing technique that initially uses a path loss metric, but proceeds to account for interference once this information is available, after power control iterations have begun convergence.

4.3.2.1 Routing metric

Path loss routing is a simple and instantaneous routing method, however, it suffers from assuming minimum path loss gives minimum transmission power. This is not the case in an interference limited system in the multi-user case, unless other users' interference is below the margin of C/I processing gain. The required transmission power for user i transmitting to user j is

$$P_{ij} = \epsilon_j - pg + \Gamma[i,j] + I_{MAI} + I_{ODMA} + I_{ad} + N \tag{4.1}$$

Where I_{MAI} is the interference from other users transmitting to user j. I_{MAI} is dependent on the number of users transmitting to user j. I_{ODMA} depends on the path loss between other transmissions and user j, and their solution to Equation (4.1), hence this is a highly interactive system. It can be seen that a lower transmission power will result by moving to another relay, k, with a larger path loss than transmitting to j, as long as

$$\Gamma_{ik} + I_{MAI_k} + I_{ODMA_k} < \Gamma_{ij} + I_{MAI_j} + I_{ODMA_j} \tag{4.2}$$

This re-routing according to interference will reduce the transmission power for an identical system, as this is a condition of the routing. Hence it is fair to also consider this technique as transmission power routing. It is important to note that this system is only finding a local

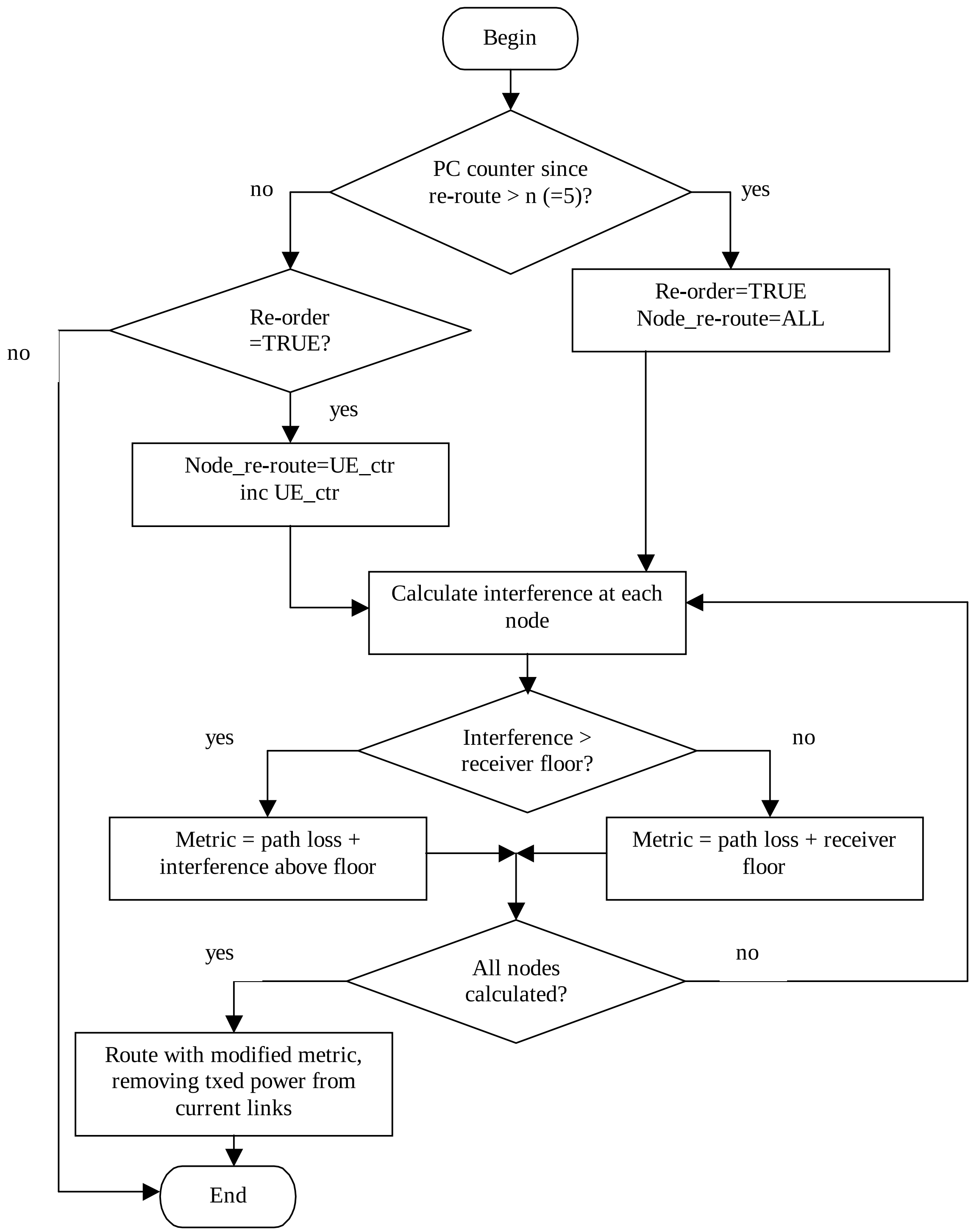

Figure 4.4: *Interference based routing flow*

minimum from an initial condition, and for a single route within a highly related system. This technique reduces required transmission power, and hence outage from exceeding the maximum transmit power. Unfortunately the power control problem is not necessarily asymptotic for every local minimum [108], so this is not an optimal solution.

Initial routing is performed as in Section 4.3.1.1 for central routing and Section 4.3.1.2 for local routing. Once the power control has reached a steady state, the system is re-routed according to the modified metric, minimizing overall P, Equation (4.1), for each entire route. Any interference above the receiver floor plus processing gain at each receiver is added to the matrix of path loss between users. This gives an indication of the necessary transmission power for that link, this is just an approximation as the re-routing changes I_{ODMA} and I_{MAI} for other users in the system. The re-routing is performed on a route by route basis in order to prevent many users jumping to a low interference route at once and causing instability in the routing. The predictive outage calculation described in section 4.4 is suspended until all routes have had the chance to re-route, avoiding unnecessary outage.

4.4 Interference based admission control

With a star topology based CDMA system the number of allowed calls is relatively constant due to the single receiver in the uplink. In an ad-hoc environment, the capacity will vary depending upon the position of users and the links that are required. This means that admission cannot be based simply on the number of calls currently in progress. The technique used in this paper is to start with a desired number of calls and attempt to make all of them. Instead of waiting until the maximum permitted transmit power, in this case set at 10dBm, is reached and the link involving the offending transmitter removed from the current calls, a prediction technique as shown in Figure 4.5 is used. The convergence rate of the power level is used to analyze which receiver suffers the worst interference and then a decision based on a metric to determine which call to terminate in order to make the greatest reduction in interference for that user.

The power level $P(t)$ for each user is extrapolated by approximating the first and second derivatives by their respective time differences, taken from a running average for iteration i. The power level at some later iteration, j, (when the power control may reasonably be expected to have converged), can then be predicted using a Taylor expansion, as in equation (4.3) below. If the second derivative is of an opposite sign to the first, the iteration when the power is expected

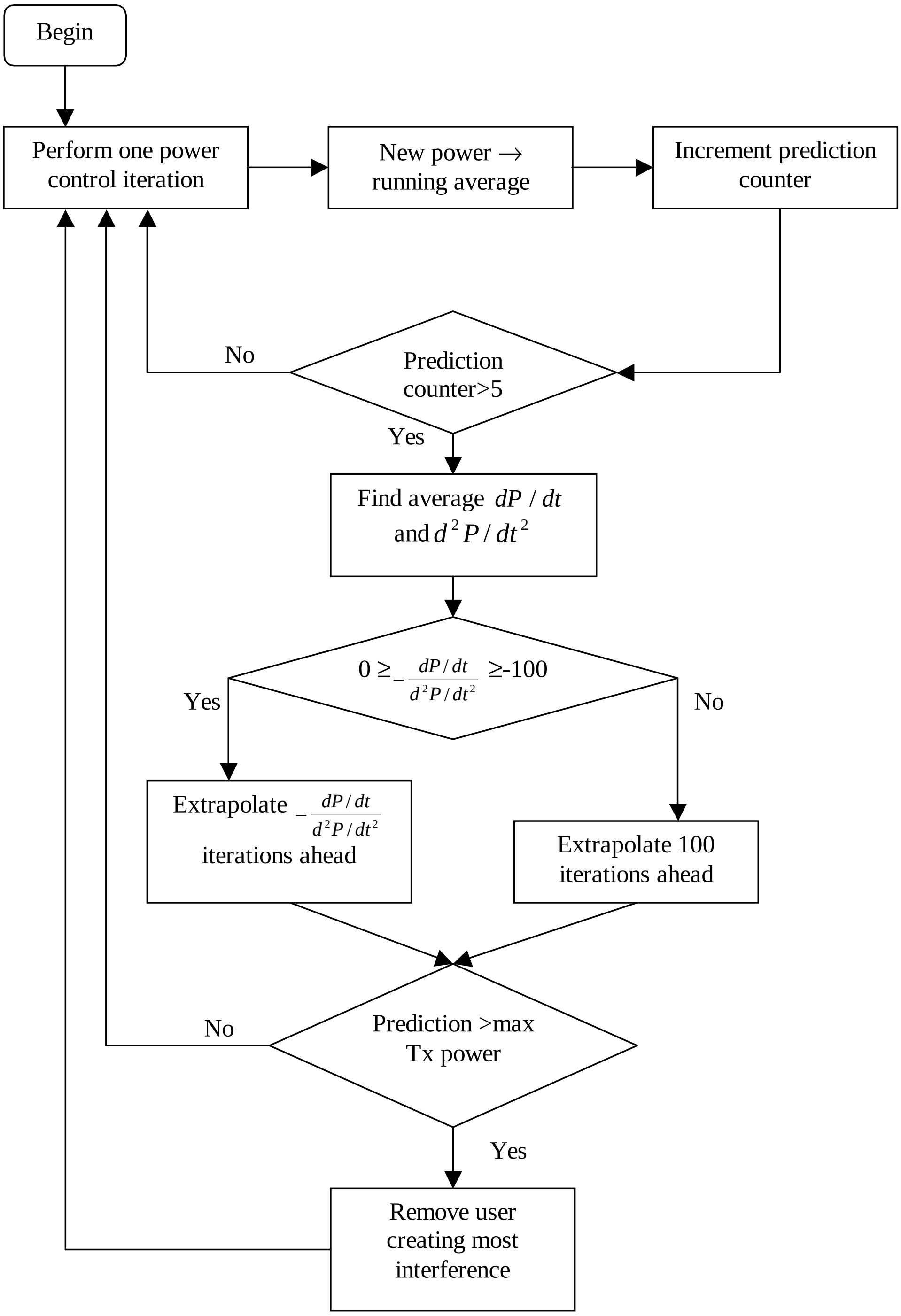

Figure 4.5: *Interference based admission flow*

to have converged is predicted to be $j = i - (dP_i/dt)/(d^2P_i/dt^2)$. A modification of this is introduced if the predicted iteration j is greater than $(i + 100)$. The procedure is repeated for $j = i + 100$ instead of the predicted value. This capping of the iteration is also applied when dP/dt and d^2P_i/dt^2 are of the same sign.

$$P_j = P_i + (j - i)\frac{dP_i}{dt} + \frac{d^2P_i}{dt^2}\sum_{k=1}^{j-i} k \tag{4.3}$$

If any of the predicted powers exceed the maximum transmit power the interference is analyzed. All of the interference above desired signals from interfering transmissions is summed, and the link with the greatest contribution removed. After any links are removed, or the routing is changed, the power control will need to take account of the new scenario. To prevent any users who will have acceptable power variables being unnecessarily put into outage, prediction is switched off until the averaging takes account of the new situation.

This extrapolation technique has two advantages over a wait and see approach. Convergence of the power control is reached earlier in a system that does not have a feasible solution below the maximum transmit power without one or more users being placed in outage. Secondly, the greatest interferers are removed, allowing increased capacity.

Power control is performed on an iterative basis according the to target C/I ratio at the receiver at a rate of one iteration per time slot. As the simulation is static, the main requirement is a convergent solution. In order to achieve this the loop uses exponential convergence, which results in slow but stable and predictable performance. For macroscopic congestion based ODMA, Section 4.5, the system produces enough information to directly calculate the required power from the Perron-Frobenious eigenvector [18], indeed a more advanced form of admission control using the power control feasibility requirement of $\lambda < 1$ may be implemented. In order to produce a comparison between the routing effectiveness, however, all systems share the same power and admission control.

4.5 Congestion based routing

The routing methods considered in Section 4.3 use path loss each route to initialize the routing. This technique is appropriate where there is little or no interaction between users, such as where a single user is allocated all of the available bandwidth at a particular instant. This is often the case for the packet radio systems where the relaying concept originated [9]. For civilian CDMA systems this is rarely the case. In order to mitigate destructive interaction between users, this section considers a measure of this interaction, termed congestion, which can be assessed both locally and centrally. A simple algorithm is presented that attempts arrange the routing in order to minimize this interaction.

4.5.1 Congestion measures and routing

A measure of congestion in a spread spectrum system has been formulated by Hanly [122] as a development on his work on cell-site selection [26] and has also been independently proposed as a routing metric [123]. The measure is in the form of the lower bounds on the Perron-Frobenious eigenvalue [18], λ, for a positive $M \times M$ matrix of the form

$$B[i,u] = \frac{\alpha_i \Gamma[u, c_i]}{W \Gamma[i, c_i]} \tag{4.4}$$

where α_i is a QoS requirement, $\Gamma[x, y]$ is the path loss between x and y, c_i the BS for user i and W the bandwidth. In the above scenario the only operational potential to change $\boldsymbol{B}$ is to change c_i through cell-site selection. In the multi-hop scenario the situation is more akin to sources and sinks than a fixed BS receiver, hence our problem formulation may be minimized in several dimensions. Generalizing (4.4) to allow for all users in the cell to be available as receivers we obtain

$$B[j,k] = \left(\frac{\sum\limits_{Rx_u = Rx_j} \alpha_u}{W} \right) \left(\sum_{Rx_u = Rx_k} \frac{\alpha_u}{\sum\limits_{Rx_i = Rx_j} \alpha_i} \frac{\Gamma[Tx_u, Tx_j]}{\Gamma[Tx_u, Tx_k]} \right) \tag{4.5}$$

where Tx_i and Rx_i are respectively the transmitter and receiver for link i, and the size of the matrix being governed by the number of links, not the number of users, though it can be shown that as the eigenvalues for all links transmitting to the same node are identical, λ is the same as if it were formulated for number of users (potential receivers) in the cell. Initially λ allows us to assess whether our current connectivity has a feasible power control solution $(\lambda < 1)$, see Section 5.1.3. The advantage of this formulation over the interference based algorithm is that not only is interference assessed at the intended receiver, the interaction between all users is accounted for, hence optimization of the system is possible. By reformulating $\boldsymbol{B}$ for potential routing candidates and using approximate eigenvalue methods, we perform routing by minimizing λ.

4.5.2 Local congestion metric

The formulation in (4.5) is a near-optimal one for a local solution with a congestion based metric. It is not optimal due to the approximation of counting self interference (in the $i = u$ terms in (4.4)). It is still quite computationally intensive, and suffers from the disadvantage that all the path losses in the system need to be known at the central database, a non-trivial task requiring a large signalling overhead and the disadvantages detailed previously for central lists. Fortunately a result also presented in [122] is that for a decentralized power control algorithm, where $I_k^{(\nu)}$ is the interference at receiver k for iteration ν, λ can be assessed locally due to the convergence of

$$\frac{I_k^{(\nu+1)} - I_k^{(\nu)}}{I_k^{(\nu)} - I_k^{(\nu-1)}} \to \lambda \text{ as } \nu \uparrow \infty \tag{4.6}$$

as long as the path gains remain fixed between iterations. Hence we can assess the impact on congestion for different routes by utilizing a channel probing technique, avoiding the need for collection of all path loss information and facilitating a decentralized congestion based routing algorithm. Routing is performed by attempting to minimize λ by evaluating other routes. This takes place in the slot that would otherwise be used for signalling overheads. There is no reason not to transmit desired packets during this process so, if the target is reached during the optimization, little capacity is sacrificed by the probing. The disadvantage of this technique is the necessity for static path loss values, increasing the error in approximation, and the instantaneous empirical nature of the algorithm, not allowing for system wide optimization. It is likely, however, that in a peer to peer situation users will be slow moving or static, so this should not generally be a problem.

4.5.3 Central congestion metric

Routing is initially performed as in Section 4.3.1.1 to provide a reasonable starting point for optimizing λ. This gives us a point of reference as to whether our re-routing in improving system performance. The trellis is then re-navigated for each user attempting a call, except that instead of summing the required metric distance at each stage, $\boldsymbol{B}$ is reformulated allowing λ to be recalculated. λ is then used as the distance to determine the winning entrant at each node. The same selection criterion is used at each stage to determine whether to proceed to the next, i.e. is $\lambda_{\nu-1} > \lambda_{\nu}$ at stage ν, with the exception that no shadowing deviation allowance is made, the same approach is used to select the appropriate final routing.

In conjunction with the cell site selection procedures detailed in [26] another level of optimization is available on the network organization level through cell breathing as detailed in Section 4.2. This approach is an extension of hand-over regions to include a region centred on all users, not just the BS. This region determines whether peer to peer transmission takes place, and if not which BS handles the call. This may be integrated into a routing algorithm if the target is not fixed (i.e. may be the destination MS or any BS), and the computation encompasses several cells.

4.6 Signalling overheads and latency

All of the above routing algorithms require signaling that will serve to reduce the useful available resources of the system. This needs to be offset against any capacity gains that may result from the use of these algorithms. The amount of signaling required varies according to the routing algorithm used and information gathering technique used. Without detailing a specific signaling protocol it is not possible to determine the exact overhead required, however Table 4.1 shows the required information for each protocol and the proportional increase in required signaling bandwidth for each system.

A common question regarding relaying systems concerns system delay. This is dependent on the relaying technique in question, some proposed systems [124] simply use the relay as a signal booster with a resultant degradation in the C/I [125] and hence system capacity; the delay will then be dependent purely on the circuit design. Another approach is to piggyback data by reducing the processing gain, hence increasing the bit-rate. It has been argued that this will actually reduce system latency due to the increased bit-rate [101], however this does not account for decoding, encoding and delays through the RF hardware. The TDD system investigated in this thesis does not support concurrent transmission and reception, hence neither of these schemes are feasible. The system instead uses the next time slot for relaying, hence the system delay is the length of the time slot times the number of hops used.

With the exception of the interference based ODMA and the local congestion ODMA, the

Routing protocol	Required information	Signaling amount per user proportional to n users/cell
Direct	Path loss to target	invariant
Central ODMA	Path loss between all users	n^2
Local ODMA	Path loss to neighbour list	invariant
Central interference ODMA	Path loss between all users, interference at all users	$n^2 + n$
Local interference ODMA	Path loss to neighbour list, interference for neighbour list	invariant
Macroscopic congestion ODMA	Path loss between all users	n^2
Local congestion ODMA	Power control probe to test route	invariant

Table 4.1: *Required information and proportionality of signalling load per user*

protocols produce a final routing table purely from the initial information. This makes them suitable for highly mobile and / or bursty data. For the other systems, however, the protocol will converge towards the routing at the same rate as the power control convergence, and thus are unsuitable for high mobility and bursty traffic unless fast power control is in use.

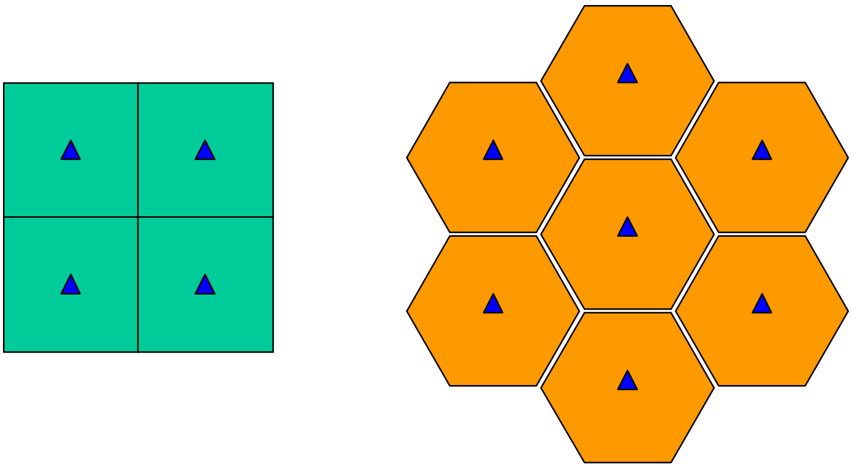

Figure 4.6: *Square and Hex Scenarios*

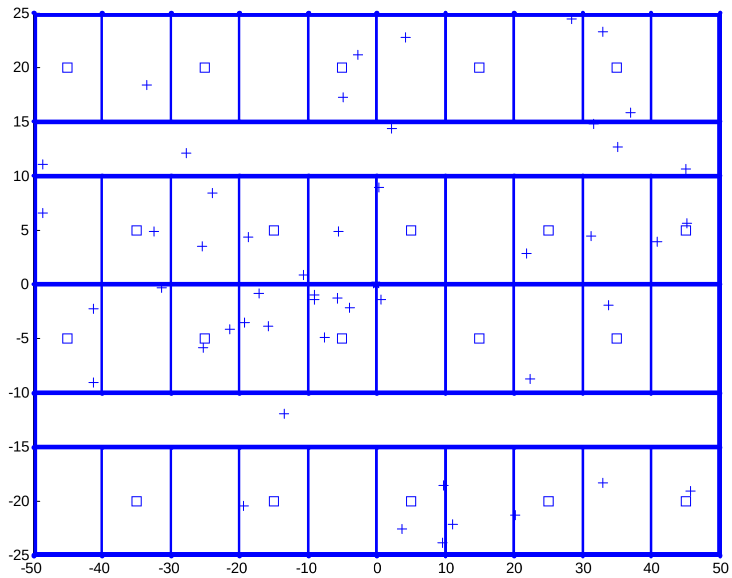

Figure 4.7: *3GPP Indoor Office Scenario*

4.7 Results

While three scenarios were investigated; 4 square cells, 7 hex cells, Figure 4.6, and the 3GPP indoor office as shown in Figure 4.7, the plots shown are all for the square scenario. The hex scenario is the closest to a conventional cellular plan, and the 3GPP indoor office is applicable for indoor peer to peer communications with repeaters / backbone nodes placed in some rooms. The square cell is a good approximation of the hex scenario, and is used in most results due to the reduced simulation complexity. A table is presented 4.7.1.1 to show the affect on capacity of the different scenarios. The scenarios were modeled using a MATLAB based scenario generator [63]. The model randomly generates the users with a uniform distribution and uses the COST 231 model for path loss [126].

4.7.1 Capacity

The capacity of systems limited to 2 hops and multiple hops were examined separately. The 2 hop systems are simpler to implement and should be more robust and predictable in fast fading environments, especially for local lists, as the whole route can be determined simply from communication with the relaying node. Systems not limited to 2 hops have more possible routes available, and should be able to use lower power on average as shown in Figure 3.12. Apart from Section 4.7.3 all the results presented are for the BS or cell centred network

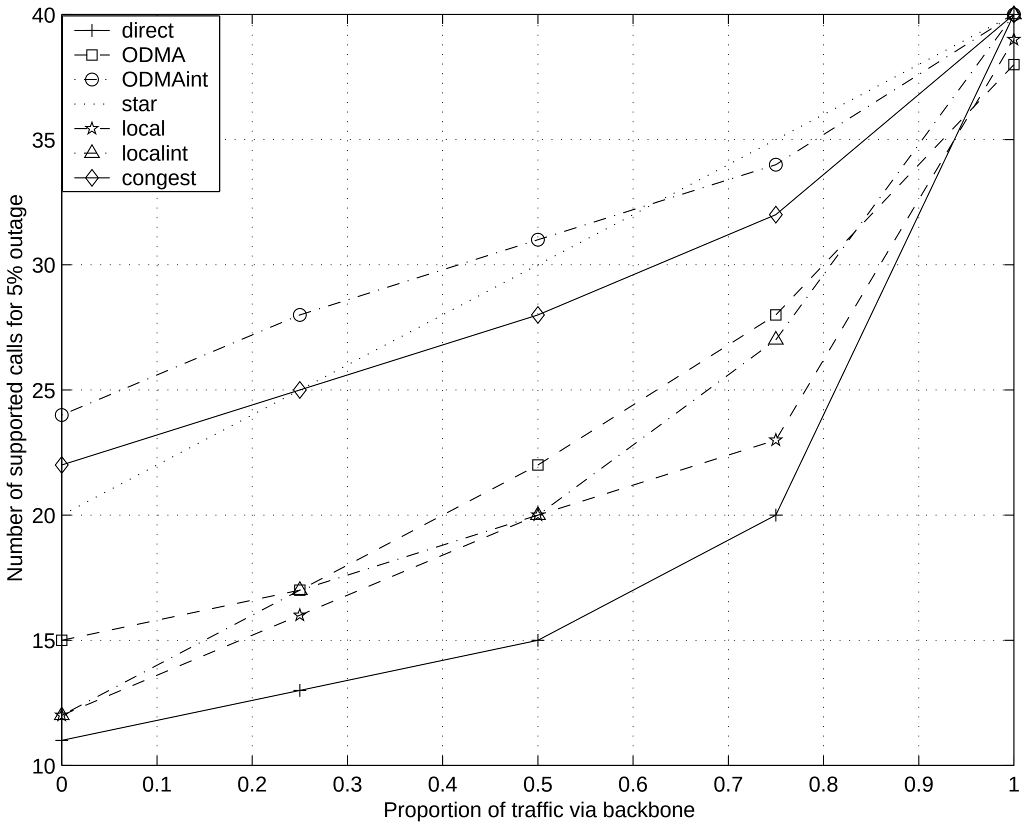

Figure 4.8: *Number of supported calls for 5% outage for different proportions of local and non-local traffic, cell centred network, 2-hop routing strategies*

allocation as shown in Figure 4.2. For the 2 hop strategies the congestion results presented are interchangeable for local and macroscopic methods, as the results are identical. For the multi-hop routing only the macroscopic congestion method was implemented.

4.7.1.1 2-hop Strategies

Figure 4.8 shows the number of supported calls in all 4 cells for 5% outage against different ratios of local to non-local traffic. The star curve represents the number of supported calls that could be expected for a star topology with either the direct or interference based ODMA. This is calculated for the number of supported calls for all non-local traffic and doubling the number of required calls for local traffic to account for the BS being required to forward the data onwards to the local target. It can be seen that for all cases, except interference based ODMA, at higher ratios of local to non-local traffic the star topology delivers greater capacity. It is important to note that much of the outage is due to the simplistic selection of local targets from BS hand-over

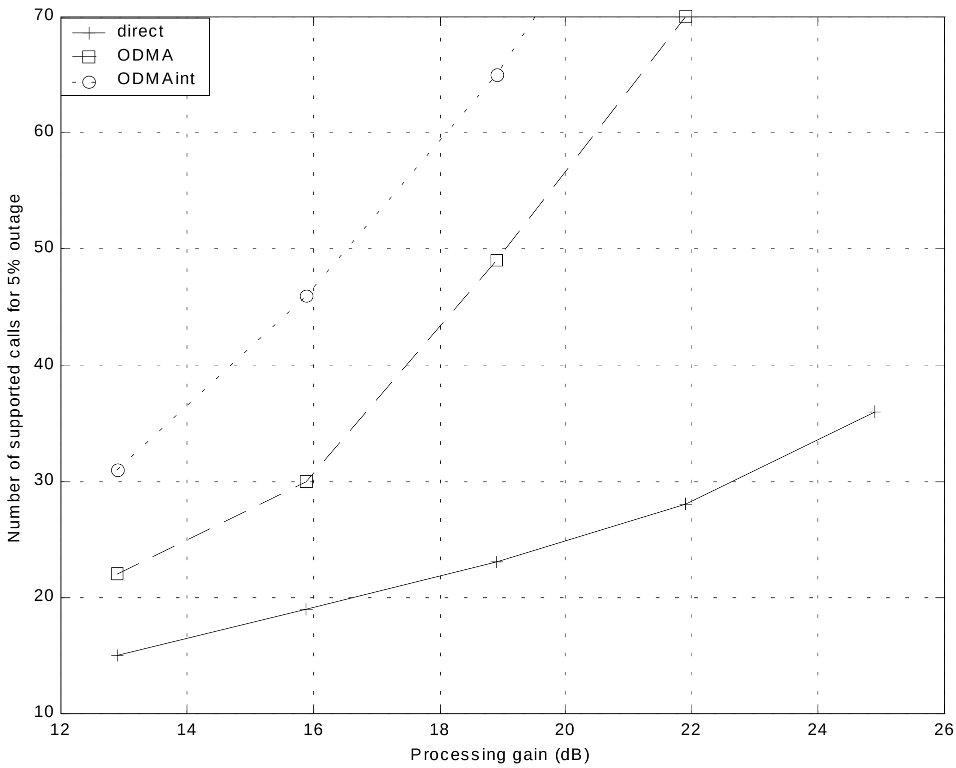

Figure 4.9: *Number of supported calls for 5% outage for various processing gains*

regions as is shown in Section 4.7.3. For example, it is very likely that a target will be selected that requires the user to transmit in a path that crosses the BS, inherently creating very high interference at the BS and thus the user may well be put into outage as it is a problem interferer. A more intelligent selection of users available for local traffic would be achieved from making local decisions by the user, based on neighbour lists, however this approach would not be possible for the direct approach without an extended signalling complexity. The approach investigated can be considered as a worst case for local routing. Intelligence in the selection of local traffic should reduce outage in all scenarios, meaning that peer-to-peer communication will only be established if it will enhance capacity, power levels, etc.

It can be seen that for the non-relaying scenario that the capacity is about half that which could be expected if a star topology was used, apart from when all traffic is via the backbone when the situation is identical. This is because the use of peer-to-peer communication introduces a power control problem that is likely to be insoluble. This is due to users transmitting to other users on the other side of the cell, hence power controlling the peer instead of the BS. This will introduce high interference levels at the BS that cannot be compensated for with power

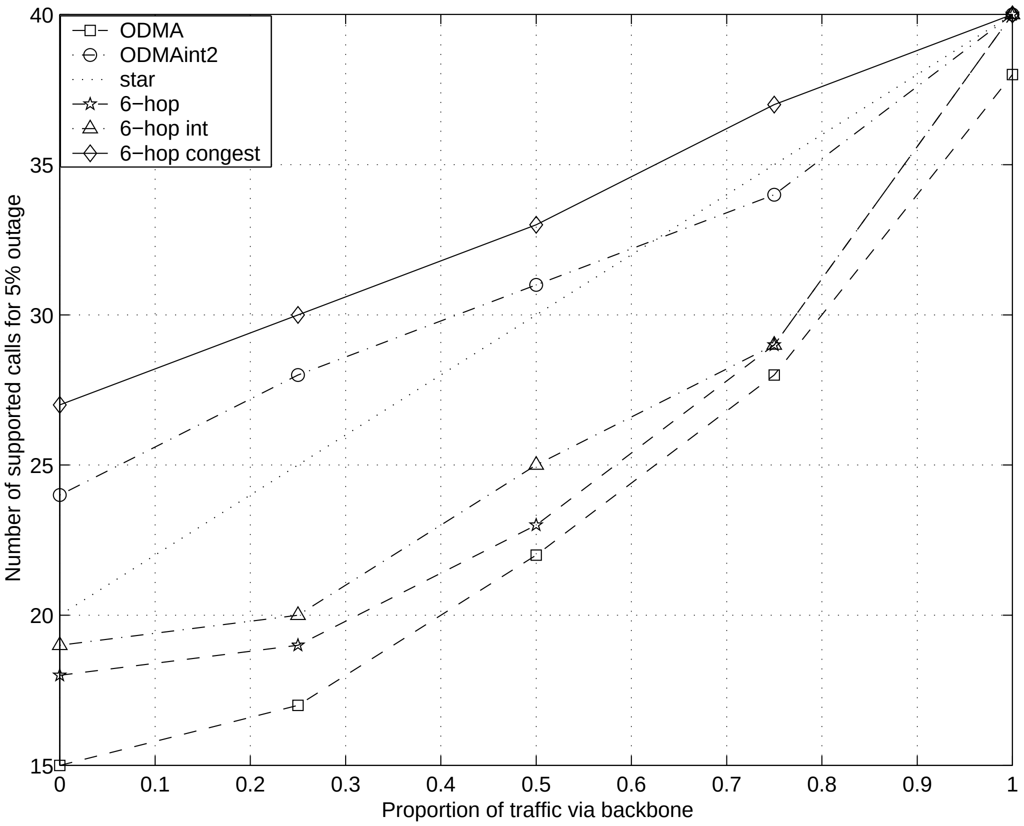

Figure 4.10: *Number of supported calls for 5% outage for different proportions of local and non-local traffic, cell centred network, multi-hop routing strategies*

control, as increasing the received power has a feedback effect on the required power to be received at the local target due to the increased interference at that user. The results for the direct transmission indicate that there is no reason to implement the presented local/non-local topology in a conventional CDMA system unless there is a severe problem with coverage.

The path loss based ODMA shows about a 50% improvement over the non-relaying system for all scenarios involving local traffic, however it is still significantly worse than the conventional star topology. The gains arise because ODMA systems generally involve lower transmission power than conventional systems, hence interference problems are more localized so they will not have such a detrimental effect on other users due to feedback in the power control.

Interference based ODMA shows a gain where the local traffic is at least 50% of the total, performing best when all traffic is local. When non-local traffic is dominant it is roughly equivalent to the conventional system. Path loss based routing does not take account of the

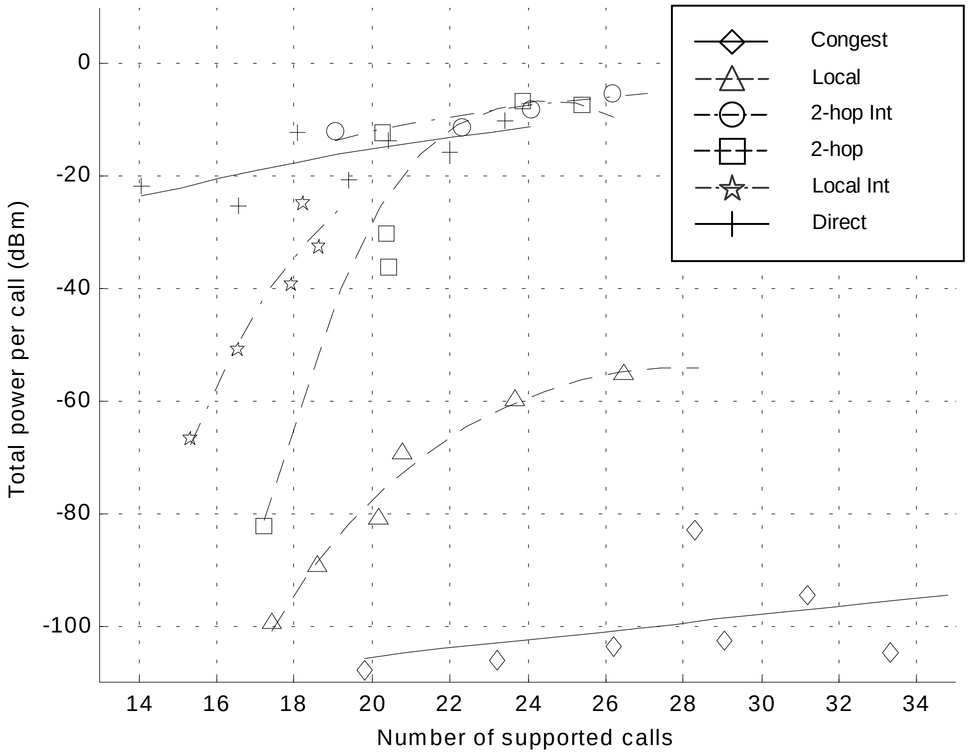

Figure 4.11: *Total power per call against number of supported calls for all local traffic, cell centred network*

congestion due to interference, mainly in the centre of the cell, when routing, the interference based system will avoid these problem areas unless absolutely necessary. This means that transmission, even to the other side of the cell, is possible without destroying desired signals at the BS as the signal is routed to avoid relays in this area. On the downside any ODMA system requires increased complexity both in signalling to establish routing, and in the handset's ability to relay the signal. It also takes longer to establish the routing as the dynamic routing requires the power control to converge after each iteration. Congestion based 2-hop relaying shows a slightly reduced capacity from the interference based routing, but will be as up to date as the path loss information that is gathered, as no prediction is required. The local list based routing methods show a comparable, and sometimes lower, capacity to the simple ODMA.

As can be seen from Table 4.7.1.1, in all scenarios, the greatest number of users are supported by interference based ODMA. The most dramatic improvement is for the 3GPP scenario as this involves high losses in certain paths due to walls. A non-relaying system has no path diversity and is forced to use this transmission path. The relaying system has several choices available

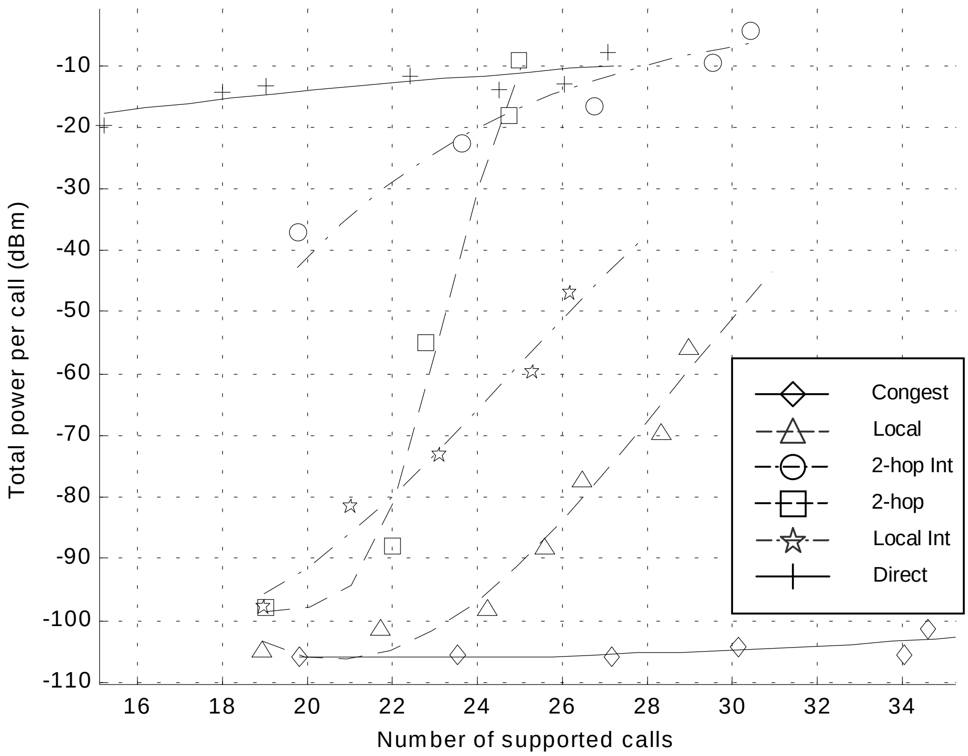

Figure 4.12: *Total power per call against number of supported calls for 50% local traffic, 50% non-local, cell centred network*

to it, and so it is likely that it will be able to avoid these areas of high signal attenuation. In this scenario the wall losses are the dominant problem so path loss and interference based ODMA have similar performance.

Figure 4.9 shows the number of supported calls against processing gain for the square cell scenario. The ratio of local to non-local traffic is 1:1. The systems all show a reduced performance than that which could be expected from increasing the processing gain, where it should roughly double and the data rate half for each 3dB increase in the processing gain. This is due to the increased number of users creating greater likelihood of strong interactions between local transmissions thus creating power control difficulties. This can be avoided by intelligent local target selection. Both ODMA systems show similar increases in the supported number of users with increasing processing gain, not too far below conventional systems, however the direct routing shows greatly reduced performance with just over double the number of users for 1/16 of the data rate for the lowest processing gain.

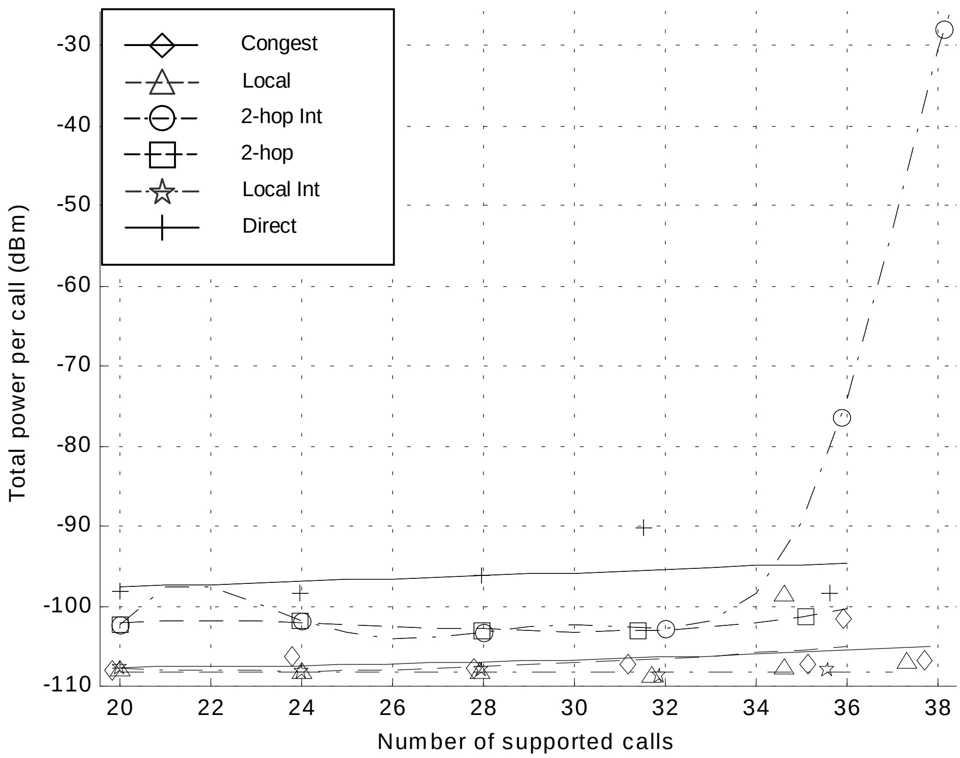

Figure 4.13: *Total power per call against number of supported calls for all non-local traffic, cell centred network*

4.7.1.2 Multi-hop Strategies

Figure 4.10 shows the supported calls for various ratios of local to non-local traffic, however in this case the routing strategies are allowed to utilize more than 2 hops, with a maximum of 6. No local list routing schemes are analyzed, as it is considered that for more than two hops the reduced signalling advantage of this system will be compromised. The highest capacity 2-hop system, interference based ODMA, and 2-hop ODMA are shown for comparison.

It can be seen that for all traffic ratios the increase in allowed number of hops gives the benefit of slightly increased capacity for the simplest, path loss, routing strategy. This increase is slightly reduced as the majority of traffic moves from local to central. The best performer for 2-hops, interference ODMA, is severely compromised by the move to an increased allowed number of hops, with performance little or no better than the non-interference based system. It is likely that this is due to the system being locked in by the initial starting condition, which comes from the path loss routing. This starting condition will utilize more and smaller hops on average than for 2-hops, hence the iterative probing for low interference routes is likely to

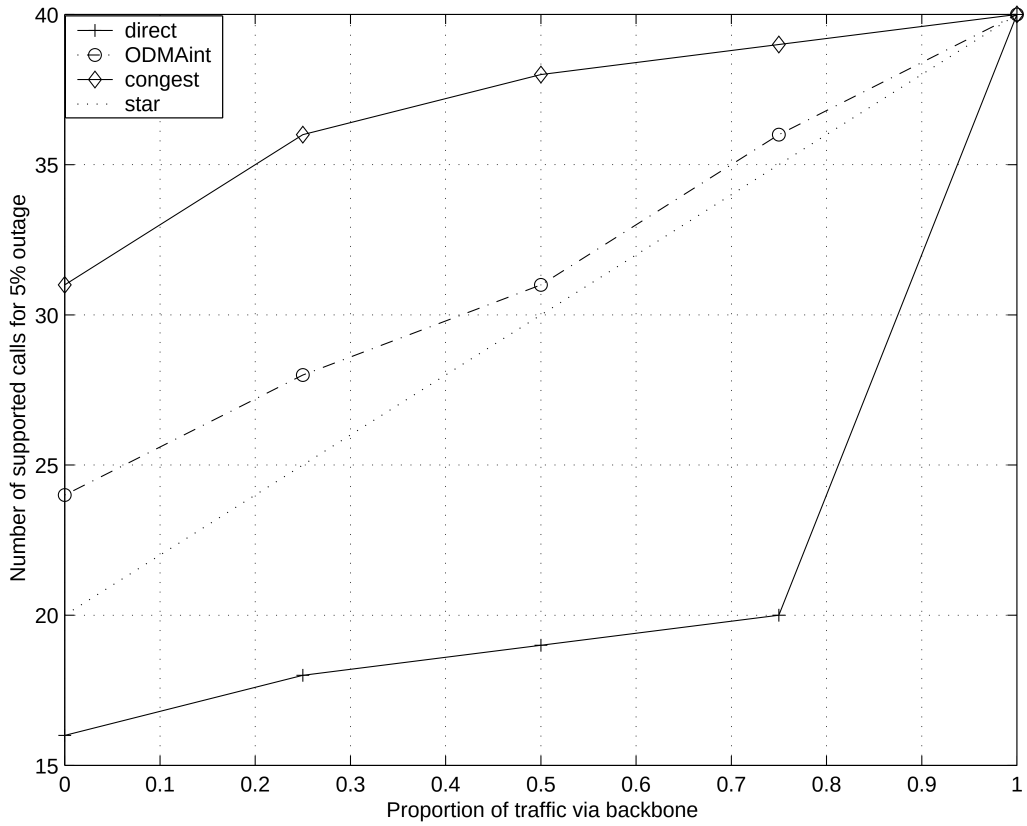

Figure 4.14: *Number of supported calls for 5% outage for different proportions of local and non-local traffic, user centred network*

involve introducing larger hops which will not result in lower interference. The problem is that the local minimization for a larger number of hops generally finds a locally higher minimum than the 2-hop scenario. A solution to this would be a search algorithm that transcends the local problem.

The routing method that shows the greatest improvement with the move to multiple hops is congestion based routing. It now out performs all other routing strategies except for all traffic via the BS, where the pole capacity is the limiting factor. The improvement is due to the trellis search employed by the algorithm being allowed more possible routes, and these routes only being used if lower congestion results. The use of more hops allows for greater capacity from this increased diversity and also the nature of the smaller hops. With a smaller hop, the path loss will be lower, without interference this will result in a lower transmitted power and hence interference. The congestion algorithm inherently takes interference into account, thus these shorter hops will be chosen so as minimize overall system impact.

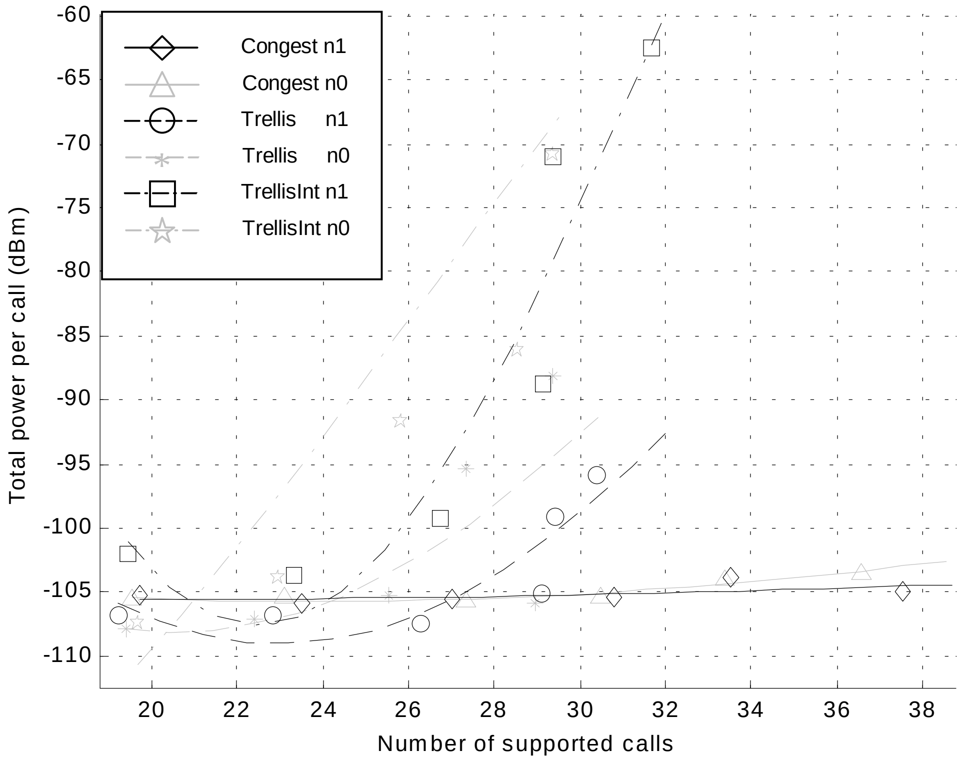

Figure 4.15: *Total power per call against number of supported calls for 50% local traffic, 50% non-local, comparing network types*

4.7.2 Power

The results in this section are all for 2 hop systems with a BS or cell centred network as shown in Figure 4.2. Power results for multiple hops and MS / user centred network allocation are presented in Section 4.7.3.

Figures 4.11-4.13 show the average power levels for the duration of a call, i.e. for a relaying scenario with two hops, this is the sum of the power for the two links. Figure 4.11 shows the situation for all local traffic. Both the direct and interference based ODMA have similar power levels, though it must be considered that the direct system has been required to put far more users into outage, e.g. to achieve 19 calls the interference based ODMA has placed one call into outage where the direct system has removed 13 calls. With the admission control described in Section 4.4, this outage will have removed the worst interferers creating a more favourable scenario than the interference based ODMA is experiencing as ODMA is more able to cope without forcing problem users into outage. In Figure 4.12, for equal local and non-local traffic, interference based ODMA shows a transmission power reduction over direct transmission for

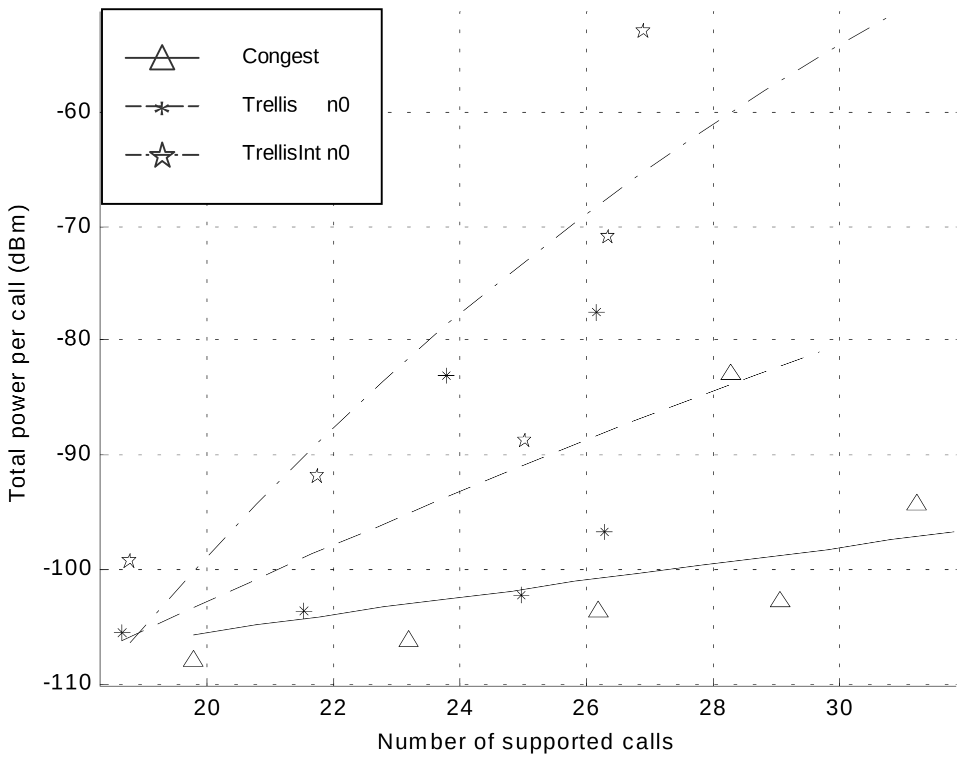

Figure 4.16: *Total power per call against number of supported calls for all local traffic, user centred network*

most scenarios. In Figure 4.13, with all non-local traffic, the transmission power is much less than the scenarios with local traffic due to power controlling only to one point. The interference based ODMA requires increased transmission power at high user densities as paths are chosen with greater path loss to avoid high interference regions.

The local list based strategies for ODMA show a greatly reduced transmission power over the centrally implemented systems for most situations. This is because, inherent in the list gathering method, communication with other nodes is established according to a maximum transmit power. Hence users will only appear as available candidates on the list if the transmit power required for a link is below this maximum. This means that links that require a high power transmission will not be considered even if they would be preferred solely on the basis of path loss.

In all traffic conditions the simple ODMA produces the lower power than interference based ODMA and direct transmission for low user densities, due to some outage of problem users and the reduced transmission power and interference of ODMA. At higher user densities the

	Number of supported users/BS		
	Direct	ODMA	ODMAint
Square, pg=12.9dB	4	5.5	8
Square, pg=15.9dB	5	7.5	11.5
Hex, pg=12.9dB	4.5	6.1	8.5
Hex, pg=15.9dB	6	9	13.5
3GPP, pg=12.9dB	1.5	3	4
3GPP, pg=15.9dB	2	5	6

Table 4.2: *Supported users per BS for various scenarios for 1:1 ratio of local to non-local traffic*

required power is increased due to the higher number of links used.

The congestion based routing results in the lowest required average transmission power in all conditions, and shows very little increase with higher user densities. As will be shown in Section 5.1.3 the congestion measure based on the Perron-Frobenious eigenvalue of (4.4) or (4.5) is directly related to the power control equation. Hence minimization of this eigenvalue directly translates into a minimum power solution, therefore this technique may also be considered as minimum power routing.

4.7.3 Network allocation

The results presented in the previous sections for capacity and power are all for BS / cell centred target allocation as shown in Figure 4.2. This is a simple technique using the same criterion as would be used for a direct transmission system's cellular hand-over. For a relaying system this is not necessarily ideal, as cellular loading may be uneven and as such it may be desirable to route a call via an adjacent cell's BS, minimizing in cell interference through the use of a relay in the adjacent cell. Cell centred target allocation also reduces the number of potential relays if a MS is located near the edge of a cell compared to one near the centre as all MS in the adjacent cell are unavailable for relaying. This section presents comparative results for a simple alternative system centred instead on each MS also shown in Figure 4.2.

Figure 4.14 shows the number of supported calls for 5% outage for different ratios of local and non-local traffic, with the target allocation centred on the user instead of the cell, and a maximum of 2 hops. The direct transmission system shows an improvement over the BS centred allocation where the traffic is 50% local or more. This is because there will be fewer peer-peer transmissions from one edge of the cell to the other. The interference based ODMA only shows improvement for 75% non-local traffic, showing that this system is already operating close to the limit for path loss initialized systems, managing to avoid the areas of high interference when they occur. The most dramatic change is with the congestion based routing. This now shows very little decrease in the number of supported users from the all non-local scenario down to 25% non-local traffic. For all local traffic there is an increase of over 40% in the number of supported users than for the BS centred target allocation. This demonstrates the extra capacity that may be available from a more appropriate choice of targets.

Figure 4.15 shows a comparison between the power for multiple hop systems for BS centred target allocation (n0) and MS centred allocation (n1) with 50% local 50% non-local traffic. It can be seen that the choice centred on the user results in a lower average power in all circumstances. This is a result of less congestion and hence power warfare at the centre of the cell. It should be noted that the multi-hop ODMA routed systems show a greatly reduced transmit power over the 2-hop systems due to the combination of non-linear path loss and the greater localization of interference resulting from shorter hops. Figure 4.16 shows the total average power for all local traffic and the MS centred target allocation. Unlike the BS centred allocation, there is very little require increase in power with the move away from power control at one point (the BS). The plot for all non-local traffic is not shown as this is identical for both forms of traffic allocation.

4.8 Conclusions

In this chapter, a network topology has been investigated that allows both peer-to-peer and non-local traffic. We have presented a new admission control that allows congested areas to be identified and problems users to be removed. It has been shown that a conventional CDMA system is unable to produce performance comparable with a star topology. Path loss based ODMA shows a capacity improvement over the non-relaying system and in most cases reduced transmission power. A new ODMA algorithm based on interference is presented that allows for greater capacity than a star topology when scenarios involve at least 50% local traffic and comparable capacity when non-local traffic dominates. This provides the highest capacity of the presented strategies where there is a maximum of two hops and target allocation is based on conventional cellular hand-off.

A congestion based routing algorithm is presented that attempts to minimize the overall power of the system as well as providing a measure of feasibility. This technique provides the lowest required transmit power in all circumstances, and the highest capacity in all cases except those outlined above for interference based ODMA. A simple alternative to conventional hand-off based target allocation is presented. This shows capacity and power benefits in all circumstances. When combined with the congestion based routing, a capacity increase of up to 44% over a conventional star topology is shown when peer-peer communication is involved.

Chapter 5
Multi-hop DCA

Congestion based routing, as developed in the previous chapter, is shown to require the lowest transmitted power, and in most cases achieves the highest capacity of all the routing algorithms examined in Chapter 4. All of these routing algorithms have allocated TDD time slots on a first come first served basis and according to the rules outlined in section 3.4.1. This allocation only serves to ensure that the limitations of the TDD hardware are considered. It makes no attempt to optimise time slot allocation.

The allocation of time slots with regard to system performance has been shown to be an effective technique to mitigate interference [34]. Integrating slot allocation, or DCA, into the routing algorithm would appear to be the most effective approach due to the interactive nature of interference. This approach will also need to conform to the extra limitations imposed by relaying. In addition to the rules in 3.4.1, it is obvious that the slot allocation must be in the same order as the relays. A combined DCA will allow minimisation of the desired measure, in this case congestion, simultaneously in routing and slot allocation.

This chapter develops a combined routing and resource allocation algorithm for TDD-CDMA relaying. It starts by reviewing one such algorithm applicable to TDMA and FDMA. A novel method of time slot allocation according to relaying requirements is then developed. Two measures of assessing congestion are presented based on matrix norms. One is suitable for current interior point solution, the other is more elegant but is not currently suitable for efficient minimisation.

5.1 Combined routing and DCA algorithm

This section presents a development of a simultaneous routing and resource allocation algorithm [127] to include CDMA and explicit DCA.

5.1.1 Simultaneous routing and resource allocation

An algorithm has been published that allows for simultaneous routing and resource allocation for multi-hop networks using FDMA or TDMA air interfaces [127]. CDMA is not considered as the authors could not adapt the capacity for an interference limited system to their model. Within TDMA, time slot allocation is only considered as a discrete resource, i.e. there are so many time slots each with a fixed capacity. There is no explicit allocation of time slots, especially w.r.t. the sequential nature required by a relaying system. The basic development of their algorithm consists of 3 stages. Firstly a network flow model is presented, then a relevant capacity model is coupled to the flow problem. This creates a linear program with convex constraints which can be solved globally by recently developed interior point methods [21, 128, 129]. The algorithm concludes with an analysis of the associated dual problem [109] in order to improve algorithm efficiency, however this final stage is not considered in this chapter. This section describes the formulation as described in [127]. Subsequent sections are additional to anything contained in that paper.

The network topology is represented by a *node-link incidence matrix* $A \in \mathbf{R}^{N \times L}$, where N is the total number of nodes and L is the total number of links. This matrix has entries such that

$$A_{nl} = \begin{cases} 1 & : \text{ node } n \text{ is transmitting on link } l \\ -1 & : \text{ node } n \text{ is receiving on link } l \\ 0 & : \text{ otherwise} \end{cases} \tag{5.1}$$

For example the system as shown in Figure 5.1 would have an incidence matrix given by

$$A = \begin{bmatrix} 1 & -1 & -1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & -1 & -1 & 1 \end{bmatrix} \tag{5.2}$$

In order to specify the nodes between which communication is desired a *source-sink vector* $s^{(d)} \in \mathbf{R}^N$ is introduced for each destination d, where $d = 1, ..., D$. The nth ($n \neq d$) entry is the flow injected into the network by node n. From the conservation of flow, the sink flow at d is defined as

$$s_d^{(d)} = - \sum_{n, n \neq d} s_n^{(d)} \tag{5.3}$$

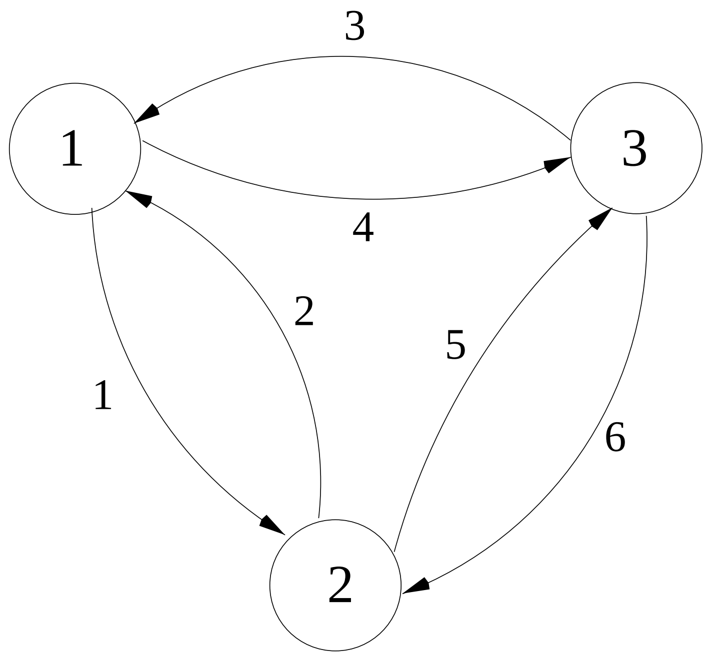

Figure 5.1: *Link connectivity example*

For each link, a *flow vector* $x_l^{(d)}$ determines the amount of flow destined of destination d where $x^{(d)} \in \mathbf{R}_+^L$. Hence the total amount of traffic for link l is given by $t_l = \sum_d x_l^{(d)}$. Requiring that the traffic does not exceed the capacity, the following minimization problem is defined

$$\begin{array}{lll} \text{minimize} & f(x,s,t,r) & \\ \text{subject to} & Ax^{(d)} = s^{(d)}, & d = 1,...,D \\ & x^{(d)} \succeq 0, \quad s^{(d)} \succeq_d 0, & d = 1,...,D \\ & t_l = \sum_d x_l^{(d)}, & l = 1,...,L \\ & t_l \leq \phi_l(r_l), & l = 1,...,L \end{array} \tag{5.4}$$

where $\phi(r)$ is the capacity as a function of the communications variables r, $\succeq$ means component-wise inequality and $\succeq_d$ means component-wise inequality except for the dth component. If the function ϕ is concave and monotone increasing in r and the objective function is convex then this is a convex optimization problem. This type of problem can be solved globally and efficiently by recently developed interior-point methods [21, 128, 129].

5.1.2 Time slot allocation

The allocation of time slots is not explicitly addressed by the formulation in (5.4). This problem is more difficult than for the single hop DCA case outlined previously. This is because, unless it is tolerable to introduce sufficient buffering and hence extra packet delay, the next routed hop needs to take place in the subsequent time slot. Previous implementations of a TDD-CDMA multi-hop routing algorithm [91, 123], and Chapters 3-4 have used arbitrary time slot allocation subject to the restrictions outlined in section 3.4.1. This section presents a formulation of the link-incidence matrix that allows for integrated routing and time slot allocation, or DCA.

In the formulation (5.4) there is no way of determining in which time slot the link occurs. If the link incidence matrix were to be explicitly represented for each time slot this would become possible. An important feature of (5.1) is that for the equality contained in (5.4),

$$Ax^{(s)} = s^{(d)} \quad d = 1...D \tag{5.5}$$

or more generally

$$Ax^{l} = s^{l} \tag{5.6}$$

where x^l is the collection of flow vectors and s^l the collection of source-sink vectors. If node n is not the destination, s^l_n will be zero. This can be interpreted as the necessity that if there is flow incident to a node then there must be a corresponding and equal flow leaving the node, hence flow is conserved. This is achieved by having 1's and -1's on the same row with appropriate values in the flow vector. Therefore in order to define the time discrete link incident matrix, and require flow into the next time slot, it is necessary to separate (5.4) into transmitting and receiving matrices, A_+ and A_- respectively, where A_+ contains only the positive entries of A and A_- only the negative entries. Thus the links between the nodes can be represented in a time discrete fashion as

$$\zeta = \begin{cases} \zeta_{((c-1)\times N+1):(c\times N),((c-1)\times L+1):(c\times L)} & = A_+ \quad c = 1...C \\ \zeta_{(c\times N+1)\bmod(C\times N):((c+1)\times N \bmod(C\times N),((c-1)\times L+1):(c\times L))} & = A_- \quad c = 1...C \\ & = 0 \quad \text{otherwise} \end{cases} \tag{5.7}$$

where C is the total number of time slots. Therefore ζ will take the form

$$\zeta = \begin{bmatrix} A_+ & 0 & 0 & \cdots & 0 & A_- \\ A_- & A_+ & 0 & \cdots & 0 & 0 \\ 0 & A_- & A_+ & \cdots & 0 & 0 \\ 0 & 0 & A_- & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & A_+ & 0 \\ 0 & 0 & 0 & \cdots & A_- & A_+ \end{bmatrix} \tag{5.8}$$

Hence the receiving nodes are aligned with the same node transmitting in the next time slot. This means that the only way to satisfy (5.6) is by transmitting in the next time slot if there is flow incident into a node.

A problem with this formulation is the specification of s. If a non-zero value is allocated, then for a positive value the packet initiation, and for a negative value the packet reception is tied to a specific time slot. Clearly this is incompatible with our objective of combining the routing algorithm and time slot allocation. To overcome this failing we can break the problem down further than the time slots. There are 4 possible classifications of a link:

1) Neither transmitter or receiver is an initiating source or a terminating sink, i.e. both are relays. This is described by ζ as the corresponding value s_n^l for node n is 0.

2) The transmitter is an initiating source, the receiver a relay. s_n^l is positive for the transmitter, 0 for the relay.

3) The transmitter is a relay, the receiver the destination sink. s_n^l is 0 for the transmitter, negative for the relay.

4) Transmitter is an initiating source, the receiver the destination sink. This corresponds to the non-relaying scenario. s_n^l is positive for the transmitter, negative for the relay.

If these modes can be incorporated into our link incidence matrix as separate entities, then it is possible to specify s^l such that any time slot is available for route initiation or termination. This may be achieved by breaking each link into the 4 types described above. This split flow is described by x, the sum of which is equal to x^l, and the sum of each group corresponding to link l is equal to the value of x^l for that link. Thus the link incidence matrix is expanded column-wise 4 times for the different modes, has an extra 2N rows to facilitate the specification of s^l for required source and sink nodes. The required link incidence matrix may be broken down into 4 sub-matrices, T^u, T^t, T^r, and T^d respectively for each of the cases above.

$$T^u = \begin{cases} T^u_{N+1:(C+1)\times N,:} & = \zeta \\ & = 0 \quad \text{otherwise} \end{cases} \tag{5.9}$$

$$T^t = \begin{cases} T^t_{1:N,((c-1)\times L+1):(c\times L)} & = A_+ \quad c = 1...C \\ T^t_{N+1:(C+1)\times N,:} & = \zeta_- \\ & = 0 \qquad \text{otherwise} \end{cases} \tag{5.10}$$

$$T^r = \begin{cases} T^r_{N+1:(C+1)\times N,:} & = \zeta_+ \\ T^r_{(C+1)\times N+1:(C+2)\times N,((c-1)\times L+1):(c\times L)} & = A_- \quad c = 1...C \\ & = 0 \qquad \text{otherwise} \end{cases} \tag{5.11}$$

$$T^d = \begin{cases} T^d_{1:N,((c-1)\times L+1):(c\times L)} & = A_+ \quad c = 1...C \\ T^d_{(C+1)\times N+1:(C+2)\times N,((c-1)\times L+1):(c\times L)} & = A_- \quad c = 1...C \\ & = 0 \qquad \text{otherwise} \end{cases} \tag{5.12}$$

where ζ_+ contains only the positive entries of ζ, and ζ_- only the negative entries. The composite time discrete link incidence matrix, T, can be written as

$$T = [T^u T^t T^r T^d] \tag{5.13}$$

though the order of the sub-matrices, or indeed any column exchange is allowed, the only change being that the corresponding value for flow in x will appear in the exchanged position when the solution to the system is found. Reformulating s^l as s for the time discrete link incidence matrix T

$$s = \begin{cases} s_{1:N,:} & = s^l_+ \\ s_{(C+1)\times N+1:(C+2)\times N,:} & = s^l_- \\ & = 0 \quad \text{otherwise} \end{cases} \tag{5.14}$$

The condition

$$Tx = s \tag{5.15}$$

can replace (5.6) in (5.4), the resulting x in the solution will contain the DCA allocation, and the solution will be find the time slot allocation such that the solution is a global minimum.

5.1.3 A CDMA feasibility condition

The initial work on congestion [122] has been mainly concerned with determining system feasibility. We can show that a congestion measure is a sufficient condition for feasibility by starting from the initial power control equality for a single receiver.

$$P_i\Gamma[i, c_i] = \frac{\alpha_i}{pg}\left(\sum_{u\neq i} P_u\Gamma[u, c_i] + \eta[c_i]pg\right) \tag{5.16}$$

where $\eta[k]$ is the power of the unspread noise in the system. As the power control problem takes the form:

$$(I - A)P = b_{M\times 1} \tag{5.17}$$

where $b_{M\times 1}$ is the $M \times 1$ vector with ith entry $b[i] = \eta[c_i]\alpha_i/\Gamma[i, c_i]$. As it is necessary for all elements of p and b to be ≥ 0, it is a necessary and sufficient condition (bar maximum power constraints) that $(I - A)$ be invertible and $(I - A)^{-1}$ be non-negative. Substituting the eigenvalue problem

$$Ax = \lambda x \tag{5.18}$$

into Equation (5.17) gives

$$(1 - \lambda)P = b \tag{5.19}$$

hence the condition that the largest, in this case Perron-Frobenious, eigenvalue is < 1.

In order to integrate the congestion matrix into the link based formulation of (5.4) we need to be able to modify the matrix according to the traffic flowing on a particular link. Examining

(4.4) we can break matrix into two parts, the path loss ratio, G, for all links which is formed from the path gain matrix for a single time slot.

$$H[i,u] = \begin{cases} \frac{pg}{v} & : \text{Rx}_i = \text{Tx}_u \text{ or } \text{Rx}_u = \text{Tx}_i \\ \frac{\Gamma[\text{Tx}_u, \text{Rx}_i]}{\Gamma[\text{Tx}_i, \text{Rx}_i]} & : \text{otherwise} \end{cases} \tag{5.20}$$

where Tx_n and Rx_n are respectively the transmitter and receiver for link n and v is the minimum quanta of flow. The term for conflict in Tx and Rx means that simultaneous Tx and Rx infeasible in the formulation. G is formed with H on the diagonal for each time slot.

$$G = \begin{bmatrix} H & 0 & \cdots & 0 & 0 \\ 0 & H & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & H & 0 \\ 0 & 0 & \cdots & 0 & H \end{bmatrix} \tag{5.21}$$

The QoS element, Q, can be formed directly from the required traffic flow

$$Q = \frac{1}{pg}\text{diag}(t) \tag{5.22}$$

where t is the vector containing the traffic for all the links. Hence the congestion matrix for the link based approach may be written

$$A = QG \tag{5.23}$$

The Perron-Frobenious eigenvalue for this matrix is given by the spectral norm $\|\bullet\|_2$ [130] since it is defined as

$$\|A\|_2 \equiv \max \sqrt{\lambda} : \lambda \text{ is an eigenvalue of } A^*A \tag{5.24}$$

it is an induced norm, and λ can be calculated from

$$x^*A^*Ax = \lambda\|x\|_2^2 \tag{5.25}$$

hence we can reformulate (5.4) to include CDMA as follows

$$\begin{array}{ll} \text{minimize} & x^*(QG)^*(QG)x \\ \text{subject to} & Tx = s \\ & x^{(d)} \succeq 0, \quad s^{(d)} \succeq_d 0, \quad d = 1, ..., D \\ & t_l = \sum_d x_l^{(d)}, \qquad\qquad l = 1, ..., L \\ & (I - QG)p = b \\ & p_{min} \preceq p \preceq p_{max} \end{array} \tag{5.26}$$

unfortunately this formulation cannot be solved by current interior point methods, although if the progress on minimizing the eigenvalues of asymmetric matrices, e.g. [131, 132], continues at its current rate this may soon be possible. Until that time we can break the problem down somewhat.

The Euclidean, l_2, or Frobenius norm, $\| \bullet \|_F$, is defined [130] as

$$\|A\|_F \equiv \left(\sum_{i,j=1}^{n} |a_{ij}|^2 \right)^{1/2} \tag{5.27}$$

$\| \bullet \|_F$ is not a vector bound norm, as $|\!|\!| \bullet |\!|\!|_2$ is, but it is compatible with $|\!|\!| \bullet |\!|\!|_2$ [133], hence the inequality

$$|\!|\!|A|\!|\!|_2 \leq \|A\|_F \tag{5.28}$$

Therefore we can calculate an upper bound on λ without the complexity of calculation for an induced norm. One implication of this simplification is that we can no longer use the pg/v factor to eliminate simultaneous Tx and Rx for a node. This is because, with the removal of the vector term, these factors may no longer be multiplied by zero, and will dominate the Frobenius norm. One approach to this problem is to allocate nodes to odd or even time slots prior to the optimization. This removes some degree of freedom from the routing algorithm, hence the DCA may not be as favorable as in (5.26). There is still a great deal of integration between routing and DCA as the formulation in (5.15) is still applicable. The preallocated time-slot congestion matrix may be formed from H^* where

$$H^* = \begin{bmatrix} H^o & 0 \\ 0 & H^e \end{bmatrix} \tag{5.29}$$

this is similar to the formulation in [123]. Initially receiving nodes are arbitrarily split between H^o and H^e and the matrices formed as in (5.20) with the proviso that a node is only available as a transmitter if it is not a receiver in that time slot. This means that no terms to prohibit simultaneous Tx/Rx appear. There follows an exchange of receiving nodes between H^o and H^e until the Frobenius norm for this matrix is minimized. G is now formed from $T/2$ entries of H^* (as H^* covers 2 time slots) as

$$G = \begin{bmatrix} H^* & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & H^* \end{bmatrix} \tag{5.30}$$

We can now write the minimization problem

$$\begin{array}{ll} \text{minimize} & \sum_{i,j=1}^{n} \left|\sum_{k=1}^{n} q_{ik} g_{kj}\right|^2 \\ \text{subject to} & Tx = s \\ & x^{(d)} \succeq 0, \quad s^{(d)} \succeq_d 0, \quad d = 1, ..., D \\ & t_l = \sum_d x_l^{(d)}, \qquad\qquad l = 1, ..., L \end{array} \tag{5.31}$$

which may be solved globally and efficiently through interior point methods as a semidefinite program (SDP) [134]. The power allocation may then be performed as a minimization problem

$$\begin{array}{ll} \text{minimize} & P \\ \text{subject to} & (I - QG)P = b \\ & P_{min} \preceq P \preceq P_{max} \end{array} \tag{5.32}$$

There may then be a feedback loop between (5.32) and (5.31) altering s according to requirements for outage probability, power allocation, or traffic maximisation.

5.2 Results

The results presented in this section compare the congestion based routing explained in Chapter 4 with the DCA outlined in this chapter. All results are for the square scenario described in Chapter 4, a processing gain of 12.9 dB, a bandwidth of 2048kHz, user centred network allocation, and a required signal to noise ratio of 3dB. The throughput is calculated for all users maintaining the same data rate, whilst maximizing this data rate by stacking transmissions. The limiting factor is that no user may exceed the maximum transmit power with its required overall transmit power.

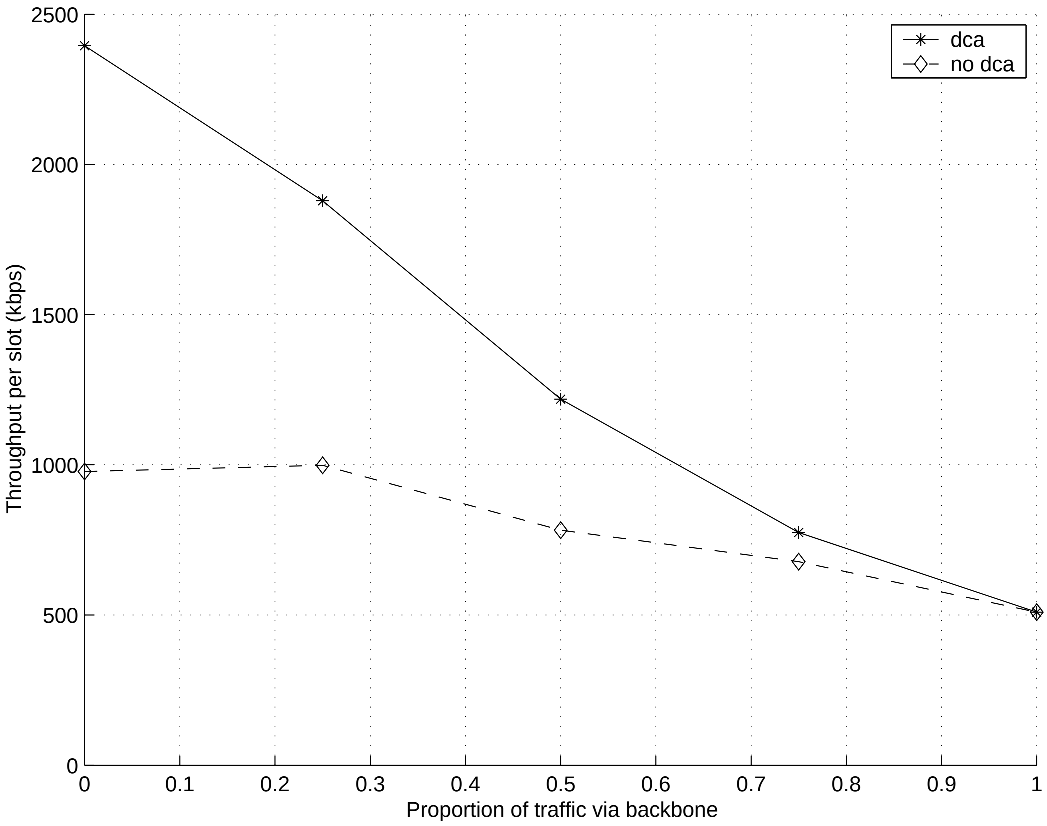

Figure 5.2: *Throughput against proportion of traffic via backbone for 8 timeslots, 28 active users, and 12.9dB processing gain*

The results showing the performance of the DCA compared to the non DCA congestion based routing are shown in Figure 5.2. These results use a system with 8 separate time slots available to 28 users. It can be seen that the throughput of the DCA based routing outperforms the non-DCA based routing in every situation, except where all traffic is routed via the BS. In this case the throughput is limited by the pole capacity of the BS. In Chapter 4 this non DCA based routing is shown to have the highest capacity of all the non DCA systems investigated. The performance gain of the DCA increases as the proportion of ad hoc traffic increases. For entirely ad hoc traffic there is about 140% increase over the congestion based routing, and while not shown, there is almost a 10 fold increase over a non relaying star topology (where 2 links are required for in cell communication). This increase can be entirely attributed to resource reuse and interference avoidance inherent in the minimization problem of (5.31).

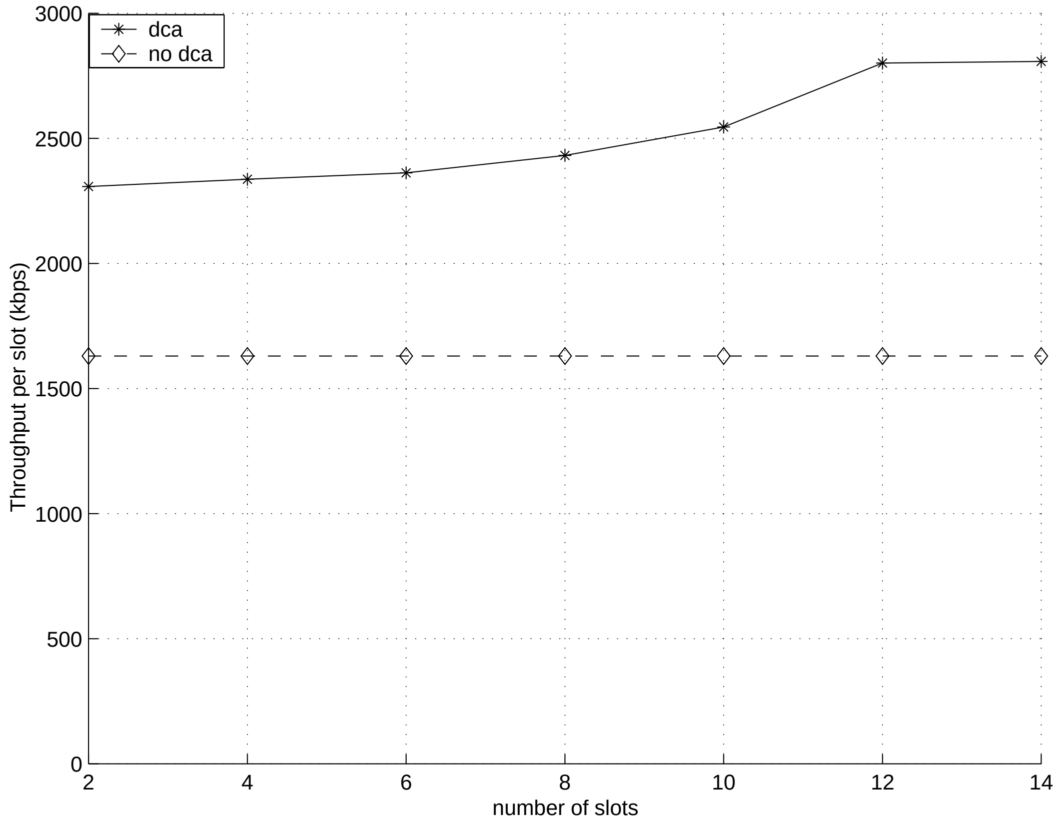

Figure 5.3: *Throughput against number of number of timeslots for 28 active users and 12.9dB processing gain*

Results for different numbers of timeslots available to the DCA are shown in Figure 5.3. This corresponds to the number of H terms in (5.21). It can be seen that the non DCA system is not able to exploit an increased number of timeslots. This is due to the arbitrary time slot allocation of this routing algorithm outlined in 3.4.1. As would be expected for the DCA, extra timeslots allow for an increase in throughput, with about a 20% increase per slot by going from 2 to 12 slots. After this point there does not seem to be any considerable increase in throughput. The most significant increase in throughput with number of slots occurs just before this plateau. It would seem reasonable to assume that the increased throughput is generated by the DCA having more options / flexibility in reducing congestion with an increased number of time slots. It is interesting to note that the DCA performs almost as well with 2 slots as with 6, which could either be taken as the 2 slot case coping well or the 6 slot not taking full advantage of the flexibility due to the compromises made in (5.31).

The results in Figure 5.4 show throughput against number of users, again with 8 time slots.

For the non DCA routing it can be seen that the increase in user numbers causes a reduction in the available throughput. This is considered to be due to the extra terms not controlled to the same point introduced into the power control problem, and subsequent increased interference. Moving from 20 to 24 users the DCA system also suffers this drop in throughput. After this point, however, an increase in throughput occurs. It is likely that there is a balance between number of active links creating interference, and the number of different available links allowing for more routing opportunities. The DCA seems more able than the non DCA based routing to exploit these opportunities and thus utilise the increased number of active users in its favour.

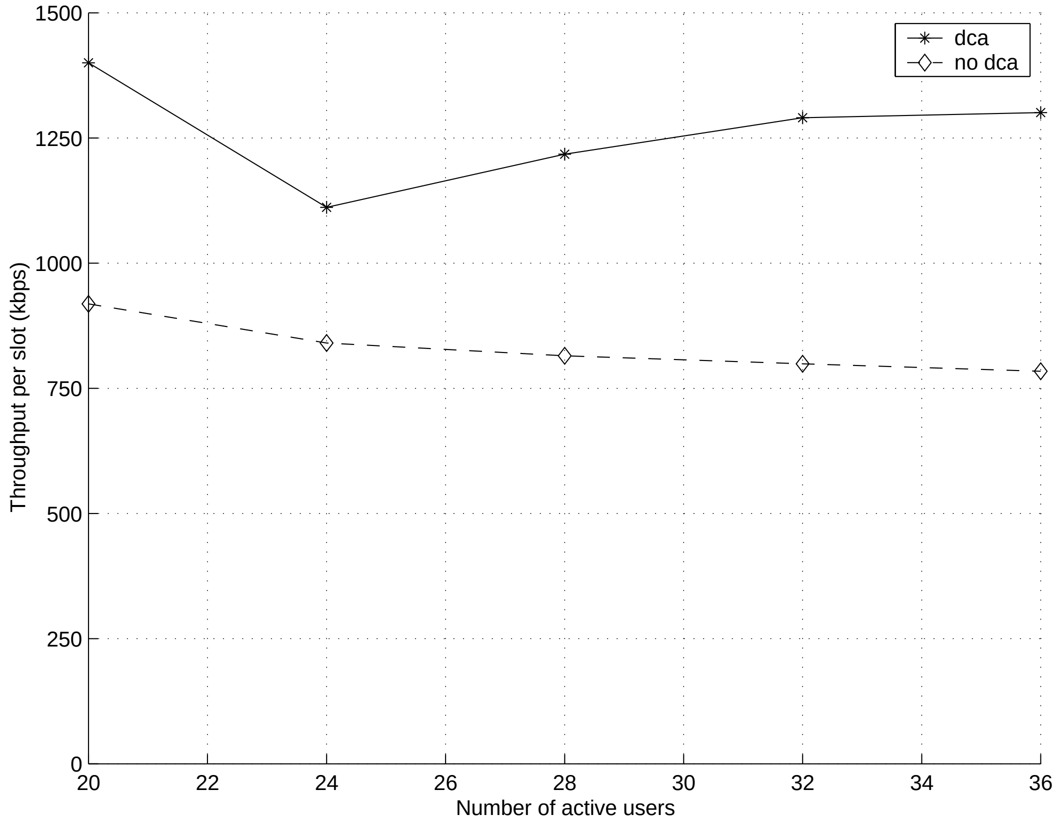

Figure 5.4: *Throughput against number of number active users for 8 timeslots, and 12.9dB processing gain*

5.3 Conclusions

A novel DCA algorithm has been developed exploiting the novel congestion based routing from chapter 4. Simultaneous routing and resource allocation was formulated for TDD-CDMA.

Specifically, time slot allocation has been performed in a novel manner, that produces specific sequential allocation in the same order as required for relaying.

The novel formulation of the time slot matrix, with discrete allocation for each slot enables the minimisation of a congestion measure, through combined routing and time slot allocation, in order of hop. This allocation reduces delay and terminal complexity, and ensures a feasible relaying configuration. The matrix structure, in addition to performing time slot allocation and routing, enables the selection of any BS for optimal relaying hand-over, according to congestion.

A congestion measure was presented that is suitable for minimisation though interior point methods, which find a global solution. This formulation requires an initial partitioning of relaying nodes, and a final phase of power allocation. Another formulation was presented, that whilst unsuitable for minimisation with current interior point methods, requires no pre-partitioning, integrates power allocation for maximum C/I, and should further improve performance beyond the interior point compatible version.

Results for the multi-stage DCA showed increased throughput compared to the non-DCA congestion based routing, except when all traffic is routed via the BS, where performance is identical. For entirely peer-to-peer traffic, throughput was shown to increase by 140% over the best non-DCA routing, and by almost 1000% over a non-relaying system. Increasing the number of time slots considered in the allocation improves throughput, at the cost of computational complexity. Furthermore, the increased opportunity provided by a higher number of active users was exploited by the DCA. Other routing approaches in this thesis had actually shown slightly impaired performance for an increased numbers of users, through failure to mitigate the increased number of interference sources.

Chapter 6
Conclusions

6.1 Summary

Two key issues facing wireless communications may be addressed by breaking communications links into multiple hops. These are increasing the capacity of the expensive and limited radio spectrum, and the entangled problem of reducing required transmitted power. Code division multiple access (CDMA) potentially provides the most efficient frequency re-use, through the cellular concept, of current access technologies. The main factor reducing the capacity of CDMA is interference from from other users. Multi-hop relaying of the communications signal may be able to reduce the required transmitted power, hence overall levels of interference. This may lead to increased capacity through greater frequency re-use and lower received interference. There may also be the added benefit that users should see a more consistent service, even when there may be poor or no coverage with a conventional system. At the initiation of this thesis, little investigation had been made into the combination of relaying and CDMA. Therefore is was considered that this partnership should be examined as to whether it could provide capacity and power gains.

Time division duplex (TDD) is a technique that permits variable levels of traffic asymmetry, necessary for efficient use of bandwidth in many data based applications. TDD was also shown to be a cost efficient method of implementing relaying in combination with CDMA. Power control methods were discussed as a means of achieving the signal to noise ratios required at a receiver, reduce transmitted power levels, and as a method of BS hand-over. Several existing routing algorithms are discussed, generally falling into two categories, table driven and on-demand, according required routing overheads. These algorithms have different goals, including minimising number of hops, minimising overhead, adapting to high mobility, robustness, and maximising battery life, but, in general, are not specific to radio access method.

The interference and coverage properties of opportunity driven multiple access (ODMA), a relaying system included in early drafts of UTRA-TDD, were analysed in chapter 3. The routing protocol is based on minimising overall path loss. Using a single cell, local connectivity, and the ETSI indoor office path loss model, ODMA was shown to produce a reduced level of interference compared to a conventional CDMA system. The greatest level of interference, hence relaying bottleneck, was generally found to be at the last hop before the BS. Additionally, taking shadowing into consideration, the conventional system showed an increased level of interference. Interestingly, relaying showed a further reduction in interference for some high shadowing scenarios. The likely mechanism for this was that, as well as the problematic higher path losses, zero mean log-normal shadowing also creates lower path losses. These will be inherently selected by a routing algorithm using a minimum path loss metric. A correlated shadowing model was shown to produce the same effect, though slight differences in the interference contour were found. The results from the more realistic model, with correlation between shadowing variables for distance and angle of arrival, ensured that the phenomena was due to relaying, as opposed to the model. Through further simulations, imposing a maximum transmit power, relaying was shown to extend cellular coverage far beyond the that of a conventional TDD system. As the number of users available for relaying increased, the coverage of the ODMA cell was also found to increase. Reducing the number of allowed calls was shown to extend coverage by a factor far greater than the conventional coverage-capacity trade-off [15]. A relaxed probability of outage requirement, especially with a lower number of supported calls, further extended coverage by a factor greater than that for a single transmission. This probability of outage was shared between all users, not just those outside the transmission radius limit of the non-relaying system.

In chapter 4 several novel routing algorithms were developed and analysed in conjunction with a novel network topology designed to exploit one of the novel findings of chapter 3, namely that, with all calls going via the BS, the limiting relaying hop is next to the BS. This new topology allows users to communicate without the use of a BS if they fall within a specific region. It was shown that the path loss routing employed by UTRA-TDD ODMA was unable to exploit the new topology. Consequently, a novel routing algorithm based upon iteratively minimising interference was developed in an attempt to improve system capacity. A novel admission control was presented, based on predicting whether the power control would converge. If the power control will not converge, or the solution is deemed to require powers higher than the maximum permitted, the route causing the greatest interference contribution is removed. When implemented centrally using a maximum of 2 hops, these algorithms were shown to increase system capacity beyond that of a non-relaying system when the amount of peer-to-peer traffic equaled or exceeded that of calls via the BS. Neither the distributed version, or a 6 hop maximum implementation of this algorithm achieved similar performance gains. Whilst 2 hop, centralised, interference routing improved capacity in some circumstances, the potential reduction in transmitted power was not realised. Consequently, a novel routing algorithm, based on a congestion measure, was developed and analysed. The congestion measure is related to the power control solution for maximum carrier to interference ratio. Attempting to minimise this congestion measure, through trellis routing, produced the lowest required transmitted power of all relaying and non-relaying systems. When a maximum of more than two hops was allowed, the congestion based routing showed the highest capacity of all the techniques.

Finally, a novel dynamic channel allocation (DCA) algorithm was developed that exploited the congestion based routing from chapter 4. The algorithm took a similar approach to a previous algorithm to perform simultaneous routing and resource allocation for FDMA and TDMA relaying [127]. It was reformulated for TDD-CDMA, and enhanced to explicitly specify time slot allocation. The algorithm minimises a congestion measure, through combined routing and allocation of sequential time slots, in order of hop. This allocation reduces delay and terminal complexity, and ensures a feasible relaying configuration. A novel matrix structure was developed that performs time slot allocation, and enables the selection of any BS for optimal relaying hand-over, according to congestion. A congestion measure is presented that is suitable for minimisation though interior point methods, which find a global solution. This formulation requires an initial partitioning of relaying nodes, and a final phase of power allocation. Another formulation was presented, that whilst unsuitable for minimisation with current interior point methods, requires no pre-partitioning, integrates power allocation for maximum C/I, and should further improve performance beyond the interior point compatible version. Results for the multi-stage DCA showed increased throughput compared to the non-DCA congestion based routing, except when all traffic is routed via the BS, where performance is identical. For entirely peer-to-peer traffic, throughput was shown to increase by 140% over the best non-DCA routing, and by almost 1000% over a non-relaying system. Increasing the number of time slots considered in the allocation improves throughput, at the cost of computational complexity. Furthermore, the increased opportunity provided by a higher number of active users was exploited by the DCA. Other routing approaches in this thesis had actually shown slightly impaired performance for an increased numbers of users, through failure to mitigate the increased number of interference sources.

6.2 Conclusions

Relaying has the potential to reduce transmitted power and subsequent interference in a TDD-CDMA system though breaking communications into a series of hops. A relaying system is able to further reduce transmitted power in a high shadowing environment, whereas non-relaying systems experience a higher mean transmitted power requirement. A conventional cellular approach, however, prevents capacity gains due to reduced interference, as all traffic must be routed through the BS. This produces the same, or marginally reduced, capacity as a non-relaying system, unless comparison is made with a non-relaying cellular system suffering from capacity reduction due to a large coverage requirement. In this case the relaying system can show a higher number of supported users.

A network topology where traffic may be routed between users, without requiring the BS to take part in all calls, may avoid the capacity limits resulting from all calls routing via a single transceiver. Routing based purely upon minimising path loss is unable to achieve these potential capacity gains. A novel routing algorithm based upon iteratively minimising interference was presented. This was shown to increase capacity with the novel topology when at least 50% of traffic is in-cell, but does not reduce the mean transmitted power requirement.

A congestion measure, based upon the dominant eigenvalue of the path loss matrix, relates to the power control solution for maximum C/I ratio via the associated eigenvector. Routing using this eigenvalue as a metric was shown to reduce the mean required transmitted power below that of any other TDD-CDMA based relaying system, for the simulated scenarios. When the number of permitted hops is greater than 2 and there is some local traffic, allows the greatest number of users for a system without intelligent time slot allocation.

Integrating time slot allocation into the minimisation of the congestion measure, as a form of DCA, allowed another dimension in which to optimise routing. Time slot allocation can be an effective method of further mitigating interference. The ad-hoc nature of the proposed topologies mean that we cannot guarantee power control feasibility for a particular number of users, if all they are simultaneously involved in calls. Combined congestion routing and time slot allocation is an efficient method of grouping power vectors into a feasible set for each allocation unit. Consequently, the technique was shown to improve throughput beyond that of any other analysed TDD-CDMA relaying approach, apart from when it was limited by capacity of a single node. For applications where data does not require forwarding to another network, the congestion based DCA was shown improve throughput by almost 10 times that of a non-relaying system.

6.3 Limitations and future work

Throughout the research presented in this thesis, certain assumptions were necessary to allow its completion. Within a communications system there are a large number of parameters that are either a part of its specification, or properties of its users and the environment. All the results relied upon the ETSI indoor office path loss model, apart from when a correlated shadowing model was introduced to corroborate a result in chapter 3. The mean and variance of the variables contained in the path loss matrix are determined by the model, user distribution, and cellular size. The use of a different model or real world data, and subsequent change in statistics is likely to affect the gains achievable with a relaying system. System parameters such as processing gain or maximum transmitted power also affect results, but it is not possible to examine all possible combinations of such variables. The consequence is that the conclusions presented cannot be generalised to every possible situation.

All the scenarios examined in this work had a static user population. Mobility between users will cause changes in the path loss matrix resulting in imperfections in received power, unless the rate of change is able to be tracked by the power control. More importantly, routing based upon data that has changed is likely to show impaired performance. Additionally, it is likely that users may become unavailable for routing, and so the system needs to be able to cope with these broken links. The amount of overhead information required to cope with system changes is related to the rate of change, hence the level of mobility may severely impact upon potential capacity gains. As the overhead is related to mobility, it was not included in static system throughput calculations. Although the trade-off between mobility and overhead requirement has been investigated for some relaying systems, the impact of mobility upon the various algorithms presented for TDD-CDMA is currently an area for investigation.

An important area of study within the area of CDMA is the structure of receivers. In this thesis, the signals from other users were considered as Gaussian interference, as is the case for a simple receiver. This approach was taken for simplicity and as an extension of the concept of TDD-CDMA terminals as low complexity units. It is likely, however, that future advances will reduce advanced receiver cost and complexity. Detectors using approaches such as minimum mean square error (MMSE) and successive interference cancellation improve system performance for non-relaying CDMA systems beyond the presented non-relaying results. The impact of these receiver structures will affect the relaying performance, but the nature of this impact is an area for research. As the congestion measure is also based upon the notion of Gaussian interference, a reformulation according to the effective C/I for a particular receiver is likely to improve performance. Similarly, the choice of spreading codes is not considered. Intelligent code choice may be able to further mitigate interference. Indeed, the addition of time diversity employed by the DCA in Chapter 5 may be extended to include diversity in frequency and codes to further improve system performance. Previous work has shown that a time-slot opposing algorithm can be used to mitigate TDD-CDMA interference [34]. This approach may also be considered for integration into the DCA routing algorithm.

The original formulation of simultaneous routing and resource allocation for FDMA and TDMA included an analysis of the dual problem as a means to optimise the algorithm. This approach with regard to TDD-CDMA is an area for future research. Additionally, the DCA is formulated to minimise a congestion measure. It is possible to reformulate the problem to optimise system parameters such as throughput, transmitted power or QoS, if power control feasibility is included as a condition. This may allow for resource allocation more suited to an operator's requirements.

The work in this thesis focuses on relaying for mobile communications. Several systems currently under investigation such as sensor arrays and 'spray-on' computers are fields that require communications between a number of discrete nodes. As such, it is possible that they will be able to benefit from the relaying concept.

As a part of this work, distributed algorithms were developed concurrently with the centralised algorithms. Unfortunately, none of them were able to realise the gains produced by their centralised relations. It has been shown for non-relaying systems that techniques such as combined power control and cell-site selection, and DCA are able to achieve identical performance with distributed and centralised approaches. An added complexity of relaying is that it difficult to predict how re-routing will affect the system if there is more than one hop beyond the node being selected. This issue is an important area for future work if successful distributed multi-hop algorithms are to be developed. One of the motivations for a distributed algorithm is that all the required parameters of an entire system do not need to be communicated to a central decision making device. The DCA algorithm, and several of the other routing algorithms require knowledge of the path loss matrix for the entire system. When there are many users this may be a prohibitively large overhead requirement. To reduce this overhead, future work may investigate the consequences of implementing the algorithms with a partial path loss matrix.

The concept of relaying enables a greater number of communications link permutations than has previously been possible in TDD-CDMA. Routes selected without consideration for the whole may only serve to diminish resource utilisation. It has been demonstrated, however, that configurations may be chosen which dramatically improve system performance beyond that of a non-relaying system.

Appendix A
Publications

- T. Rouse, S. McLaughlin, and H. Haas, “Coverage-capacity analysis of Opportunity Driven Multiple Access in UTRA TDD”, Proceedings of the IEE International Conference on 3G Mobile Communication Technologies (IEE 3G 2001)”, (London, UK), pp. 252-256, IEE, 26-28 March 2001

- T. Rouse, S. McLaughlin, and I. Band, “Capacity and power investigation of multi-hop relaying networks in TDD-CDMA based systems”, Proceedings of the IEEE International Conference on Communications (ICC 2002), (New York, USA), 5 pages in CD-ROM, IEEE, 28 April-2 May 2002

COVERAGE-CAPACITY ANALYSIS OF OPPORTUNITY DRIVEN MULTIPLE ACCESS (ODMA) IN UTRA TDD

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Abstract - **The multi-hop, ad-hoc wireless networks of ODMA can be shown to reduce overall transmission power compared with single hop transmission, however, for simple receivers and low user density, the actual capacity of UTRA TDD may be marginally reduced from the maximum non-relaying capacity. This paper analyses the capacity of ODMA in relation to the coverage of a cell. It is shown that after the coverage limit of non-ODMA UTRA TDD has been reached, ODMA will provide enhanced coverage. As the number of calls and/or quality of service is decreased the cell coverage can be increased beyond conventional coverage-capacity trade-offs, allowing operators a far greater degree of flexibility.**

I. INTRODUCTION

Unlike the implications of its name, Opportunity Driven Multiple Access (ODMA) is not a true multiple access technique. It is a relaying protocol potentially providing benefits such as reduction of transmission power, overcoming dead spots, and a decrease in, and more even distribution of interference.

The basic principle of ODMA is that compared to the conventional approach, where a Mobile Station (MS) in a cell communicates directly with the Base Station (BS), or vice versa, in a single line of sight transmission, it is more efficient to break the path into smaller hops, as shown in Fig 1. This is achieved by making use of other MS in the cell to relay the signal. The optimal routing is calculated using intelligence in the MS and BS to try and achieve the minimum total path loss for the transmission.

The UTRA-TDD standard includes provision for ODMA [1], as a modification of a Patent by Salbu Pty. Ltd. [2] although the implementation is currently far from finalised.

It has been shown by Harrold and Nix [3,4] that a relaying system with distributed intelligence can show an average reduction of 21dB in required transmission power or increased coverage [3], and that under certain circumstances, with a sufficient density of relaying users there may be a capacity enhancement over conventional TDD [4].

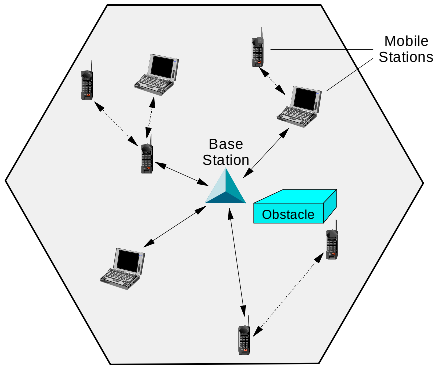

Fig 1: ODMA scenario showing routing with path broken into shorter links, and avoiding shadowing.

The purpose of this paper is to analyse the capacity-coverage trade-off within ODMA in comparison to a conventional TDD system. The connectivity of ODMA is sufficiently different to traditional CDMA MS-BS communication that it is not reasonable to use the conclusion of Veeravalli and Sendonaris [5] that for a maximum transmission power the coverage of a cell is inversely proportional to the number of users. This information may allow for a coverage based admission control. As it is likely that the greatest bottleneck in an ODMA relay link will be the final MS-BS hop, it may be advantageous to allow cell breathing, or dynamic cell geometry through BS assignment. This would provide for a more even loading of BSs, optimising system requirements.

II. THEORETICAL ODMA PERFORMANCE

Capacity and Interference

As a user may relay any other, the ODMA cell can be considered as a network of pico cells, the effective BS in each case being the relaying MS. If the interference is assumed to be Gaussian the bit energy to interference ratio, ε_j, for each node can therefore be considered as

$$\varepsilon_j = \frac{pgPu_j}{\sum_{i:i\neq j}^{M}\sum_{k=1}^{H_i} Pu_{ik} + I + N} \qquad (1)$$

where *pg* is the processing gain, Pu_j is the received strength of the desired signal, M is the number of calls in the cell, H_i the number of hops for user *i*, Pu_{ik} the power at node *j* from the route for user *i*, hop *k*, *I* other cell interference and *N* thermal noise.

Thus the link for each user is limited by the lowest value of ε_j on route. This means that interference throughout the cell affects the uplink, not just at the 'real' BS. In the majority of cases, however, the most problematic link is the final hop to the BS. This is due to power warfare occurring when there is heavy cell loading. MS nodes do not suffer too severely from this issue as they will normally only relay a fraction of the total number of users, whereas everyone has to route to the BS, unless the target MS is in the same cell.

By splitting the interference into intra-cell interference, I_{ODMA}, corresponding to interference at the BS due to in-cell MS-MS transmissions, and adjacent cell interference, I_{ad}, the received bit energy to noise for each user with perfect power control at the BS for the uplink can be reformulated from (1)

$$\varepsilon_j = \frac{pgP_u}{P_u(M-1) + I_{ODMA} + I_{ad} + N} \qquad (2)$$

where M is the number of users transmitting directly to the BS, and P_u the received power at the BS. If pg is constant for all links, i.e. calls are not aggregated together as two or more calls at a higher data rate and all users are transmitting at the same rate, it can be seen that M is an upper limit on links / timeslot for calls involving an uplink to the BS. Rearranging with respect to the number of users, M

$$M = \frac{pg}{\varepsilon_j} - \frac{I_{ODMA} + I_{ad} + N}{P_u} + 1 \qquad (3)$$

In comparison with the pole capacity for a CDMA system from (4)

$$M_{MAX} = \frac{pg}{\varepsilon_j} + 1 \qquad (4)$$

It can be seen that the only variables we have control over that limit the number of users that can route to the BS are I_{ODMA} and P_u. This means that if the limiting interference at the relaying nodes is linearly related to the transmission of the M users we can mitigate the effects of adjacent-cell interference and receiver noise but the reduction in capacity due to I_{ODMA} cannot be minimised by increasing P_u, as this will result in a corresponding increase in I_{ODMA}. There is, however, more scope for optimising P_u as the effective reduction is cell size for MS-BS transmissions mean that the average MS-BS path loss is reduced, hence outage due to maximum transmit power being reached will be lower.

I_{ODMA} is dependent in several factors, including shadowing, routing, power control and call admission. The routing in conjunction with shadowing will determine the relationship between P_u and I_{ODMA}. The number of hops per link is a balance between minimising transmission power, as discussed in the next section, and the number of interferers, albeit at a lower transmit power. Power control in conjunction with call admission is a trade off between the benefit of reduced transmission power, and increasing capacity by increasing power.

It is important to note that the above equations only hold for single user detectors where the interference from other users is Gaussian distributed. Multi-user detection and selective use of spreading codes invalidates the assumption of Gaussian distributed interference. Indeed with a more sophisticated receiver, I_{ODMA} could be used as a form of antenna diversity, actually improving system capacity.

Transmission Power

One of the main cited benefits for ODMA is the reduction of transmission power for a link. This is achieved by splitting the transmission into a series of hops using other MS as relays. The transmission power is reduced due to the non-linear nature of path loss, as shown in Fig.2. The gain shown is the reduction in overall path loss over a single transmission. The path loss model is of the form (without shadowing),

$$L(dB) = k_1 + k_2 \log_{10} d \qquad (5)$$

where k_1 is a constant loss, and k_2 the path loss exponent, and d the transmission distance in m. The larger the path loss exponent, the greater the potential gains. Linear path loss would not show any gains for relaying. The gains are the maximum available for the non-shadowing scenario, with MSs spaced equidistantly along the line of sight path from the MS 100m from the BS.

It can be seen that gains of almost 30 dB can be achieved in the vehicular model, and 15 dB typical for the indoor model. Although the overall transmission power is reduced, this lower burden is shared between users not directly involved in the call.

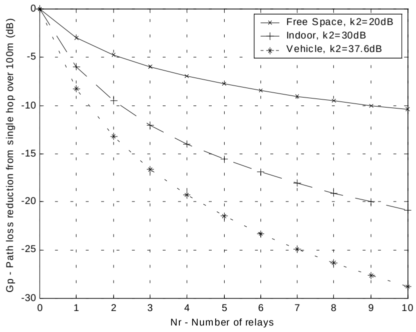

Fig 2: Path loss reduction against number of relays for 100m transmission.

A possible approach to sharing of resources is to allow mobiles that are transmitting in other time slots to be viable relays, for example in a UTRA-TDD context with each user transmitting one slot per frame on average. This would allow a routing pool 15 times the size of available calls per slot, and remove the need to run down the batteries of users not making calls. A potential drawback is that users near the BS may experience a higher power requirement than with a conventional system, but this should be contrasted with the overall reduced power / call requirement, and a more predictable and consistent power usage. Meaning that on average everyone should benefit.

III. ROUTING STRATEGY

The original patent [2] describes a basic routing strategy. First a neighbour list is built up, this can be either from listening to other mobiles or by probing. The latter is a request for information from surrounding mobiles. A request is sent out for identity and quality of received signal (path loss, noise level). There is no ability to tell if the transmission is going in the optimal direction, the strategy is to transmit to the MS with the best signal quality that has communicated with the BS. Some power reduction seems to be the only requirement, but it is suggested that the route will be known up to three hops ahead.

The proposals to Delta concept group [6] add to this basic idea in relation to UMTS. The neighbour list is required to contain at least five entries. If this is not met after transmitting at the lowest power and highest data rate the power is increased. If the condition is still not met at maximum power, the next lowest data rate is used and the power reset to a minimum, and so on. This adaptation also works if the neighbour list is too large. The routing is addressed by two connectivity types. Local connectivity is available up to two hops away, with all path loss and noise information available to the MS, and a link budget analysis is made to minimise transmission power. End to end connectivity is used for more than two hops, using an origin and destination ID. There is a ‘time to die’ criterion after which the packet is deleted, so delay time is considered in the routing algorithm for this mode.

The basic intention of all previous routing algorithms is to minimise the mean transmitted power along the route, although this is often implemented by minimising path loss. The main difficulty is to make the correct decision whilst achieving a minimum of network overhead.

IV. UTRA TDD ODMA

UTRA TDD uses only short non-orthogonal spreading codes, the longest being length 16, corresponding to 16 kbps [7]. From the limit of the pole capacity [5] the small processing gain limits the number of users that may be routed through a node, and ultimately to the BS. There is no explicit routing algorithm in [1]. The routing strategies discussed previously in combination with the ODMA principles indicates the following requirements:

(1) optimise node loading according to pole capacity,
(2) minimise overall transmission power,
(3) minimise interference at nodes.

TDD allows diversity in time, however, optimising this allocation is beyond the scope of this paper. The initial step for routing is to assess the path loss to and interference at other MS. This is achieved by probing neighbours. The description of probing is probably the most complete part of the standard [1], it consists of several modes designed to get an initial neighbour list and then keep updated with a minimum of interference.

UTRA-TDD is low mobility due to the open loop power control’s time constant being governed by the slot length. Its advantages include terminal simplicity, and asymmetric uplink and downlink bandwidth through timeslot allocation. This indicates possible uses for LANs, or other data transfer such as mobile IP.

V. SIMULATION MODEL

Considering UTRA-TDD’s suitability for low mobility data use, the path loss model for the indoor office test environment is used [8],

$$L(dB) = 37 + 30\log_{10} d + 18.3 n^{((n+2)/(n+1)-0.46)} + \xi \,. \qquad (6)$$

TABLE 1–UTRA-ODMA-TDD simulation parameters

Parameter	Value
Maximum transmit power	10 dBm
Target E_b/I_0 at MS	5 dBm
Target E_b/I_0 at BS	2 dBm
Logn. Standard deviation, σ	5 dB
Noise figure (receiver)	5 dB
Bit rate	16 kbps

where d is the transmission distance in m, n is the number of floors in the path, n=3 for this simulation. ξ is lognormal shadowing in dB, with a standard deviation of σ and a zero mean. A correlated shadowing co-efficient is used, as it is considered that due to the path diversity available in ODMA, non-correlated shadowing could produce over optimistic results, with low shadow paths available in all areas of the cell.

The simulation is performed in a single cell with MS distributed in a random fashion with a uniform distribution. It is considered that joint detection is available to the BS but not to the MS due to complexity. This is modelled by different target signal to interference ratios at the respective targets.

The routing is allocated according to the minimum path loss, and more than 1 call/route is provided by increasing the data rate with a lower processing gain. Time slots are allocated such that final hop to the BS will not clash with an uplink transmission, that is it will be in a slot allocated for the downlink as for non-ODMA TDD

Power control is implemented as a simple step based increment if the desired signal to interference ratio is not achieved at the receiver. A link is in outage if the maximum transmit power is reached at any stage in a link. This is not the optimal method for power control / call admission as capacity may be increased by more selective pruning, however, the intention is to model a simple distributed algorithm. Monte-Carlo analysis is applied to assess the capacity.

VI. RESULTS

Fig. 3 shows the average number of supported calls for each timeslot in the TDD frame. Until the cell size reaches 30m the conventional TDD system achieves greater capacity. This is due to the combination of I_{ODMA} and the simple receiver architecture, where all received signals must be at the same power for optimum capacity. At 30m all systems are equivalent. After this point the non-relaying system quickly loses the ability to reliably support calls, this is due to many of the MS lying in a region where the path loss is too great for the signal to reach the BS with the required signal to interference ratio above the receiver noise.

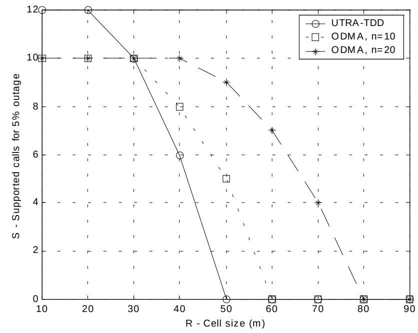

Fig. 3 Supported number of users per time slot against the coverage of the cell, for less than 5% outage, n is the number of users available for routing

Reducing the target number of calls allows for a small increase in the coverage but ultimately the MS cannot increase their power enough.

The ODMA scenario where the number of calls is initially the same as the number of users available for routing offers a gain in capacity of 2 users at 40m and will support 5 users when the conventional system cannot cover that radius. When the number of users available for routing is double the initial limit for call admission the capacity is conserved until 40m and almost full capacity is offered when the conventional system has failed. After this point a reliable system is available for another 30m for an albeit reduced number of users.

Fig. 4 shows the probability of outage for different numbers of allowed calls against the coverage of the cell. For the conventional system once outage starts to occur the gradient is such that the number of dropped calls is too great for service to be maintained, this corresponds to users outside a particular radius getting no service. As the number of allowed calls for ODMA is decreased, not only does the coverage increase for a particular probability of outage, the gradient of the curve decreases. For the 4 user case there is a 4% probability of outage in a 70m cell. Coverage is still available, however, at 90m with a 16% probability of outage, much less than the 40% outage for the greater area in the conventional scenario, i.e. in the conventional scenario all MS between 70 and 90m would be in outage.

IV. CONCLUSIONS

Through the use of multi-hop transmissions, ODMA will extend the coverage of a cell, but only after the cell size is large enough to prevent a comparable single hop system from achieving its maximum capacity.

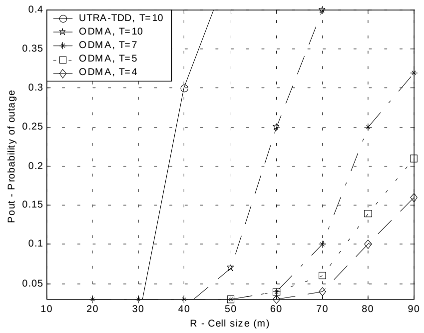

Fig.4 Probability of outage against the coverage of the cell, for different numbers of allowed calls, T, with 20 users available for routing.

When coverage is a more important criterion than capacity ODMA will provide a reliable service far beyond the coverage of a conventional TDD system.

As the number of users available for relaying increases, the coverage of the ODMA cell increases, and the gradient for coverage-capacity decreases. Reducing the number of allowed calls means that ODMA can provide a reliable service for an area greater than the normal capacity-coverage trade-off. By allowing a reduced quality of service the operator can further extend coverage, the outage being shared between all users, not just those outside the transmission radius limit of the non-relaying system. For unevenly loaded adjoining cells, ODMA could be used to even out the loading by dynamically changing the cell size.

The use of ODMA will provide operators with a far greater degree of flexibility in cell planning, and to go beyond the conventional trade-off between coverage and capacity.

ACKNOWLEDGEMENT

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Capacity and Power Investigation of Opportunity Driven Multiple Access (ODMA) Networks in TDD-CDMA Based Systems

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***Abstract*-ODMA is a multi-hop relaying routing protocol, the use of which has been investigated in conventional cellular scenarios. This paper compares the performance of ODMA with direct transmission for cases where links maybe required directly to other nodes, as well as to a controlling (back-bone) node. For an interference-limited system, it is shown that whereas the topology is not supportable by a conventional (single-hop) system, a relayed system is able to provide service. A new admission control and routing algorithm based on receiver interference is presented which is shown to further enhance performance.**

I. Introduction

With the wide scale adoption of mobile technology and the continually increasing utilization of networking for productivity, it is likely that future generations of mobile communications devices will be expected to form networks in both local and wide area environments. Many air-interfaces for future mobile communication systems are based on CDMA, which inherently is interference limited. Consequently, to reduce the level of interference, it may be preferable for users to be able to achieve peer-to-peer communications, offloading base station (BS) resources and thus achieve better performance than that offered by a direct link to the BS.

In conventional CDMA systems, the reverse-link, or uplink is power controlled to a single BS in a cell, generally giving the best performance when all users are received at the same power, and the downlink is power controlled to the user with the weakest reception. For mixed traffic, with some users transmitting to receivers in-cell and others via a BS to non-local equipment, perfect power control becomes impossible for all receivers and system performance may be severely degraded.

ODMA is an ad-hoc multi-hop relaying protocol first proposed by Salbu Pty [1], and then considered in a modified form by a concept group for 3GPP. Provision was made in early revisions of the standard [2], although it now appears to have been dropped in order to achieve a finalised standard as a result of concerns over complexity and signalling overhead issues. However, ODMA remains an attractive prospect for future mobile communication systems, due to advantages offered by a reduction in transmission power [3], potentially enhanced coverage and with a greater trade-off possible between Quality of Service (QoS) and capacity in the extended coverage region [4], and under certain circumstances may show increased capacity [5].

II. CDMA Networking

The conventional technique for networking in interference limited systems is a star topology in order to ease the problem of power-control. The topology used in this paper, described in more detail in section III, consists of sources and sinks, with communication targeted outside a cell and routed through a BS, while that within cell is targeted at the desired recipient. Whilst this minimises the number of links for maintaining a cellular paradigm, there is no longer a single point to which the power must be controlled. As there is more than one receiver it is not guaranteed that all the transmissions can be received at the same level by all receivers, and in some cases the interference generated by one user may mean that others close by may not be able to receive the desired signal, no matter how much the source increases power. In these cases it may be better to revert to a star topology, though it must be considered that two calls are now required where one sufficed previously.

Admission Control

With a star topology based CDMA system the number of allowed calls is relatively constant due to the single receiver in the uplink. In an ad-hoc environment, the capacity will vary depending upon the position of users and the links that are required. This means that admission cannot be based simply on the number of calls currently in progress. The technique used in this paper is to start with a desired number of calls and attempt to make all of them. Instead of waiting until the maximum permitted transmit power, in this case set at 10dBm, is reached and the link involving the offending transmitter removed from the current calls, a prediction technique is used. The convergence rate of the power level is used to analyse which receiver suffers the worst interference and then a decision based on a metric to determine which call to terminate.

The power level $p(t)$ for each user is extrapolated by approximating the first and second derivatives by their respective time differences, taken from a running average for

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iteration *i*. The power level at some later iteration, *j*, (when the power control may reasonably be expected to have converged), can then be predicted using a Taylor expansion, as in equation (1) below. If the second derivative is of an opposite sign to the first, the iteration when the power is expected to have converged is predicted to be $j= i–(dp_i/dt)/(d^2p_i/dt^2)$. A modification of this is introduced if the predicted iteration *j* is greater than $(i+100)$. The procedure is repeated for $j=i+100$ instead of the predicted value. This capping of the iteration is also applied when dp/dt and d^2p_i/dt^2 are of the same sign.

$$p_j = p_i + (j-i)\frac{dp_i}{dt} + \frac{d^2 p_i}{dt^2}\sum_{k=1}^{j-i} k \qquad (1)$$

If any of the predicted powers exceed the maximum transmit power the interference is analysed. All of the interference above desired signals from interfering transmissions is summed, and the link with the greatest contribution being removed. After any links are removed, or the routing is changed, the prediction is switched off so that the averaging only takes account of the new situation.

This extrapolation technique has two advantages over a wait and see approach. Convergence of the power control is reached earlier in a system that requires outage for a solution below the maximum transmit power, and the greatest interferers are also removed earlier allowing increased capacity.

III. ODMA

The basic principle of ODMA is that compared to the conventional approach, where a Mobile Station (MS) in a cell communicates directly with the BS, or vice versa, in a single radio-hop, it is more efficient to break the path into a number of smaller radio-hops, by making use of other MS in the cell to relay the signal. The optimal routing is calculated using intelligence in the MS and BS to try and achieve the minimum total path loss for the transmission. In this paper the MSs also utilise relaying to communicate with each other without the use of a BS, a network sometimes referred to in the literature as an ad-hoc network.

Routing protocols

Within the scenarios users are required to communicate either with each other or to achieve a link onto a backbone. The criterion for the local routing is that the target is in the same cell as the transmitter. It is likely that greater capacity would be achieved if the region for local routing were centred instead on the user, however, a simple mechanism for call assignment was selected.

Previous work on ODMA [3-5] uses path loss between terminals in the metric to determine the routing. This is a quick and efficient way to establish routing, however it does not take account of bottlenecks in the system due to interference caused by many users routing through a particular area. Indeed it will encourage bottlenecks as users will all try to route via low path loss regions. In this paper, we also investigate a new algorithm, based on minimising interference [6], so that three network topologies may be investigated and compared.

1)*Direct routing*. If the desired target is within the handover region of a BS the MS transmits directly to the recipient. For calls outside the cell the call goes directly to the BS in the user's cell.

2)*Simple ODMA*. For in-cell calls, the user probes to find the path loss to other nodes, and their path loss to the target. The routing is determined by choosing the route with the minimum path loss overall. For out of cell calls a similar probing is performed, but the target may be any BS. This means that the user may be outside the handover region of the BS that it linked with.

3)*Interference based ODMA*. The initial routing is performed as in 2), but once the power control has had some chance to take account of interference the system is re-routed according to a modified path loss metric. Any interference above the receiver floor plus processing gain at each receiver is added to the matrix of path loss between users. This gives an indication of the necessary transmission power for that link. The re-routing is performed on a route by route basis in order to prevent many users jumping to a low interference route at once and causing instability in the routing. The predictive outage calculation described in section II is suspended until all routes have had the chance to re-route, avoiding unnecessary outage.

IV. Simulation Model

Description of the scenario generator

Software to allow the interactive location and specification of a variety of network components and associated parameters to generate a representative scenario has been developed under MATLAB. In the model, each entity within the network is represented by one or more nodes. These nodes have certain associated features, which may be conveniently grouped into fields of a structure. Those fields common to all nodes are an index to allow node identification, the location of the node with respect to the standard 3D Euclidean co-ordinate system, a field describing the type of object represented and a number of fields containing hierarchical information. These relational fields permit an association of the node with other nodes in the network. Where required, additional fields, e.g. the attenuation of an rf signal by transmission through the obstacle associated with the node may also be specified. In this way, a number of physical objects may be represented, including 0-dimensional (point) objects such as terminals, network nodes and representative point scatterers, and 1-dimensional (edge) objects, obtained by associating two point nodes at the same level in the hierarchy.

Simple polygonal objects may be modelled as a collection of edges, and this technique may be extended to model more complicated structures, such as standard building models [7] or complex building structures specific to individual requirements.

Once a scenario has been defined, a path loss model may be specified. Determination of path loss is performed for both link directions (to allow for FDD transmission or interaction between systems using different frequencies) between all relevant nodes in the network. The determination of which nodes are deemed relevant is achieved through the type field and provides an efficient way to avoid e.g. calculating path losses between the two nodes defining an edge. Lognormal shadowing is also incorporated, with total path loss values lower-bounded by that of free space, as recommended in [7]. The model has two modes of operation, one allowing for the interactive generation of nodes, and the other for offline generation of a number of realisations of a scenario, based on specified statistical parameters of the generation of node positions.

The type field encodes the nature of the object represented, but the routing algorithm may change this parameter, since election of any participating network node to a clusterhead [8] or controlling node, or demoting it to a passive node at the end of a routing chain may be modelled simply by a redesignation of the node's type. In this way, various networking strategies may be evaluated for the same geometrical scenario layout. In addition, various parameters for individual nodes may be specified or changed once a scenario has been generated. As an example, the length of the routing table may be specified for individual nodes, to model the effects of a mixture of complexity capabilities of mobile/fixed terminals. Network traffic characteristics may be controlled by specifying the relative location of the target node with which a given terminal is requesting communication. Three classes of target node are available; the node may be requesting communication with a) an entity outside the considered network (in which case its target is a node connected to some back-bone), b) a node which is 'local', in the sense that the nodes share a controlling node, as determined by path loss, or c) any other node in the network. The proportion of terminals within each class is defined by two parameters $0 \le a1 \le a2 \le 1$. For each terminal, these parameters are used with a uniform random deviate in the range [0,1] to assign traffic class. If no local nodes can be determined for a particular node, then its target is simply set to be its controlling node.

Scenario descriptions

Three scenarios have been chosen for investigation. The first corresponds to a set of four base stations located at the corners of a square, centred at the origin and of side 50m, serving an area 100m by 100m, in which a variable number of mobile terminals are uniformly randomly distributed. The second is a set of seven base stations, with one base station at the origin and the remainder located at the corners of a hexagon of (maximum) radius 50m. In this case, the positions of a variable number of users are uniformly randomly distributed within the hexagons defined by the base station limits. The third consists of a variable number of users within the standard 3G Indoor Office model [7]. This consists of 20 base stations, with the required number of mobile terminals again uniformly randomly located within the office area, but with 85% of the mobiles located within a room and 15% in a corridor. In all scenarios, the mobiles are stationary so that effects due to movement are not considered.

The standard 3GPP indoor office path loss model was chosen for all scenarios, and the lognormal shadowing standard deviation was set at 5dB for the first two scenarios, and 12 dB for the third [7]. Only one floor was considered, so effects due to propagation between floors were not investigated.

V. Results

While three scenarios were investigated; 4 square cells, 7 hex cells, and the 3GPP indoor office, the plots shown are all for the square scenario.

Fig. 1 shows the number of supported calls in all 4 cells for 5% outage against different ratios of local to non-local traffic. The star curve represents the number of supported calls that could be expected for a star topology with either the direct or interference based ODMA. This is calculated for the number of supported calls for all non-local traffic and doubling the number of required calls for local traffic to account for the BS being required to forward the data onwards to the local target. It can be seen that for all cases, except interference based ODMA, at higher ratios of local to non-local traffic the star topology delivers greater capacity. It is important to note that much of the outage is due to the simplistic selection of local targets from BS handover regions. For example, it is very likely that a target will be selected that requires the user to transmit in a path that crosses the BS, inherently creating very high interference at the BS and thus the user may well be put into outage as it is a problem interferer. A more intelligent selection of users available for local traffic would be achieved from making local decisions by the user, based on neighbour lists, however this approach would not be possible for the direct approach without extended signalling complexity. The approach investigated can be considered as a worst case for local routing. Intelligence in the selection of local traffic should reduce outage in all scenarios, meaning

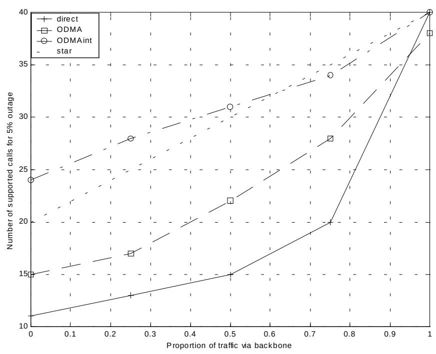

Fig. 1: Number of supported calls for 5% outage for different proportions of local and non-local traffic

that peer-to-peer communication will only be established if it will enhance capacity, power levels, etc.

It can be seen that for the non-relaying scenario that the capacity is about half that which could be expected if a star topology was used, apart from when all traffic is via the backbone when the situation is identical. This is because the use of peer-to-peer communication introduces a power control problem that is highly likely to be not solvable. It is due to users transmitting to other users on the other side of the cell, hence power controlling the peer instead of the BS. This will introduce high interference levels at the BS that cannot be compensated for with power control, as increasing the received power has a feedback effect on the required power to be received at the local target due to the increased interference at that user. The results for the direct transmission indicate that there is no reason to implement the presented local/non-local topology in a conventional CDMA system unless there is a severe problem with coverage.

The path loss based ODMA shows about a 50% improvement over the non-relaying system for all scenarios involving local traffic, however it is still significantly worse than the conventional star topology. The gains arise because ODMA systems generally involve lower transmission power than conventional systems, hence interference problems are more localised so they will not have such a detrimental effect on other users due to feedback in the power control.

Interference based ODMA shows a gain where the local traffic is at least 50% of the total, performing best when all traffic is local. When non-local traffic is dominant it is roughly equivalent to the conventional system. Whereas the path loss based routing does not take account of the congestion due to interference (mainly in the centre of the cell) when routing, the interference based system will avoid these problem areas unless absolutely necessary. This means that transmission, even to the other side of the cell, is possible without destroying desired signals at the BS as the signal is routed to avoid relays in this area. On the downside any ODMA system requires increased complexity both in signalling to establish routing, and in the handset's ability to relay the signal. It also takes longer to establish the routing as the dynamic routing requires the power control to re-converge after each iteration.

As can be seen from Table 1, in all scenarios, the greatest number of users are supported by interference based ODMA. The most dramatic improvement is for the 3GPP scenario as this involves high losses in certain paths due to walls. A non-

	Number of supported users/BS		
	Direct	ODMA	ODMAint
Square, pg=12.9dB	4	5.5	8
Square, pg=15.9dB	5	7.5	11.5
Hex, pg=12.9dB	4.5	6.1	8.5
Hex, pg=15.9dB	6	9	13.5
3GPP, pg=12.9dB	1.5	3	4
3GPP, pg=15.9dB	2	5	6

TABLE 1: Supported users per BS for various scenarios for 1:1 ratio of local to non-local traffic.

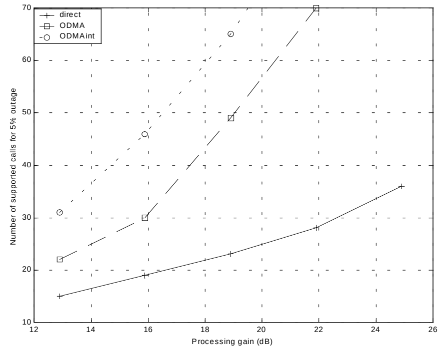

Fig 2: Number of supported calls for 5% outage for various processing gains.

relaying system has no path diversity and is forced to use this transmission path. The relaying system has several choices available to it, and so it is likely that it will be able to avoid these areas of high signal attenuation. In this scenario the wall losses are the dominant problem so path loss and interference based ODMA have similar performance.

Fig. 2 shows the number of supported calls against processing gain for the square cell scenario. The ratio of local to non-local traffic is 1:1. The systems all show a reduced performance than that which could be expected from increasing the processing gain, where it should roughly double and the data rate half for each 3dB increase in the processing gain. This is due to the increased number of users creating greater likelihood of local transmissions thus creating an unsolvable power control. This can be avoided by intelligent local target selection. Both ODMA systems show similar increases in the supported number of users with increasing processing gain, not too far below conventional systems, however the direct routing shows greatly reduced performance with just over double the number of users for 1/16 of the data rate for the lowest processing gain.

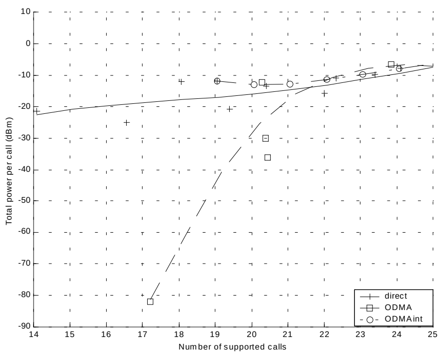

Fig. 3: Total power per call against number of supported calls for all local traffic

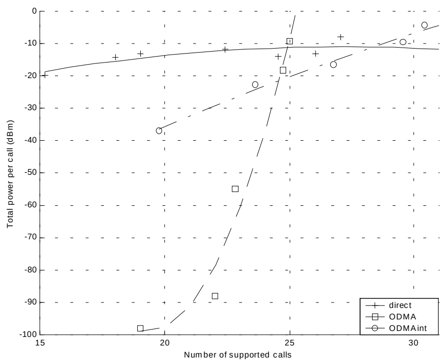

Fig. 4: Total power per call against number of supported calls for 50% local traffic, 50% non-local

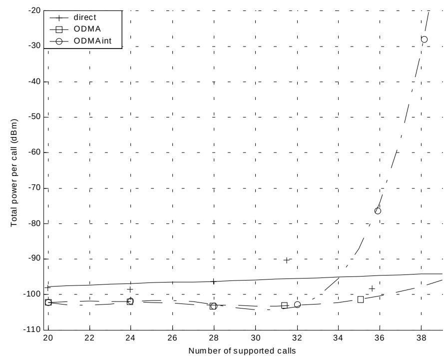

Fig. 5: Total power per call against number of supported calls for all non-local traffic

Figs. 3-5 show the average power levels for the entire call, i.e. for a relaying scenario with two hops, this is the sum of the power for the two links. Fig. 3 shows the situation for all local traffic. Both the direct and interference based ODMA have similar power levels, though it must be considered that the direct system has been required to put far more users into outage, e.g. to achieve 19 calls the interference based ODMA has placed one call into outage where the direct system has removed 13 calls. With the admission control described in section II, this outage will have removed the worst interferers creating a more favourable scenario than the interference based ODMA is experiencing as ODMA is more able to cope without forcing problem users into outage. In Fig. 4, for equal local and non-local traffic, interference based ODMA shows a transmission power reduction over direct transmission for most scenarios. In Fig. 5, with all non-local traffic, the transmission power is much less than the scenarios with local traffic due to power controlling only to one point. The interference based ODMA requires increased transmission power at high user densities as paths are chosen with greater path loss to avoid high interference regions.

In all traffic conditions the simple ODMA produces the lowest power for low user densities, due to some outage of problem users and the reduced transmission power and interference of ODMA. At higher user densities the required power is increased due to the higher number of links used.

VI. Conclusions

In this paper, a network topology has been investigated that allows both peer-to-peer and non-local traffic. We have presented a new admission control that allows congested areas to be identified and problems users to be removed. It has been shown that a conventional CDMA system is unable to produce performance comparable with a star topology. Path loss based ODMA shows a capacity improvement over the non-relaying system and in most cases reduced transmission power. A new ODMA algorithm based on interference is presented that allows for greater capacity than a star topology when scenarios involve at least 50% local traffic and comparable capacity when non-local traffic dominates.

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