EFFECTS OF USER BEHAVIOUR ON GSM AIR INTERFACE PERFORMANCE

By

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Declaration

I hereby declare that this submission is my own work towards the MSc and that to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of another degree of the University, except where due acknowledgement has been made in the text

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Abstract

A model is developed based on the multi-agent paradigm for the study of user behavior and its impact on the blocking probability at the air interface of GSM networks. Aspects of user behavior studied are the flashing phenomenon and the effects of variations mean call duration for a given traffic load per user. The effect of encouraging users to modify their behavior through feedback under high load situations is also studied. The results indicate that both flashing and the increase in call intensity due to reduced mean call duration for a given traffic load per user have a detrimental effect on performance. The use of feedback during period of network congestion was also found to improve performance.

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Abbreviations

AGCH ....Access Grant Channel

AUC ....Authentication Centre

BCCH.............Broadcast Control Channel

BSC ....Base Station Controller

BSS ....Base Station Subsystem

BTS ....Base Transceiver Stations

CCCH.............Common Control Channel

DCCH ....Dedicated Control Channel

EIR ....Equipment Identity Register

FACCH ....Fast Associated Control Channel

FCCH ....Frequency Control Channel

FDD................Frequency Division duplex

GMSC ....Gateway Mobile Services Switching Centre

GSM...............Global System for Mobile Communications

HLR................Home Location Register

IMEI ....International Mobile Equipment Identity

ISC ....International Switching Centre

ISDN ....Integrated Subscriber Digital Network

LA ....Location Area

MS..................Mobile Station

MSC ....Mobile Services Switching Centre

NSS ....Network Switching Subsystem

OMC ....Operation and Monitoring Centre

PCH................Paging Channel

PLMN ....Public Land Mobile Network

PSTN..............Public Switched Telephone Network

RACH ....Random Access Channel

SACCH ....Slow Associated Control Channel

SDCCH ....Standalone Dedicated Control Channel

SCH................Synchronization Channel

SIM ....Subscriber Identity Module

SMS................Short Message Service

TCH................Traffic Channel

TCH/F ....Full Rate Traffic Channel

TCH/H............Half Rate Traffic Channel

TDMA............Time Division Multiple Access

USSD ....Unstructured Supplementary Data

VLR................Visitor Location Register

Dedications

To Modesta Efua Gavor and Harriette Apio for always encouraging me to be my best.

To Alphonse Dzikuni, RIP.

Acknowledgement

First, Thanks must be given to **Mawu**. He, being the one who orders our path in this life. It is He who also blesses us with people who stand behind us to make sure that we follow the path He has laid for us. I would like also to thank the people who stood behind me in this endeavour, **Nana Dr Kwasi Diawuo** – for supervising my work, **Professor Willie Ofosu** – without your contributions I may not have finished this work , and **My course mates** – My inspiration when times got tough.

CHAPTER ONE

1.0 INTRODUCTION

In the introduction to their paper, "Modelling customer redial phenomenon in mobile networks", Tran-Gia and Mandjes [1] state that

"... the Quality of service (QoS) experienced subjectively by individual customers or mobiles is the crucial factor to determine system performance"

They went on further to state that,

"... a proper modeling of customer behaviour is essential in order to gain realistic input for network planning".

QoS is defined by a combination of parameters [2], salient amongst them being;

- Transmission quality (level, crosstalk, echo, etc.)
- Dial-tone delay, and post dial delay
- Grade of service
- Fault incidence and service deficiency

In network planning the aim is to implement a network that achieves a certain level of QoS in an efficient and cost effective manner. The aspects of customer behavior alluded to by the above include, call rate, call holding time and mobility. Some of the QoS parameters mentioned above are directly impacted by these facets of user behaviour. For instance, the grade of service which is the ratio of the number of unsuccessful calls to total number of call attempts during the busy hour [3] is directly impacted by the call rate. Some of these aspects of user behavior have been extensively studied particularly customer mobility and the redial phenomenon. Examples in this regard include the works of Liu et al [4], Camp et al [5], Zimmermann et al [6] and Lin et al [7][8]. Some of the other aspects of user behavior particularly those characteristic of users in Ghana has received significantly less attention. For instance the phenomenon of flashing where users dial a number and hung up after receiving a dial tone receives very little discussion beyond its definition in literature.

A general diagram of traffic in relation to the telephone network is given in Figure 1-1[9]. The traffic demand is not fixed. Variations arise due to factors such as time of day and season.

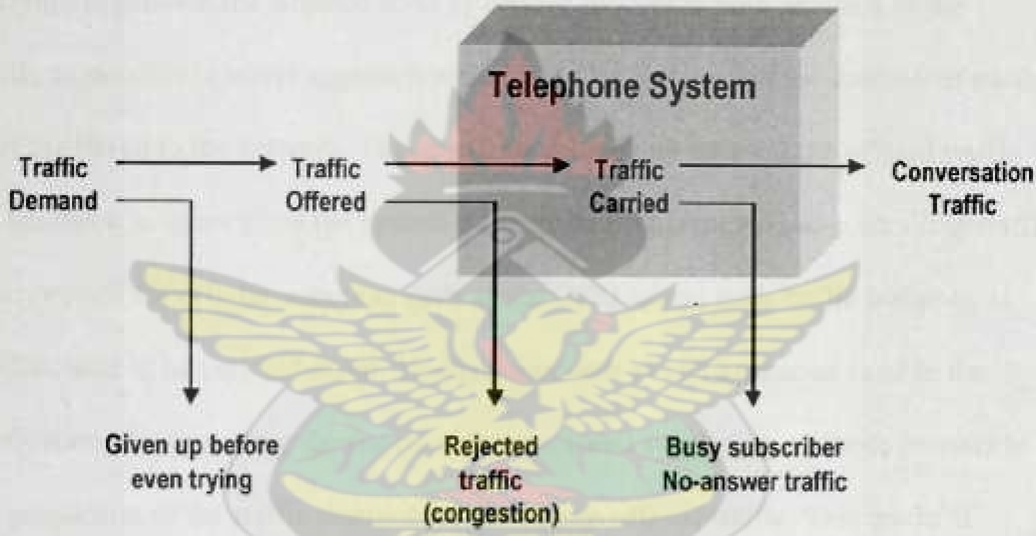

Figure 1-1Handling of Traffic by a Telephone Network

In order to achieve the QoS targets set for a network an estimate is made of the initial expected offered traffic and modifications are made to the network on an ongoing basis to make sure that the targeted service level is achieved and maintained.

Calls arrive randomly at a telephone exchange or in the case of GSM networks, base station. This means that there may be times when the traffic level significantly exceeds the busy hour level used in dimensioning the system. This may lead to a significant degradation in service level. This situation is amplified in mobile networks where users carry their terminals along with them. For instance, the hosting of a football match in a stadium may result in a large concentration of people at one place which in turn may cause a significant traffic load on the serving cell. Attempting to design a network to accommodate situations such as these would lead to over dimensioning and wastage of resources.

Instead of trying to provide the targeted level of service by coping with as much of the offered traffic as possible, a novel approach would be to try and control the fraction of traffic demand that is offered to the network. This could be done by monitoring the offered traffic and giving feedback to users when the system is congested. This method of controlling traffic is particularly suited for cellular networks such as the GSM where such traffic hotspots, as they are called, tend to be very localized. Mechanisms such as cell broadcast exist in the GSM specifications for providing the requisite feedback and suggesting methods to users to control the proportion of the traffic demand that turns into offered traffic. This mode of traffic control has been investigated by Shinagawa et al [10]. Shinagawa et al [10] also point out in their work that the feedback also tends to boost satisfaction level of customers.

The analysis of traffic offered to wireline telecommunication networks has been traditionally based on queuing models. This approach has been extended to the study of cellular telephone networks. The fundamental difference between the way in which wireline and wireless networks are organized has meant that some of the assumptions that were made in the analytical study of wireline networks have been invalidated. For instance, the traditional assumption of an infinite user population cannot be said to hold true to micro cellular networks. In addition, issues such as user mobility have increased the complexity of these models. This has led to the increasing use of more diverse methods in the analysis of cellular network traffic.

Tutschku et al [2] suggests that the analysis of traffic from the service area of mobile communication network can be one based on two approaches. In the first approach (the traffic source model) the traffic is represented as a population of individual traffic sources performing a random walk. In the second approach (the network traffic model) the system is seen from the perspective of a non moving network element, typically the base station. Both of these approaches are used in mobile network design.

In the study of user behaviour and its consequences on mobile network performance the traffic source model is the more appropriate of the two. Multi-agent simulations systems have gained prominence as effective tools in the study of systems involving large numbers of autonomous agents. Multi-agent simulations have been applied successfully in study of various systems in sociology, biology, physics, economics, and marketing [11]. Multi-agent simulation systems hold promise as a means for the study of teletraffic models that use the traffic source approach. Shinagawa et al [10] however were the only ones found in literature to have used this approach in study of teletraffic.

1.1 MOTIVATION

The behaviour of users in their interactions with the GSM network can have a significant effect on network performance and thus also on the users perception of the quality of service being received. Network planning engineers need to have a good understanding of the various aspects of this interaction in order to properly dimension and conFigure their networks. Due to the complexity of these interactions however, most of the methods available for analysis provide only a limited insight. As new methods of analysis arise therefore, it is important to go back and see whether they are able to provide further insight both at the qualitative and quantitative levels in order to improve the network planning process.

Furthermore, GSM networks are constantly being modified to meet increasing traffic demand and also to improve the quality of service. These changes however usually come at significant cost to the network operator. It is therefore necessary for the network operator to have a means of gauging the potential benefits of a proposed course of action before actually undertaking them.

1.2 OBJECTIVES

The specific objectives to be addressed in this work are listed below;

1. Develop a model for user calling patterns/behaviour with respect to their interactions with the GSM network based on multi-agent approach.
2. To apply the model in studying the following
    a. How variations in the model parameters affect blocking probability at the air interface. The parameters whose variations are considered are
        i. offered traffic
        ii. mean call duration
        iii. variations in call intensity due to flashing
    b. How modifications in user behaviour with respect to those parameters given above can improve blocking probability at the air interface

particularly during periods of congestion. The following behaviour modifications are studied

i. use of alternate services at the air interface

ii. deferment of calls

1.3 Outline

This work is divided into five chapters. Chapter one is an introductory chapter, it presents the motivation and objectives of the project. This sets the stage for the chapters that follow.

Chapter two gives a review of relevant literature. Chapter three gives a description of the model used in the simulation and the simulation itself. The chapter also contains rationalisations of some of the design decisions made. Chapter four present an analysis of results of the simulations. Chapter five contains conclusion and general recommendation as to how the results obtained can be used and areas of refinement and further study.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 GSM System Overview

The service area of a GSM network is referred to as a Private Land Mobile Network (PLMN). The PLMN is structured in a hierarchical manner as shown in the Figure 2-1 [12]. The PLMN is divided into a number of regions each of which is under the control of a Mobile services Switching Centre (MSC). This region is further divided into a number of Location Areas (LA). Location areas allow the system to keep track of the location of mobile users. Every time a user enters a new location area a location update is made. The LA consists of one or more cells.

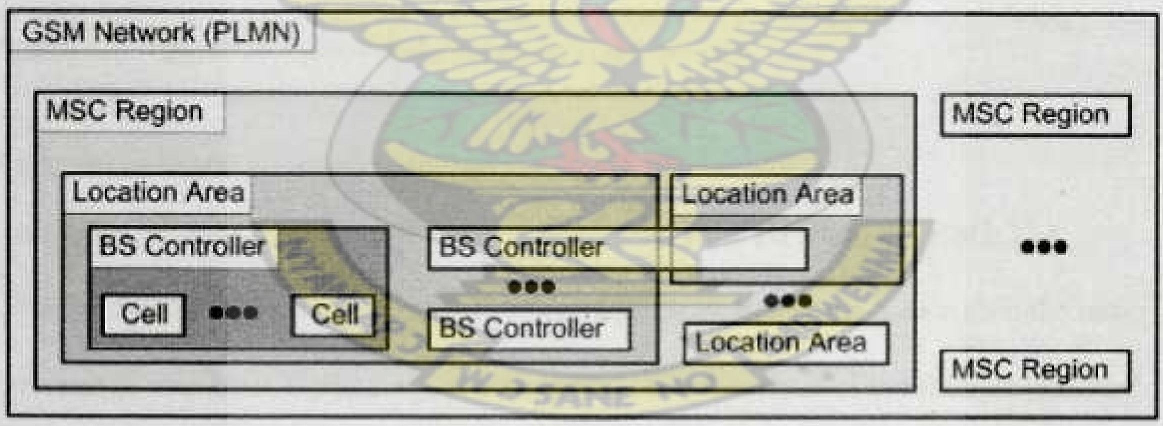

Figure 2-1: GSM Network Hierarchy

Figure 2-2 [12] shows the major functional components of a PLMN. The components are grouped into the following subsystems

- Base Station Subsystem
- Mobile Switching Subsystem

- Operation and Maintenance Subsystem

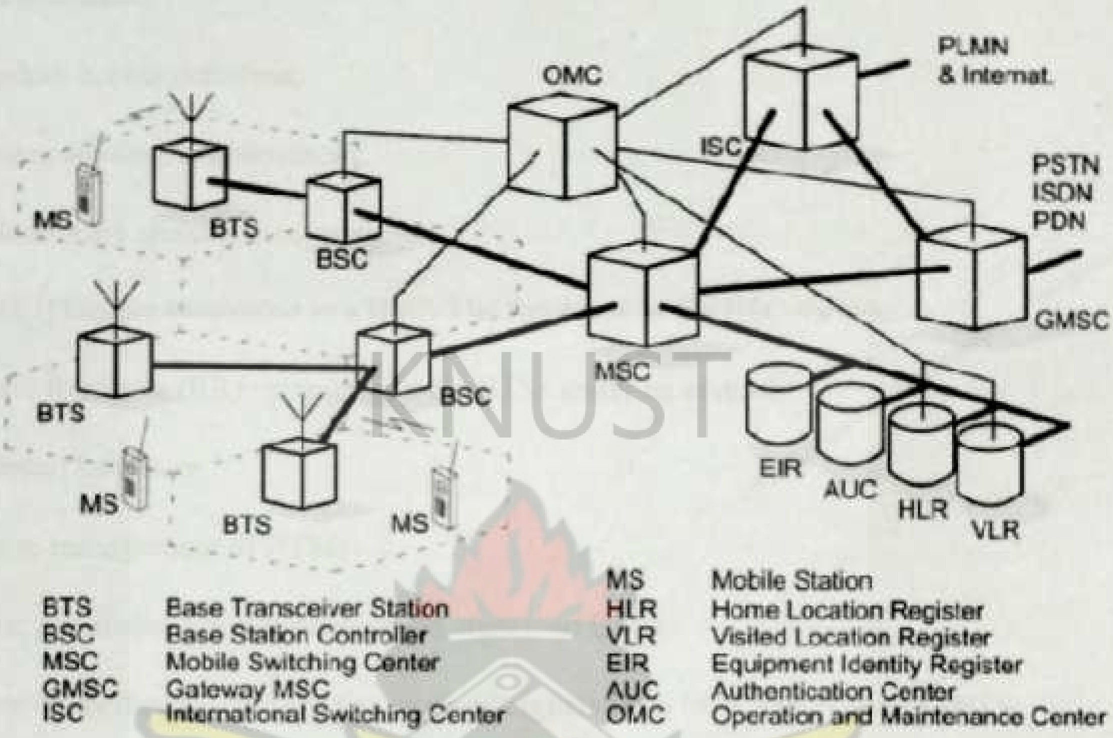

Figure 2-2: Major Functional Components of GSM Network

2.1.1 Base Station Subsystem (BSS)

The main network elements that make up the BSS are the BTS and the BSC. The coverage area is divided into a number of cells. A single cell is the area within the radio coverage of one Base Transceiver Station (BTS). The functions of the BTS as indicated in [13] include:

- Encodes, encrypts, multiplexes, modulates and feeds the RF signals to the antenna;
- Time and frequency synchronization signals transmitted from BTS;
- Voice communication through full rate or half rate speech channel;

- Received signal from mobile is decoded, decrypted and equalized before demodulation;
- Random access detection;
- Timing advance measurement;
- Uplink radio channel measurements.

A number of BTSs are connected to a BSC. The functions of the BSC include

- Radio Resource (RR) management for BTSs under its control;
- Intercell handover;
- Power management of BTSs;
- Time and frequency synchronization signals to BTSs;
- Time delay measurement of the received signals from MSs with respect to BTS clock;
- Controls frequency hopping;
- Performs traffic concentration to reduce the number of lines from BSC to MSC and BTSs;
- Provides interface to the Operations and Management for BSS.

2.1.2 Mobile Switching Subsystem (MSS)

The MSS is made up of the MSCs, GMSCs and the associated data bases. The MSCs are responsible for the call switching functions in the GSM network. The Gateway Mobile Switching Center (GMSC) is responsible for interfacing with other telecommunications networks. There are a number of databases in the MSS that perform various functions. These are listed below along with their functions

- **Home Location Register (HLR):** – This is a central database for the storage of user profiles.
- **Visitor Location Register (VLR):** – The VLR stores the profiles of users in the LAs to which it is associated. This prevents repeated queries to the HLR. The VLR may also hold information regarding the subscriber which is only of significance in the subscribers current LA e.g. temporary mobile subscribe identity (TMSI).

2.1.3 Operation and Maintenance Subsystem (OMS)

The Operation and Maintenance subsystem is responsible for continual monitoring of the network through one or more Network Monitoring Centres. Network configuration and maintenance functions fall under the OMS. In addition to this security and administration are also handled by this section.

The AUC and EIR are also considered to be part of the OMS. Their functions are described below.

- **Authentication Centre (AUC):** – Before a user is allowed access to the GSM network it is required that it is properly authenticated. The key values required for the authentication process are stored in the AUC. The AUC is usually integrated with the HLR.
- **Equipment Identity Register (EIR):** - This database stores International Mobile Equipment Identity (IMEI) which is a kind of serial number that uniquely identifies each mobile. This allows the network operator to keep track of the

mobile equipment being used on its network and for instance deny service to black-listed terminals.

2.2 GSM Air interface Architecture

GSM operated initially in the 900MHz frequency band. A frequency division duplexing (FDD) scheme is used with 890 – 915 MHz for uplink and 935 – 960 MHz on the downlink. The use of a carrier spacing of 200 kHz provided 125 duplex carrier frequencies [13]. Each carrier is further divided into 8 channels using time division multiple access (TDMA). Over time more frequency bands have been allocated for the operation of GSM networks. In Ghana for instance these networks work in both the 900 MHz and 1800MHz bands. Table 2-1 [14] lists all the frequency bands used worldwide for the operation of GSM networks.

Table 2-1: Worldwide GSM Frequency Bands

System	Band	Uplink (MHz)	Downlink (MHz)	Channel Number
T-GSM 380	380	380.2 - 389.8	390.2 - 399.8	Dynamic
T-GSM 410	410	410.2 - 419.8	420.2 - 429.8	Dynamic
GSM 450	450	450.4 - 457.6	460.4 - 467.6	259 - 293
GSM 480	480	478.8 - 486.0	488.8 - 496.0	306 - 340
GSM 710	710	698.0 - 716.0	728.0 - 746.0	Dynamic
GSM 750	750	747.0 - 762.0	777.0 - 792.0	438 - 511
T-GSM 810	810	806.0 - 821.0	851.0 - 866.0	Dynamic
GSM 850	850	824.0 - 849.0	869.0 - 894.0	128 - 251
P-GSM 900	900	890.0 - 915.0	935.0 - 960.0	1 - 124
E-GSM 900	900	880.0 - 915.0	925.0 - 960.0	975 - 1023, 0-124
R-GSM 900	900	876.0 - 915.0	921.0 - 960.0	955 - 1023, 0-124
T-GSM 900	900	870.4 - 876.0	915.4 - 921.0	Dynamic
DCS 1800	1800	1710.0 - 1785.0	1805.0 - 1880.0	512 - 885
PCS 1900	1900	1850.0 - 1910.0	1930.0 - 1990.0	512 - 810

Note: The Table shows the extent of the band and not center frequency.

- P-GSM, Standard or primary GSM 900 Band
- E-GSM, Extended GSM 900 Band (includes Standard GSM 900 band)
- R-GSM, Railways GSM 900 Band (includes Standard and Extended GSM 900 band)
- T-GSM, TETRA-GSM

Modern telecommunication networks operate using two logically distinct networks. The first is a circuit switched network that is used to carry user traffic. The second is a packet switched network that is used for control signalling. The GSM air interface has a number of logical channels multiplexed onto the physical channels which allow for the performance of these two distinct functions. Figure 2-3 given by Mehrotra [13] summarises the various logical channels found at the GSM air interface.

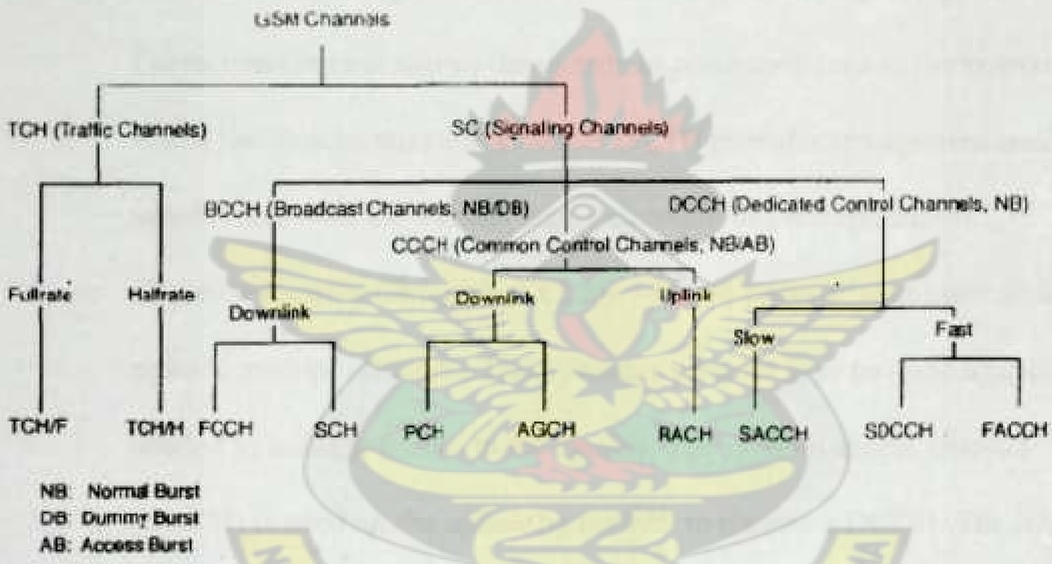

Figure 2-3: Logical Channel Hierarchy

The functions of these channels are explained below

- **Traffic Channels**: - These channels carry speech or data in a point to point fashion. The Traffic channels are of two classes. Full rate channels (TCH/F) provide data rates of 13kbps for speech and 14.5, 12, 6, 3.6 kbps for data. Half rate channels (TCH/H) are used to provide additional capacity at the air interface without increasing the number of physical channels. The half rate channels operate at half capacity of full rate channels in terms of speech transmission and at 6 kbps, 3.6 kbps for data.

- **Signalling Channels**: - these provide various signalling functions and are further divided in to three subgroups. These are
    - *Broadcast Control Channel (BCCH):-* the broadcast control channels operate in a unidirectional point to multipoint mode on the down link. It provides information about the organisation of the PLMN. This allows the mobile station to register on the system. Specifically the Frequency Correction channel allows the mobile to accurately tune to the base station whilst the Synchronization Channel (SCH) provides information needed to synchronise with the TDMA frame structure of the base station.
    - *Common Control Channels (CCCH): -* These operate in a bidirectional point to multipoint mode. Their primary purpose is to provide signalling needed to manage access to the system. The random access channel (RACH) is used on the uplink by the MS to request a DCCH. The RACH operates in multiple access mode using a principle known as slotted ALOHA. The Access Grant Channel (AGCH) is used on the downlink to allocate a DCCH to an MS whilst the Paging Channel (PCH) is used on the downlink to signal an incoming request to an MS.
    - *Dedicated Control Channels (DCCH):-* These channels are bidirectional point to point channels used to provide signalling to a specific MS. The Stand-alone Dedicated Control Channel is used to provide signalling between the MS and BSS when there is no active connection. This channel is utilized in the provision of services such as Short messaging service

(SMS) and Unstructured Supplementary data Service (USSD). There are also another class of DCCH known as the associated dedicated control Channels (ADCCH). The existence of these channels is tied to the existence of a TCH or SDCCH. There two types of ADCCH. The slow associated dedicated control channel (SACCH) is used to carry information required for optimal radio link performance. This includes information for transmit power control and measurement reports. The fast associated dedicated control channel (FACCH) is used in a situation such as during handover when a signalling channel faster than that afforded by the SACCH is needed. The channel is created by stealing some time slots from its associated TCH.

In addition to the above a Cell Broadcast Channel may also be defined. This is used to provide a service similar to SMS but which operates in a point to multipoint fashion on a per cell basis.

2.2.1 Logical Channel Combination

Not all logical channels are used concurrently by the BTS and MS. A number of channel configurations are defined by GSM standard. These are offered by the BS and utilised by the MS. The combinations offered by the BS are shown in Table 2-2 [12].

Table 2-2: Channel Combinations offered by Base Station

	B1	B2	B3	B4	B5	B6	B7	B8	B9
TCH/F	■							■	■
TCH/H		■	■						
TCH/H			■						
BCCH				■	■	■			
FCCH				■	■				
SCH				■	■				
CCCH				■	■	■			
SDCCH					■		■		
SACCH	■	■	■		■		■	■	■
FACCH	■	■	■					■	

Depending on the current state of the mobile, it can only use a subset of the offered channels. Table 2-3 shows the various combinations of logical channels used by the mobile station. M1 is used when no physical connection is present. M2 and M3 are used by active mobiles in standby mode; M4 is used when dedicated signalling is required. M5 – M8 are used when traffic is being transported with M8 used for multi-slot communication. In the case of multi-slot communication, *n* represent the number of unidirectional timeslots and *m* the number of bidirectional channels used by BTS.

Table 2-3: Channel Combinations used by Mobile Stations

	M1	M2	M3	M4	M5	M6	M7	M8
TCH/F								*n+m*
TCH/H								
TCH/H								
BCCH								
CCCH								
SDCCH								
SACCH								*n+m*
FACCH								

Figure 2-4 [12] shows how the logical channels are used in the case of an incoming call setup.

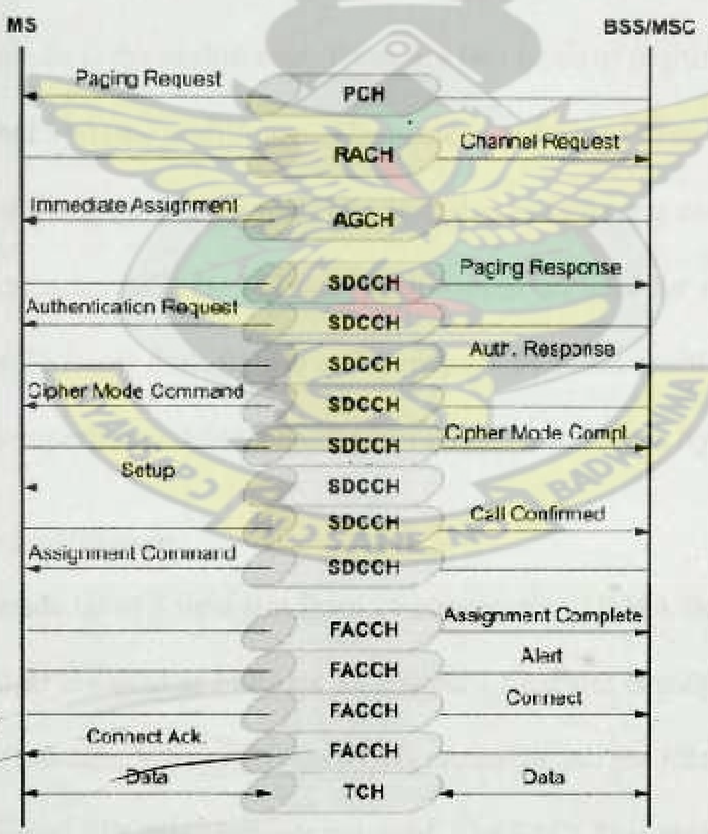

Figure 2-4: Example of Logical Channel use (Incoming call)

2.2.2 Frame Structure and Bursts

The logical channels described above are mapped onto physical channels of the TDMA frame. The structures defined for this mapping are shown in Figure 2-5 [12].

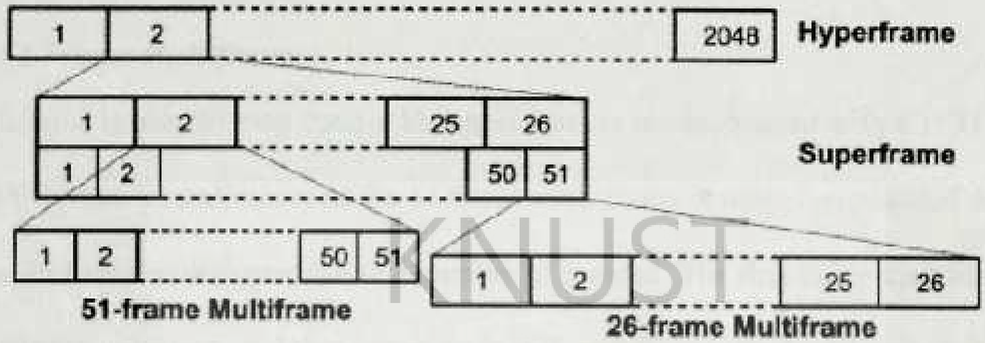

Figure 2-5: Logical Frame Hierarchy

The most basic structure is the multiframe. There are two types of multiframes, the 26 frame multiframe and 51frame multiframe. The names are derived from the number of TDMA frames comprising the multiframe. The 26 frame multiframes are mainly for the transport of user payloads whilst the 51 frame multiframes are used for signalling channels. Fifty-one 26 frame multiframes or Twenty-six 51 frame multiframes are combined to form a superframe. 2048 superframes combine to form a hyperframe.

2.2.2.1 26 Frame Multiframe

The multiframe is made up of 1 time slot from 26 consecutive TDMA frames. Twenty-four of these time slots are used as Full rate TCHs and 1 time slot is used for SDCCH. The last time slot is left idle. When half rate TCHs are employed the idle time slot is used to provide the additional SDCCH channels required. The FACCH is provided on the 26 frame multiframe by stealing bits from the traffic channels.

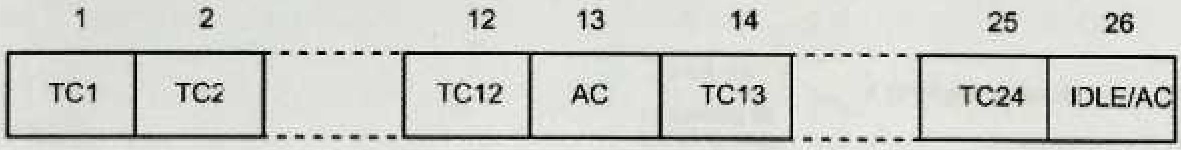

Figure 2-6: 26 Frame Multiframe

2.2.2.2 51 Frame Multiframe

This multiframe is used to map control channels that are not associated with a TCH unto the TDMA frames. The structure of the 51 frame multiframe is more complicated than that of the 26 frame multiframe due to a number of reasons. The first being that, some of the channels are unidirectional thus resulting in different frame structures on both the downlink and uplink. Furthermore, as discussed above, there are a number of channel configurations that can be adopted and the structure of the multiframe is dependent on this configuration.

2.2.2.3 Bursts

A burst is the sequence of bits carried in one time slot. There are five types of bursts. Their structure is shown in Figure 2-7 [12].

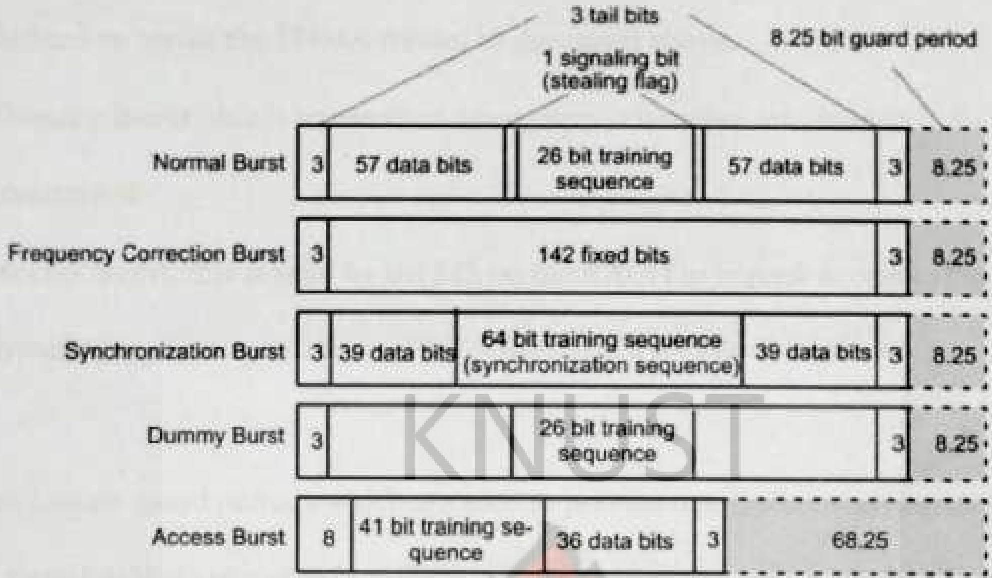

Figure 2-7: Burst Structure

- **Normal Burst**: This is used to transmit information on all channels except the RACH. At the beginning and end of these bursts there are three tail bits. The period occupied by these bits allow the transmitter power to be ramped up or down as needed. The stealing flags are set to indicate whether traffic or signalling information is being carried. This is used for instance to carry the FACCH during handover. The training sequence bits are a predefined bit sequence used for channel estimation. The rest of the bits contain error coded and encrypted information.
- **Frequency correction burst**: this is used for frequency synchronization between the BTS and MS. All the bits transmitted in this burst are set to zero which corresponds to unmodulated carrier frequency.
- **Synchronization Burst**: this burst is used to transmit information that allows the MS to synchronise in time with the BS. The Reduced Frame Number (RFN)

allows the MS to determine the current position in the logical frame structure defined on top of the TDMA frames as discussed above.

- **Dummy Burst**: this is transmitted when there is no other information to be transmitted.
- **Access Burst**: this is used by the MS on the RACH to request access to the system.

All bursts contain guard periods which are used to prevent overlap between bursts in adjacent timeslots that are transmitted from different MS which may not be perfectly synchronized. The guard period of the access bursts are especially long because of the random way in which these bursts are sent.

2.3 Services at the GSM air Interface

The services offered by the GSM network at the user network interface (UNI) can be grouped into two, telecommunication services and supplementary services. The telecommunication services are further divided into bearer services and teleservices. Bearer services offer the basic capability to transfer binary information providing a standard transport mechanism that can be used by higher level applications. Teleservices are standardized services that run on top of the bearer services providing facilities for end to end communication. The supplementary services are used in conjunction with the telecommunication services, providing increased control and extension to these services.

2.3.1 Bearer services

The bearer services provide the lower 3 layers of the OSI reference model. They provide a basic mechanism for the transport of binary information. Bearer services are classified according to the demands they place on the network as regards transmission capabilities but also internetworking functions. The basis on classification includes;

- **Access structure**: - Bearer services can be either circuit switched or packet switched. Further individual bits or frames may be transmitted synchronously or asynchronously.
- **Data rate: -** the various bearer services operate at different bits rates. Data is transmitted with bearer services with bit rates of up to 9.6kbps whilst voice is transmitted at 13kbps.
- **Transfer mode**: - Bearer services are offered as either transparent or non-transparent. The transparent mode offers a constant bit rate, constant delay transport service between the terminal equipment and internetworking function in the MSC. Forward error correction is used with the residual error dependent on channel conditions. The non-transparent mode uses automatic retransmission requests to improve the residual error and making it independent of current channel conditions. This however results in variable bit rates and delay.
- **Internetworking requirements**: - Bearer services may be classified according to the kind of internetworking function that needs to be activated when transporting it across network boundaries. In this regard the service can be either unrestricted digital data (UDI) or 3.1 kHz audio.

2.3.2 Teleservices

The teleservices operate on top of the bearer services and require that the terminal equipment contain the necessary facility to interpret the protocols used in their implementation. A number of these teleservices have been standardized with the most noTable amongst them being voice, SMS and facsimile transfer.

2.3.2.1 *Short Message Service (SMS)*

The short messaging service is a teleservice that allows an MS to send and recieve short text messages of up to 160 characters in length. Figure 2-8 shows the various network elements that facilitate the delivery of SMS [15].

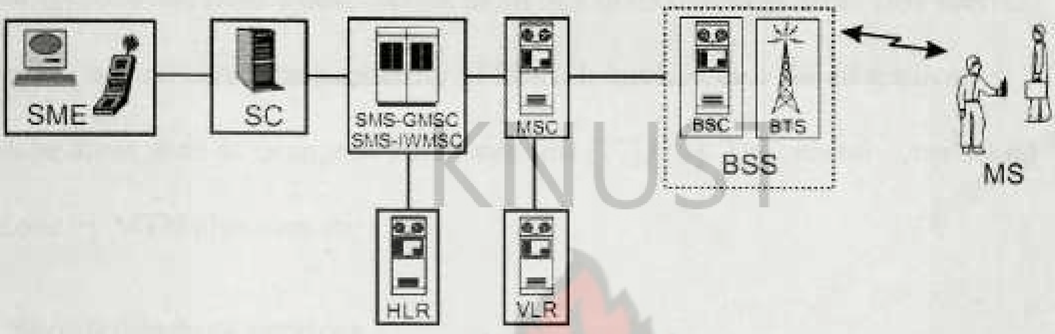

Figure 2-8 Network entities involved in the provision of SMS

The SMS is originated by an SME which may be another MS or computer connected to the service centre (SC). The function of the SC is to store and forward SMSs. The short message service–gateway mobile services switching centre (SMS-GMSC) and short message service interworking mobile services switching center (SMS-IWMSC) are dedicated functions within the MSC. The former allows the MSC to receive messaged from the SC, interrogate the HLR and forward to the message the recipient. The latter gives the MSC the MSC the ability to receive and forward SMSs to the SC for onward delivery to the recipient.

SMS since its introduction has increased in popularity and is now a major source of revenue for many operators. SMS has found application in both person-to-person and person-to-machine contexts and machine-to-machine context. Le Bodic [16] gives a summary of the various use cases.

SMS as discussed above provides a facility of point-to-point communication but the GSM standards also contains specifications for a point-to-multipoint text messaging service. This service is known as Cell broadcast service (CBS). This service is similar to SMS but is broadcast from a base station to all MS in its coverage area. This service however has not achieved the popularity of SMS. It has however found application in some niche areas such as emergency alert systems [17],[18]. The recently introduced Yello Zone by MTN also uses the CBS.

2.3.3 Supplementary services

The supplementary services are used in conjunction with the telecommunication services. They provide additional control and enhancements to these services. A number of supplementary services have been standardized in the GSM specifications. Some of the more common ones are enumerated below

- Call restriction/barring
- Call forwarding
- Call holding and waiting
- Caller line ID presentation and restriction
- Multiparty calls / conferencing

2.3.3.1 USSD (Unstructured Supplementary Services Data)

This facility allows operators to define custom supplementary services based on short codes [15]. In the first specification, the services was restricted to user activated requests. Subsequent modifications to the specification however have led to the possibility of network initiated USSD sessions. USSD being session oriented service is ideal for situations where the exchange of several messages is needed for the completion of a transaction. USSD is commonly used for the activation of supplementary services on an MS. USSD is limited to person-to-machine contexts and has found application in such areas as airtime top-up applications and call-me-back services.

2.4 Congestion at the Air Interface

The spectrum is a finite resource. It is not feasible to provide dedicated channels to every MS. Channels are therefore assigned to mobile station as needed. This can be thought of as the first stage of concentration in the GSM network. Although it allows for economical use of resources it can result in congestion, a situation where there are fewer channels than required to serve all users requesting service. When congestion occurs some users are denied service, i.e. they are unable to place calls. Boulmalf et al [19] give two situations that give rise to congestion at the air interface. These are

- Congestion of traffic channels
- Congestion of control channels

This follows from the fact that the GSM air interface is logically partitioned into control and traffic channels. Congestion on the control channels is very detrimental to system performance because they are required for the allocation of traffic channels. Thus even if there are free traffic channels, congestion on the control channels prevents allocation of these channels.

2.5 Modelling of User Mobility

Accurate modelling of user mobility is of vital importance in the study of wireless networks. The pattern of user mobility directly affects the cell residence times and this in turn affect the channel holding time and the hand over rate. Figure 2-9 presented by

Bettstetter [20] gives a summary of the various issues that need consideration in the development of mobility models.

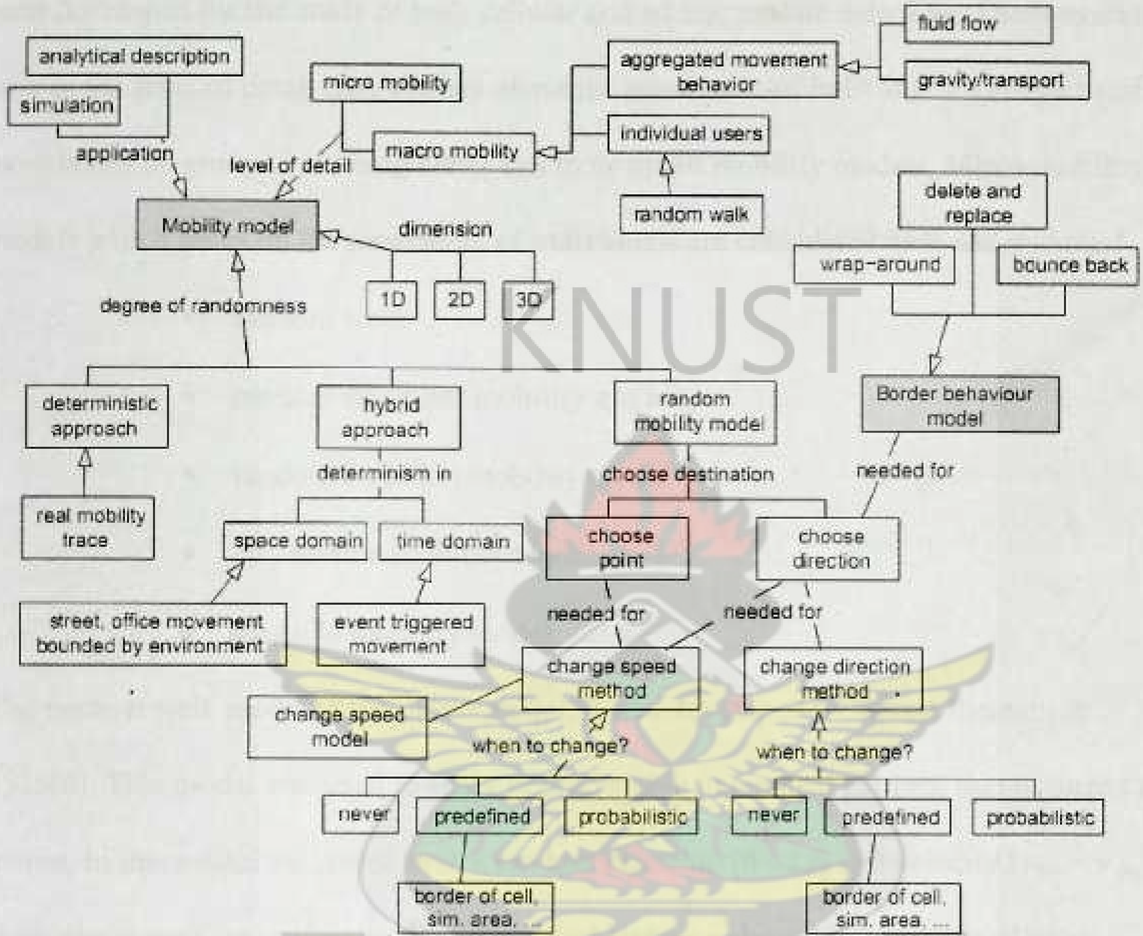

Figure 2-9: Concept map of mobility models used in simulation and analysis of wireless communication systems

There are currently two approaches to modelling mobility; these are traces and synthetic models. Traces use measurement from real system as the basis of the model. Camp et al [5] suggest that in this case, flexibility and possibilities to extend the behaviour of users are limited. Davies [21] goes on further to state that this approach cannot be easily applied to new environments where traces may not exist.

Synthetic models use random algorithms to simulate movement of users. Camp et al [5] and Davies [21] give a detailed survey of the various synthetic mobility models that have been developed for the study of both cellular and ad hoc mobile networks. These models vary in the level of detail they capture about the movement of individuals. On this basis models can be grouped as being either macro or micro mobility models. Mirco-mobility models which focus on the movement of individuals are considered here and include,

- random walk
- random waypoint mobility model
- random direction mobility model
- city section mobility model
- obstacle mobility model

The random walk model is the oldest model, it was developed by Albert Einstein in 1926[6]. This model was used to study unpredictable movement patterns that occurred in nature. In this model the nodes have a random direction $[0 - 2\pi]$ and velocity $[v_{min} - v_{max}]$. Both parameters are uniformly distributed and change value after a predefined time interval or distance. Whilst this model is useful in Einstein's context it has shortcomings which led to the development of newer more realistic mobility models.

In the random waypoint mobility model the node picks a destination and moves with a uniform speed towards it. It waits at the destination for a random time interval and repeats the process. Lui et al [4] have shown that this model has some very undesirable characteristics. These being the fact that the mean node velocity varies with time suffering a significant reduction as the simulation progresses. There is also a non uniform distribution of nodes in the simulation area as the simulation progresses.

The random direction mobility model is a modification of the random waypoint model. In this case the node moves with a constant speed and direction until it reaches the edge of the world. It waits for a random time interval and then chooses a new direction and velocity.

The city section mobility model follows the recommendation of the ESTI [4] for the outdoor pedestrian environment. In this model the simulation environment is divided into a grid form. Nodes move along the edges with random speed, changing direction at the intersections.

In general models can also be categorized based on the positions users can occupy in the simulation area. These categories are,

1. those in which the node can be in any position in the simulation area e.g. random way point.
2. those in which the nodes are restricted to move along channels in the simulation area e.g. ESTI outdoor pedestrian
3. Those in which nodes are restricted to move only along certain predefined paths. Models of this type can be applied for instance in the modelling of vehicular movement were the paths would be defined by the road network.

There are also several other models which introduce modifications to the basic models presented above in an attempt to provide more realistic models. Examples of these models can be found in the works of Bettstetter [20] and Zimmermann et al [6].

2.5.1 Border Behaviour

The simulation area is generally of finite dimension. A method is thus required to deal with nodes that move beyond the edges of the simulation area. Davies [21] and Bettstetter [20] both give three options for dealing with this situation. These are;

1. Deletion
2. reflection
3. wrapping

All these methods seek to maintain a constant node population. With the deletion method, nodes that go out of the boundaries of the simulation environment are deleted from the system and replaced by new ones placed at a random position uniformly distributed throughout the simulation area.

In the reflection scheme, nodes bounce off the boundaries of the simulation area in accordance with the laws of reflection. Thus the only parameter that is changed is the direction.

In the case of wrapping, the simulation area is viewed as the surface of a torus. Thus nodes going off at one edge appear at an opposite edge. Figure 2-8 [21] gives an illustration of the concept.

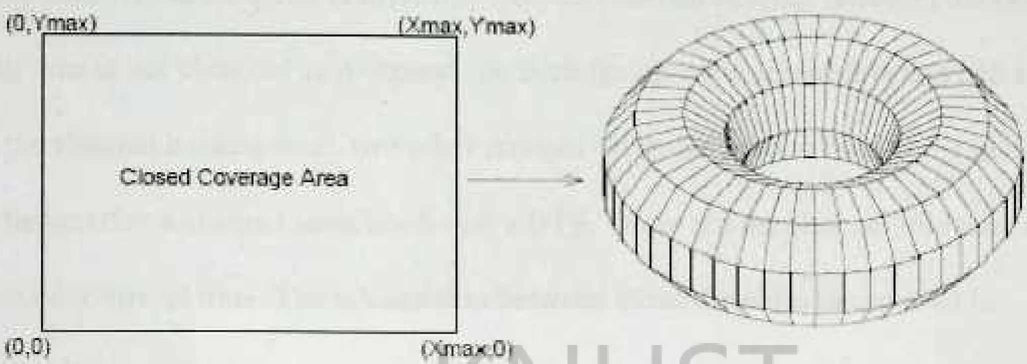

Figure 2-10: Wrapping of simulation area

Bettsteter [20] found that the first two methods of dealing with users who go outside the boundaries of the simulation environment i.e. deletion and reflection result in a non uniform distribution of nodes in the simulation area. Nodes have a higher probability of being at the centre of the simulation area.

2.6 Random Variable Associated with the Call process

The channel holding time is the amount of time a channel is assigned to a user within a cell for the purposes of making a call. In cellular mobile networks this value is different from the call holding time as the mobile terminal may move between cells during a call. The average channel holding time is equal to the average call holding time divided by the average number of handoffs per call plus one i.e. the number of cells crossed by an average call. The limit situation occurs for a stopped mobile station or an extremely large cell size; in these cases the channel holding and call holding times are equal [22].

In most literature pertaining to channel holding time the distribution is assumed to be a negative exponential one. The relationship between the call holding time and the channel holding time is not clear cut as it depends on such factors as user mobility and cell size. Aside the channel holding time, two other random variables need to be defined in order to fully characterize a channel associated with a BTS. These are the channel idle time and channel inter-arrival time. The relationship between these variables is captured in Figure 2-11.

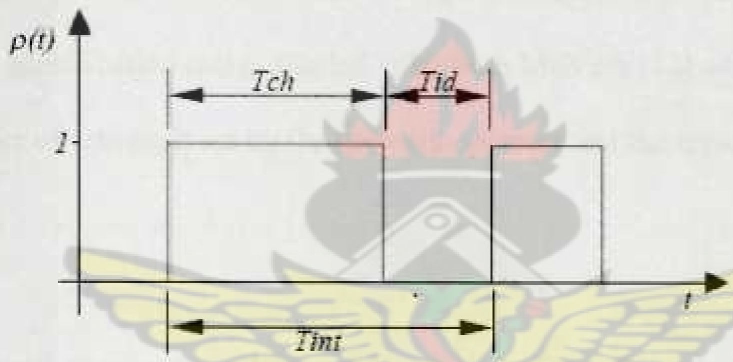

Figure 2-11: Relationship between time variables

This relationship is summarized in the channel utilization which is defined in [23] as

$$\rho = \frac{\overline{T_{ch}}}{\overline{T_{ch}} + \overline{T_{id}}} = \frac{\overline{T_{ch}}}{\overline{T_{int}}}$$

Where

$\overline{T_{ch}}$ - Average channel holding time

$\overline{T_{id}}$ - Average channel idle time

$\overline{T_{int}}$ – Average channel inter arrival time

ρ gives the traffic carried by the channel in Erlangs. If end users are assumed to have a virtual channel associated with them, then the random variable described above can also be used to characterize this channel. In which case ρ would be mean traffic offered the network by the user.

2.6.1 Repeat Call Process

Repeated call attempts have been the subject of a number of academic research efforts due to their detrimental effect on network performance. Examples of such works include those of Onur et al [24] and Tran-Gia et al [1]. During peak load repeated calls may trigger a snowball effect leading to complete denial of service.

In this work a distinction is made between two different types of repeated call processes. The first shall be referred to as retrial. This happens when a mobile terminal automatically re- request for a channel after facing blocking in earlier attempts. This is a part of the GSM specification and is alluded to by both Mehotra [13] and Onur [25]. The maximum number of retrials is set by the network operator and the retrial occurs after a fixed time lapse.

The other repeat call phenomenon distinguished is that of redialling. In this case a customer consciously repeats a call attempt after the call has been blocked. With modern mobile phones, the user can set the phone to automatically redial after the initial attempt fails or presses a single button to initiate a redial attempt [1]. This results in the mean time between redial attempts being very short.

Two random variables are of importance with regards to redials process. These are the number of redials and interval between redial attempts. Both of these random variables have been examined in a number of studies [24].

A number of models have been proposed to characterize both the number of redials and the time intervals between them. The probability of redialling after a failed request is modelled as

1. Uniform: - That is the caller redials with probability p after a blocked attempt or gives up with a probability (1-p) independent of the number of previous attempts. In this situation a caller may be limited to a maximum number of redial attempts or try until a connection is made.
2. Other models take the number of previous call attempts in consideration. In this case the probability that the user redials after a blocked attempt is a function of the number of previous failed attempts.

The time interval in between redial attempts is usually assumed to be exponentially distributed with a short mean value due to the reasons mentioned above.

2.7 Measuring User Behaviour and Service Utilization

The user behaviour and service utilization are important factors in the design of modern telecommunications networks. Kivi[26] gives an overview of how these can be measured in wireless data networks. Similar approaches can be used in the measurement of user behaviour in GSM networks were voice is the main traffic element. These measurements can be done at different levels, these being

- At the user end level
- At the radio access network level
- At the core network level

At the end user level there are two ways in which service utilisation and user behaviour can be measured. The first is through the mobile terminal. Most modern handsets operate based on complex operating systems. The advantage of this is that programs can be stored on these terminals that log user actions. The SIM application toolkit which allows small programmes to be stored on the subscribers' SIM card can also be used to perform this function. Very detailed information can be obtained via this approach.

The second approach that can be adopted at the end user level is to use the human end users themselves as sources of information. The information gathering can be done through questionnaires or may entail having users log their actions in some sort of diary. This method however is subject to the vagaries of human nature. The nature of the questions may affect the kind of answers given. The consistency with which results are recorded in the diary approach can also have a telling effect on the final results.

The radio access network which in a GSM network consists of the network of BTSs can also be employed in measuring service utilisation. In fact this approach was adopted by Barceló et al [22],[23] in their study of various channel probability distributions in an established cellular network. Since the BTSs and their associated cells are at the level of first contact with end user they offer an ideal point for making measurements. The simulations undertaken as part of this project use this approach in determining service utilization.

The core network of a GSM network contains a number of servers and databases whose sole purpose is to collect and collate charging data records (CDR).These CDRs are used for billing purposes. This information can also be used as a basis for service utilization and by applying more complicated methods for determining user behaviour. However since these systems are designed to cover the whole service area of the network it is difficult to obtain fine grain information for instance with regards to geographical distribution of demand from such sources.

2.8 Multi-agent Simulation (MAS) and Modelling

A simulation is defined by Stewart as "An imitation of a system" [27]. This imitation may be necessary for a number of reasons. Some of the reasons include;

- The fact that the complexity of the system under consideration will not allow for analytical solutions to the problems it presents.
- The required solution would be time consuming if it is obtained by other means.
- The original system is not existing any more or not yet
- Experimenting with the real system is prohibited due to undesired disturbances and costs.

In order to carry out a simulation of a system one must develop a model of the system. Due to the complexity of the system for which simulations are normally resorted to, these models must of necessity involve abstractions and simplifications of the actual system. Siebers and Aickelin [28] point out that in developing the model a distinction must be made between a simulation model and an analytical model of a system. A simulation model consist of a set of rules defining how a system changes over time given it current state, thus providing an insight into the dynamics of the system. An analytical model on the other hand is meant to be solved and provides system outputs based on specific inputs.

A model in MAS consists of a series of incorporated software objects, called agents [29]. The agent representing the 'individual' is programmed to be autonomous and can communicate with its environment and other agents. MAS has been introduced into many fields including sociology, biology, physics, economics, and marketing [11].

Macal and North [30] give the under listed as the general tasks required in multi-agent system development.

1. Identifying agents and their behaviour
2. Indentifying the relationships between agents
3. Getting the requisite agent related data
4. Validating the agent behaviour models as well and the whole model at large
5. Running the model and analysing the outputs

Siebers and Aickelin [28] give more detail about the design of MAS simulations and suggest state charts as a means of representing the internal processes of agents. The central state in the state chart is the idle start which links to all state that are not dependent on a specific order of execution. State transitions occur by means of triggers which may be in the form of rules, formulae or procedures.

Compared with the traditional methods of simulation, MAS offers some advantages. Chief among these advantages is overcoming the lack of linkage between the micro and macro level of the simulation. Traditional methods normally employ differential equations that take a macro level view of the system, ignoring the micro level interactions that lead to the manifest macro characteristics.

MAS also takes a different approach to the modelling and simulation process. Unlike the inductive methodology of collecting data first and then building models that describe and summarize those data, MAS is more like a deductive method. After a MAS model is designed and tested, the relationships between the propositions and factors can be simulated whether the data is available or not. Therefore, the inner structure of the system on macro level, which is not clear before, can be deduced or observed from MAS experiments.

These advantages make MAS suitable for the study of system where there are a large number of interacting agent since it allows for the development of the system model for the level of the interacting agents upwards.

CHAPTER THREE

3.0 Model Description

The multi-agent approach is used for modelling and simulation. The development environment used is called Netlogo [11]. Netlogo is written in java and programmed via a dialect of the logo programming language. Netlogo was chosen for this project because of its ease of learning and comprehensive set of features. NoTable amongst these features is its behaviour space, which allows a model to be run several times with varying parameters. Figure 3-1 shows a screen shot of Netlogo in operation.

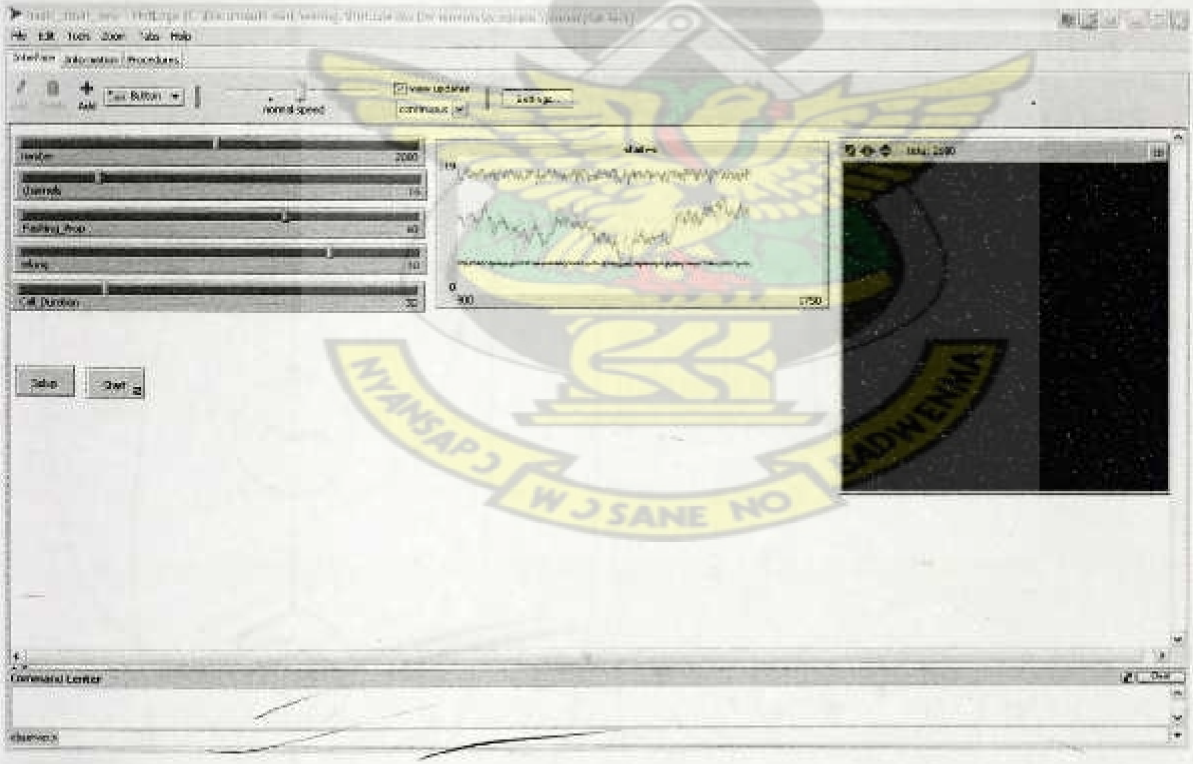

Figure 3-1: Screen Shot of Netlogo in operation

The simulation environment is made up of two types of agents. These are the caller and the base stations. These and various other parts of the simulation are described in the following sections.

3.1 Callers

The caller agents model user behaviour. User behaviour can be broken down into two distinct components, traffic generation and movement pattern. A description of the models for these two facets is given below. Figure 3-1 represents the various states the callers go through as they generate traffic.

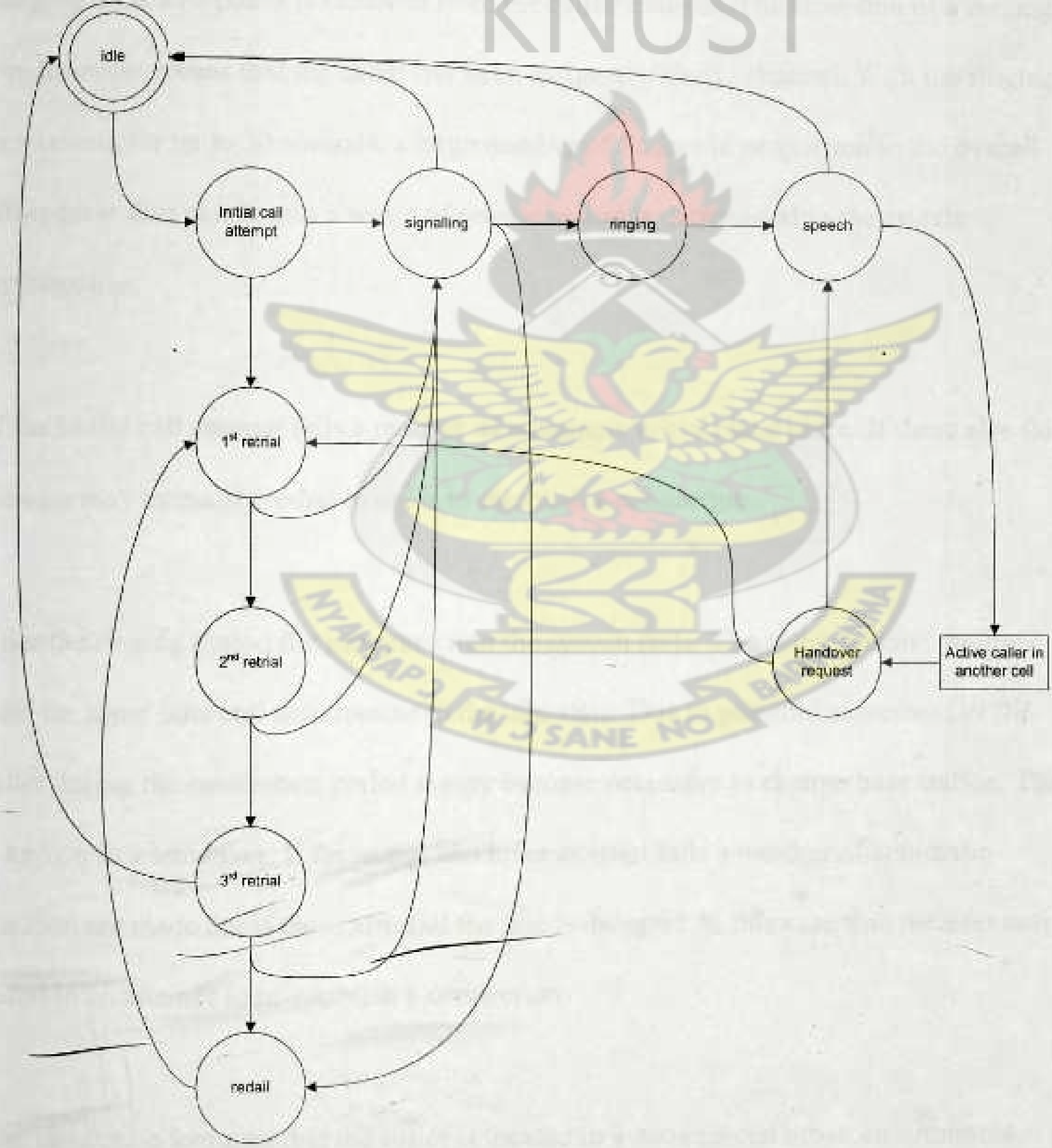

Figure 3-2: Model of Callers States and Transitions

Caller are normally in the idle state. They leave this state by generating call requests. This request may be granted by the associated base station at which time the caller then goes into the ring state. This state allows the model to capture the situation in which a user after receiving the ringing tone breaks the connection. This phenomenon is known as flashing. Flashing allows GSM users to signal each other without incurring any cost using Caller line identity presentation (CLIP). This is because most networks do not start charging until a response is received from the called number. The reception of a ringing tone however means that the caller has been assigned a traffic channel. With the ringing tone lasting for up to 30 seconds, a large number of flashes in proportion to the overall call request thus constitutes a waste of resources and is detrimental to the system performance.

If the initial call attempt fails a number of automatic retrials take place. If these also fail the user may manually redial in order to establish a connection.

After the ringing period the user goes into the speech state. The caller remains in this state for some time and then returns to the idle state. Due to possible movement of the caller during the connection period it may become necessary to change base station. This is known as a handover. If the initial handover attempt fails a number of automatic requests are made but if these also fail the line is dropped. In this case also the user may redial in an attempt to re-establish a connection.

The simulation assumes that the caller is located in a commercial urban environment. Most callers in this situation are walking with those using vehicular transport also moving at relatively low speeds. The average walking speed of an adult human is around 5km per hour [31]. The maximum speed allowed for a vehicle in the urban environment is 50 km per hour. This maximum is however not attained in the scenario that is used in the simulations. Given this background the speed of callers is uniformly distributed between 0 – 25 km per hour. At the beginning of the simulation each caller is given a velocity uniformly distributed in the range given above. After each simulation cycle the user chooses a new direction in a cone 40^0 wide in the direction of motion. This ensures that there is correlation in the direction of movement of the user.

Every time there is a change of position the caller recalculates its distance relative to all the base stations and associates itself with the nearest base station. If the caller is active and the nearest base station is different from its current base station a handover occurs. When a caller in the automatic retrial state undergoes a handover, the call is dropped. The caller treats this event as a failed call attempt.

All agents in the simulation have a number of properties. These properties are used to keep track of the state of the agent. The properties of the caller agents are enumerated below

- **base_station** : - this variable allows the caller to keep track of the base station to which it is currently associated. Channel allocation request are directed to this base station.
- **Color**: - This is used to specify the callers' state. These can take on five values which are:
    - *green* → The caller has a traffic channel assigned to it

- *blue* ➔ The caller has been assigned a signalling channel
- *yellow* ➔ An initial call attempt has failed and the caller is in automatic redial state
- *grey* ➔ The caller is waiting to redial a connection manually
- *white* ➔ The caller is in the idle state

- **Flash**: - number of flashes
- **Heading**: - current bearing of callers movement.
- **Redials**: - This variable keeps track of the number of redials. This allows decisions regarding whether or not to redial to be made based on the number of previous attempts. The probability of redialling in the model is taken to reduce geometrically with increasing redial attempts whilst the length of time between redials is exponentially distributed.
- **Retrials**: - number of retrials after last call attempt. In most GSM system this number is limited to three and this standard is implemented in the simulation.
- **speed**: - this variable keeps track of the speed at which the caller is moving and is used to modify the position (xpos, ypos) of the caller in every simulation cycle
- **time_left** : - this variable keeps track of time left for current state. The time spend in the particular state depends on the other variables such as redials, retrials and flash. This variable is decremented by one every simulation cycle. When it value reaches zero the agent moves to a new state based on the current state of the other variables.
- **xpos /ypos** : - current x/y coordinate position of caller.

As stated in Section 1.2, this thesis aims to study the effectiveness of certain approaches to encouraging users to modify their behaviour. Two types of behaviour modification are being considered. These are

- Using other communication services besides voice (i.e. SMS and USSD)
- Changing the time of the call

One additional property is defined in the modified models. The control_left property is a counter that acts as the memory of the caller. It allows the caller to keep track of the time the last prompt about congestion was received from the associated base station agent. The shorter the time lapse the more probable it is that the caller will use the modified behaviour. The probability that the caller follows the modified path is linearly dependent on the lapse since the last prompt from the associated base station.

A total of 2000 caller agents are used in every simulation.

3.2 Base station agents

These agents play the role of base station in actual GSM networks. When a caller agent requests a traffic channel, the base station checks the number of callers associated with it that are currently active. If this number is less that the number of available traffic channels the caller is allowed to change into the active state.

Base stations are also responsible for monitoring the utilisation of their traffic channels. When the utilisation exceeds a certain threshold the base station broadcast a message encouraging callers associated with it to refrain from generating traffic. This is achieved by having the base stations keep track of the number of active callers during one simulation cycle. The control message is broadcast when the average number of active callers exceeds 80 percent of the available traffic channels for a specified 300 second interval. In real networks such a procedure could be implemented using cell broadcast.

A total of 7 base station agents are used in every simulation. One is located at the centre of the simulation area and other six are arranged in a regular hexagonal pattern around it.

3.3 Air Interface

A simplified model of the air interface is adopted for the simulations. Only one type of traffic channel is modelled as opposed to the full rate and half rate channels that exist in the GSM specifications. In addition signalling channels are present in the simulation. The role of these signalling channels can be roughly equated to those of the SDCCH channels. The other logical channels are not modelled as their functions are not core to the simulation.

3.4 Simulation Process

The model described above was implemented using Netlogo. In all, three sets of simulations were performed. In the first set callers generated traffic based on the call generation model detailed in section 3.1. This set of simulations is used for the study of the effects of flashing and variations in the mean call duration. This set also serves as a basis for comparison of the two subsequent set of simulations that were performed.

The next two sets of simulations implemented the two types of user behaviour modifications mentioned at the end of section 3.1. In the second set of simulations, callers use either:

- signalling channels only (SMS/USSD) or
- signalling channels and traffic channels

when their associated base station is congested. In the final set, callers increase the amount of time they spend in the idle state when prompted by the associated base station.

The first set of simulations consisted of 140 individual simulations. In the simulations the under listed parameters of the simulation were varied and assumed one of the values indicated in brackets.

- Flashing Proportions - (0, 10, 20, 30, 40, 50, 60) percent of initial call attempts
- Traffic per caller - (20, 25, 30, 35, 40) mErlangs
- Mean call duration - (30, 60, 90, 120) seconds

In the second and third set, 20 individual simulations were performed. In these simulations the effects of flashing were not considered so only the traffic per caller and mean call duration were varied.

The code implementing the model is listed in the Appendix. At the end of each individual simulation the sum total of request from users for signalling and traffic channels along with the number of these requests that were successful were logged. The results are also presented in the Appendix. The average blocking probability P_b at the air interface is used as the metric for measuring performance. The blocking probability was estimated from the results using the definition given below.

$$P_s = \frac{No.Signalling\ Ch.Grants}{No.Signalling\ Ch.Requests} \quad \text{-----3-1}$$

$$P_t = \frac{No.traffic\ Ch.Grants}{No.traffic\ Ch.Requests} \quad \text{-------- 3-2}$$

$$P_{bs} = 1 - P_s \quad \text{-------- 3-3}$$

$$P_{bt} = 1 - P_t \quad \text{-------- 3-4}$$

$$P_b = 1 - P_t P_s \quad \text{-------- 3-5}$$

Where :-

P_b= Average overall probability of blocking at the air interface

P_t= Average probability of success in traffic channel allocation

P_{bs} = Average probability of blocking on the signalling channels

P_{bt}= Average probability of blocking on the traffic channels

P_s= Average probability of success in signalling channel allocation

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

The channel utilization as defined earlier is the ratio of the mean call duration to the inter-arrival time. This value can remain constant whilst the mean call duration and inter arrival times change in proportion to each other. The effect of varying the mean call duration for a given traffic load was investigated using the model described in chapter three. Analysis of the results follows in the subsequent sections.

4.1 Unmodified caller behaviour

4.1.1 Effects of Variations in Mean Call Duration

The effect of variations in the mean call duration for a given level of channel utilization per user is analysed first. Figure 4-1 indicates that for a given level of channel utilization per user, decreases in the mean call duration leads to an increase in the blocking probability. It can also be observed that the blocking probability increases with increasing utilization per user.

A number of reasons may be assigned to this observation, these include

- With reducing call durations the call intensity which is the number of calls per unit time increases. This has the effect of increasing the amount of traffic carried by the signalling channels although the traffic on the traffic channels in terms of speech remains constant. The increase in signalling traffic causes a decrease in P_s (equation 3-1) which in turn leads to an increase in P_b according to equation 3-5. This is borne out by the results in Table 4-1 which gives the blocking probability on the signalling channels.

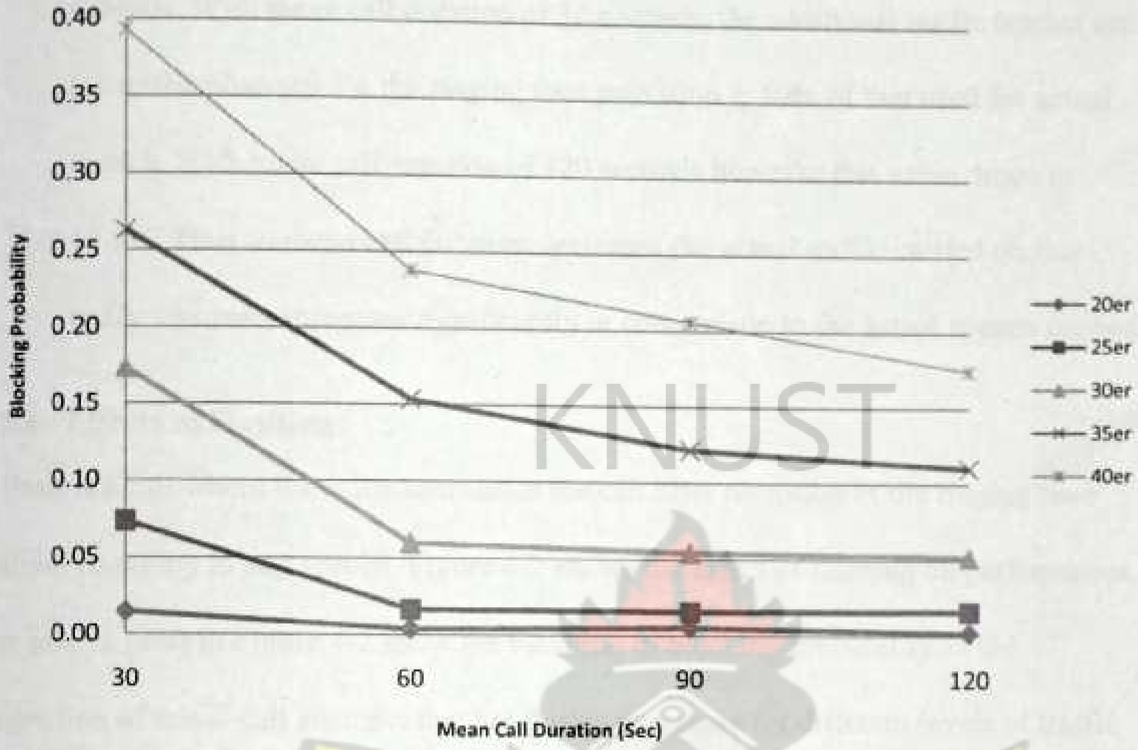

Figure 4-1Comparison of Blocking Probabilities with Increasing Mean Call Duration at Constant Offered traffic

Table 4-1 Blocking Probability on Signalling Channels (P_{bs}= 1 - P_s)

		Mean Call Duration			
		30 sec	60 sec	90 sec	120 sec
Mean traffic per user	20 mErlang	0.00181	0.00012	0.00027	0.00000
	25 mErlang	0.00742	0.00049	0.00026	0.00000
	30 mErlang	0.01546	0.00127	0.00026	0.00014
	35 mErlang	0.03734	0.00411	0.00118	0.00038
	40 mErlang	0.07107	0.00915	0.00244	0.00107

- Secondly the assignment of a traffic channel, as indicated earlier, can be broken into two distinct parts. The portion where the ringing tone is received and the portion where actual conversation goes on. With increasing call intensity the proportion of time used for providing the ringing tone on the traffic channels increases. In the simulations the mean ringing tone duration was taken to be 15 seconds. With mean call duration of 30 seconds, the additional traffic burden on the traffic channels for the ringing tone provision is 50% of that used for actual speech. With mean call duration of 120 seconds however this value drops to 12.5%. Thus as mean call duration decreases the actual traffic carried on the traffic channels increases significantly in comparison to the actual speech carried.

4.1.2 Effects of Flashing

A flash is a call where the caller terminates the call after reception of the ringing tone without engaging in any speech. Figure 4-2 shows the effect of flashing on performance. The graphs (a-d) in Figure 4-2 show the variation in blocking probability as the proportion of initial call attempts that are flashes increases for different levels of traffic per user (4.2a – 20 mErlang per user, 4.2b – 25 mErlang per user, 4.2c – 30 mErlang per user, 4.2d – 35 mErlang per user,). It can be seen from the Figures that irrespective of the traffic level per user the probability of blocking increases as the proportion of flashes increases. The degradation in blocking probability is however not very pronounced for low levels of traffic per user.

The result can be rationalised with the explanations given in Section 4.1.1. The problem is however compounded here since the flashes are basically calls with no speech component and thus place the same amount of signalling and ringing tone traffic burden on the network as actual calls involving speech.

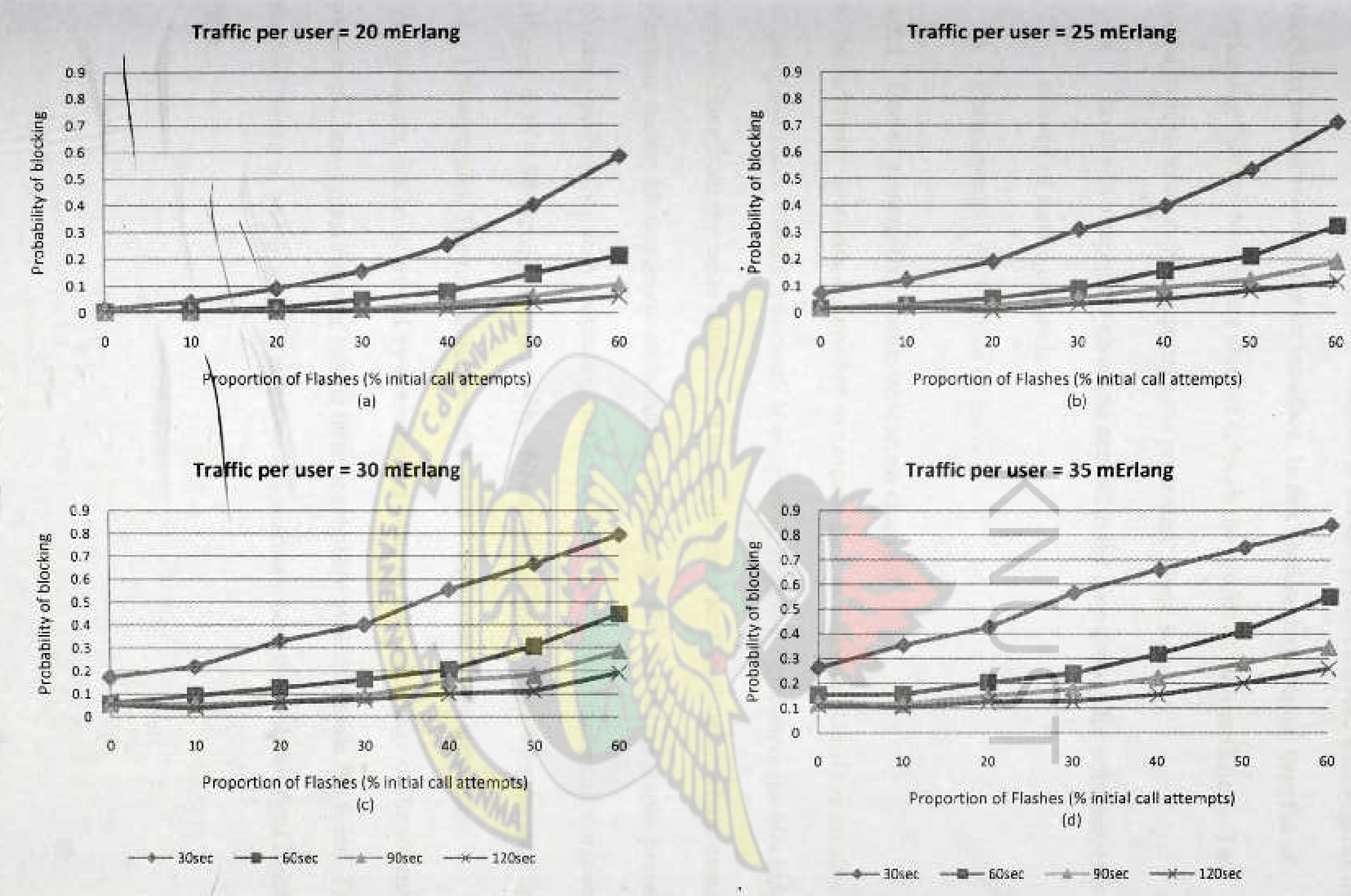

Figure 4-2: Effects of Flashing

4.2 Modified user behaviour

As has been observed above, user behaviour plays a significant role with regards to blocking probabilities at the air interface. In this section the potential benefits of harnessing this knowledge are studied through the results of the simulations. Two modifications to user calling pattern are presented. These being

- The use of alternative channels present at the air interface for communication instead of traffic channels
- Postponement of the time of the call

4.2.1 Use of alternative communication channel

In this scenario users are assumed to use means such as SMS and USSD as an alternative to using the voice when the network is congested. Figure 4-3 compares the blocking probabilities from the basic model with those obtained for the situation where users use alternate means for communication during congestion. The individual graphs present the blocking probability with increasing traffic per user for different mean call durations (Figure 4-3a – 30 seconds, Figure 4-3b – 60 seconds, Figure 4-3c – 90 seconds, Figure 4-3d – 120 seconds). The results as seen in Figure 4-3 indicate that a significant improvement can be achieved by encouraging users to take advantage of the alternative means of communication over the air interface that are available aside the voice. This method seems to be particularly effective in situation where the probability of blocking is high.

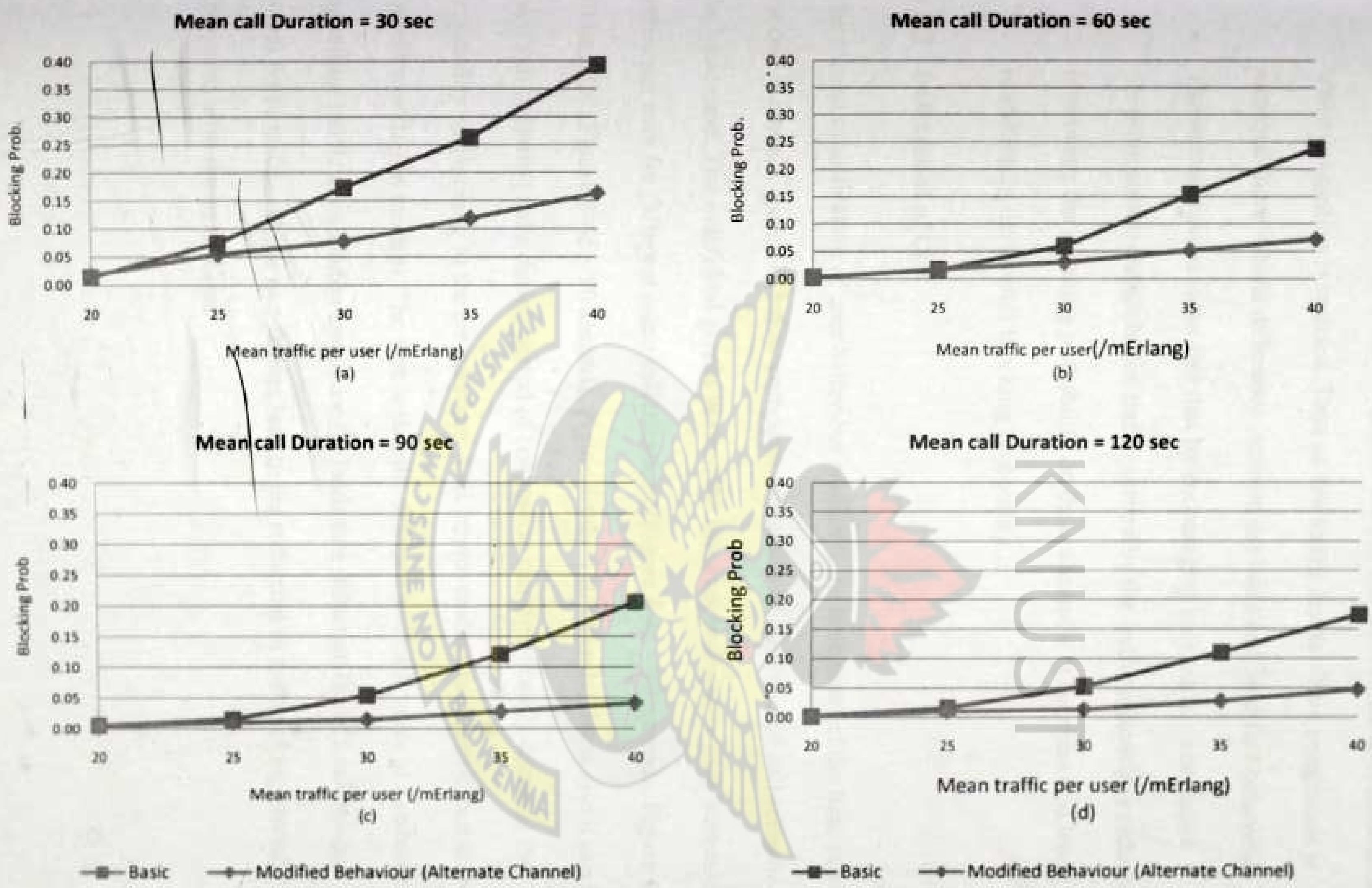

Figure 4-3: Comparison of Blocking Probabilities - basic model and model with signalling channels as alternative to traffic channels

A number of reasons can be given to justify the above observations.

- Firstly callers are only encouraged to use the alternative means of communication when congestion is realised. Thus as low traffic levels where congestion is minimal there is little difference between the basic and modified behaviour.
- The second reason is the fact that by encouraging users to use alternative communication channels, the traffic carried by the traffic channels is reduced thus improving the blocking probability on these channels. This reduction leads to a reduction in the overall blocking probability.

4.2.2 Deferment of Call

The second modification of user behaviour studied is the deferment of the time at which the call is made. Figure 4-4 below compares the results of the deferred call scenario with the basic case. The individual graphs present the blocking probability with increasing traffic per user for different mean call durations (Figure 4-4a – 30 seconds, Figure 4-4b – 60 seconds, Figure 4-4c – 90 seconds, Figure 4-4d – 120 seconds). Here also it can be seen that deferring calls during period of congestion can significantly decrease the probability of blocking at the air interface. This improvement can be attributed to two factors working in tandem. The first is that the deferment of calls leads to a reduction is signalling traffic at call setup and secondly leads to a reduction in the total amount of actual voice traffic. These two factors lead to the reduction in the blocking probability compared with the basic case.

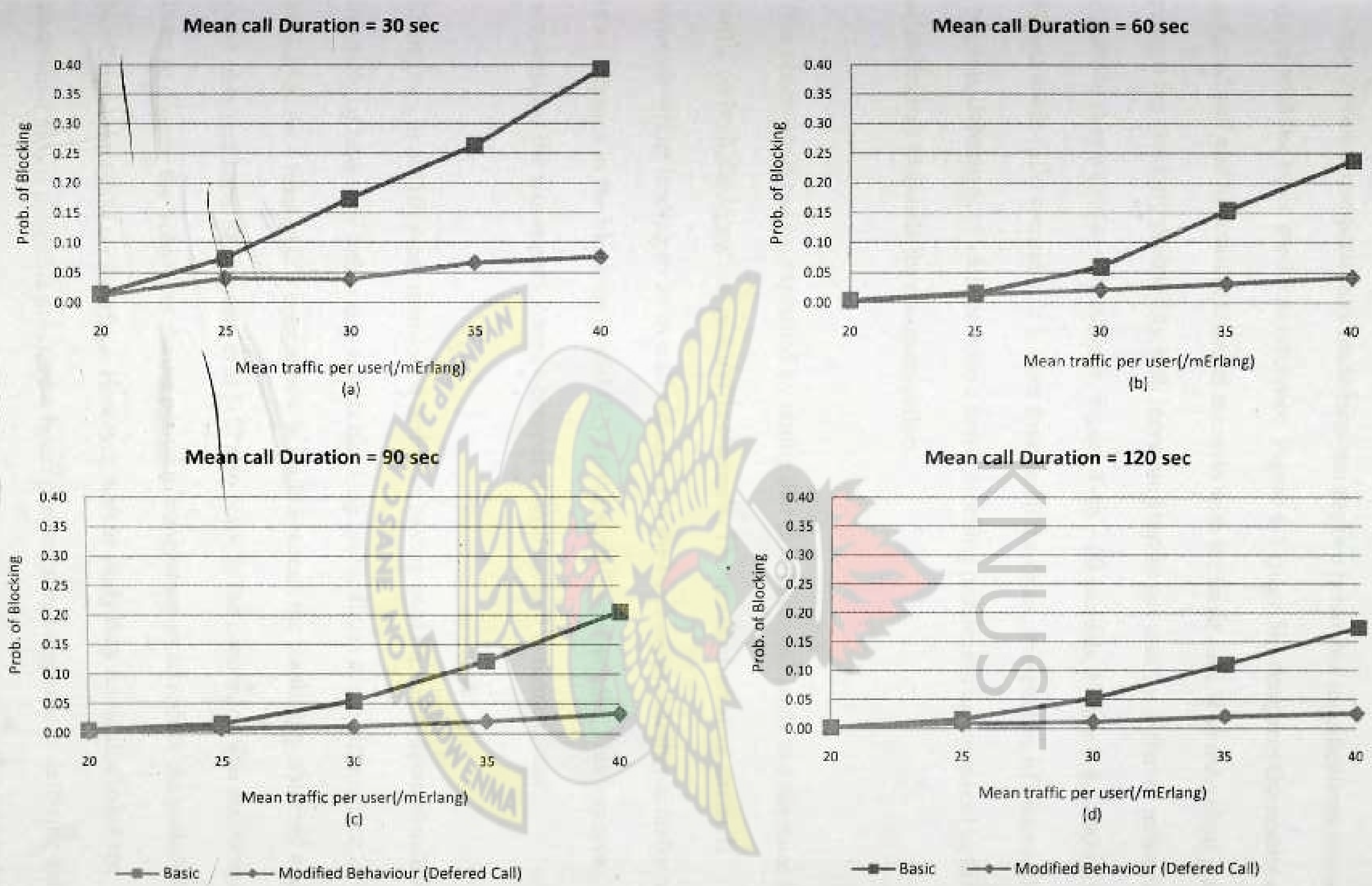

Figure 4-4: Comparison of Blocking Probabilities - Basic behaviour and Call deferment

4.2.3 Comparison

In this section a comparison is made between the two behaviour modifications considered above with the basic model as reference. Figure 4-5 (page 56) compares the results of the deferred call and alternative channel scenario with the basic case. The individual graphs present the blocking probability with increasing traffic per user for different mean call durations (Figure 4-4a – 30 seconds, Figure 4-4b – 60 seconds, Figure 4-4c – 90 seconds, Figure 4-4d – 120 seconds). It is seen from in all the cases, irrespective of mean call duration, deferment of calls provide a better blocking probability as compared to the use of alternative channels for communication.

This observation can be explained by noting that call deferment leads to a decrease in traffic on both the signalling and traffic channels. The use of alternative channels however whilst leading to an overall reduction in the blocking probability actually result in an increase in the blocking probability on the signalling channels. This increase accounts for the worse performance compared with the call deferment case.

Shinagawa et al [10] were mentioned earlier as having used the multi-agent simulation in the study of how user behaviour affects blocking probabilities at the air interface in GSM networks. As a final case a comparison is made between the result they obtained and those obtained here. Shinagawa et al [10] also come to the conclusion that encouraging users to change the behaviour during period of congestion could reduce the probability of blocking at the GSM air interface. However in their study they found that using the alternative means available provided a better performance compared to deferring calls. This difference may arise from difference in the models of user behaviour used in both simulations. Unfortunately as detailed information on their model is unavailable, a thorough analysis of the reason for the difference in the results cannot be made.

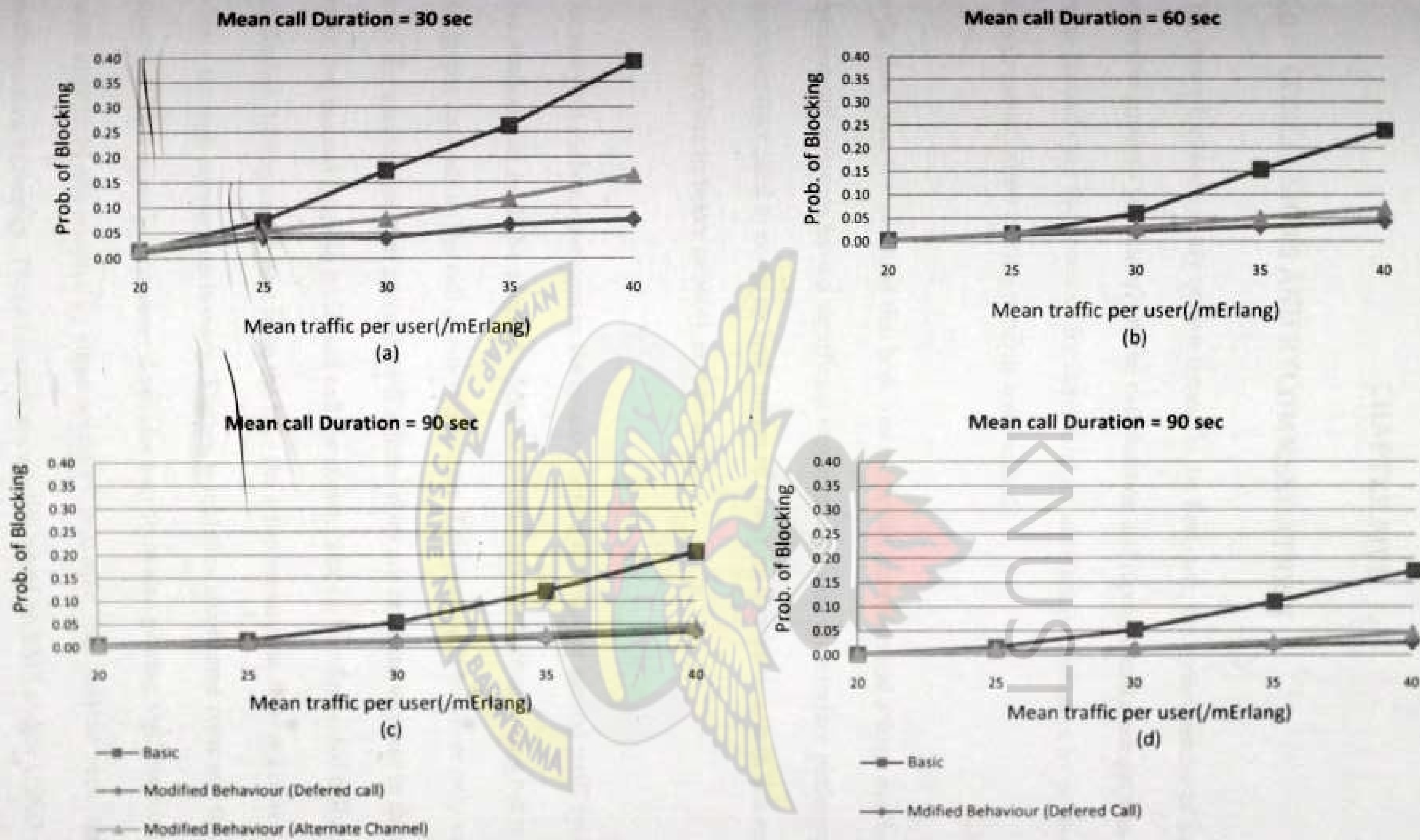

Figure 4-5: Comparison of Blocking Probabilities - Basic behaviour , alternate channels and Call deferment

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

This thesis focused mainly on two issues. In the first case, the consequences of user behaviour patterns particularly mean call duration and repeated call attempts was studied. In the second case the potential for improving air interface performance by encouraging users to modify their calling patterns was studied.

In the first case, it was found that both low mean call durations and a large number of repeated call attempts have a significant negative impact on air interface performance. Operators thus need to come up with means of changing user behaviour in this regard as it will translate to better network performance.

Currently all mobile operators in the country have a flat rate per second tariff system. One method that could be adopted would be to maintain per second billing but reduce the charge per seconds as the call duration increases. This method is however only valid under the assumption that revised tariff scheme does not cause an increase in the offered traffic but instead leads to increased call durations. Since a lot of repeated call attempts are flashes, billing could start from the time the setup message in received instead of when a through connection is made. Flashes would thus incur some costs and thus be less attractive. This approach however dissuades user from also placing legitimate calls. A better approach, one adopted by some operators, is to offer free 'call me back' services as an alternative to flashes. These services are usually based on SMS and/or USSD.

In the second case it was found that encouraging users to modify their call patterns gave significant improvements in air interface performance. Although these gains were not significant at low level of traffic per user, as traffic increased the improvements became obvious with up to 75% reduction in some cases.

During the course of this work, the general principle of providing feedback to users as means of encouraging them to change their call behaviour and thus modulate the traffic offered to the network was applied by one of the network operators in Ghana. Scancom Ghana Limited, which operates under the MTN brand name, introduced a Dynamic Discount Scheme (DDS) based on cell broadcast. Under the scheme tariffs in cells with low traffic are reduced and users informed of the reduction via cell broadcast. DDS varies from the use cases studied in this work by the fact that it seeks to increase rather than decrease traffic offered to the network. However the general principle of encouraging users to modify their behaviour as a means of controlling the traffic offered to the network is applied. This approach has been shown in this work to be a viable means of traffic control.

The model used in this study used the blocking probability at the air interface as the basic means of measuring air interface performance. The results obtained were more of a qualitative rather than a quantitative nature. This is due, however, to the MAS simulation methodology. This methodology was outlined in Section 2.8. Recent work [32] however suggests more analytical methods of performing MAS simulations. These new approaches can be used in further studies that seek to gather more information beyond the blocking probability at the air interface.

Some of the solutions and cases suggested above involve the use of SMS and USSD. These services use the same channels used for signalling procedures associated with voice channel allocation at the air interface. Given the current popularity of SMS, further increase in the usage of this service may result in failed voice call setups due to a lack of signalling resources. Careful consideration thus needs to be given to the allocation of resources at the air interface in the light of the new demands.

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Appendix

A.1 Simulation code

A.1.1 General Comments

Procedures in the code start with the "*to*" keyword and end with the "*end*" key word. Each state in the model in fig 3-2 is associated with two procedures. The first has a name of the form "go_*colour*" where colour is white, green, yellow, grey, green or blue. These procedures are executed when the caller agent enter the state associated with the colour in the name. The second has a name "color_*" where * is a number. These procedures are executed when the caller exits its current state. The state associated with the procedure is indicated in the comments describing the procedure. The amount of time spend in any state in controlled by the time_left variable which is decremented every simulation cycle the monitor_state procedure.

Comments in the code begin with a semi colon. Comments that follow after a procedure definition give a description of the function of the procedure. Comments on lines containing code concern the lines on which they are located.

Due to the space considerations only the code for the first set of simulations is presented

A.1.2 Code Listing first Simulation set

```
breed [callers caller]
breed [stations station]

;custom caller properties
callers-own [
```

```
    time_left       ;time left for current state
    retrials        ;number of retrials
    redials         ;number of redials
    base_station    ;associated base station
    speed           ;caller speed
    flash]          ;number of flashes

;global varialbes
globals [
    tch_request_attempt
    tch_request_success
    sig_request_attempt
    sig_request_success
    idle_time
    mean_flash_time]

to setup
;This procedure sets up the simulation and run via the setup button

  clear-all                                   ;clear all agents
  set-default-shape stations "circle"
  let er Erlang / 1000
  let fp Flashing_Prop / 100
  set mean_flash_time 15
  set idle_time round (Call_duration / er) * (1 - fp)    ;determine mean idle time duration from mean traffic per user and flashing proportions
  make_stations                                ;create base station agents
```

```
 make_callers number                    ;create caller agents
end

to go
;This procedure is run every simulation cycle. Each cycle is taken to be 1 sec

;each caller modifies it currents state and changes its position
ask-concurrent callers[
  monitor_state
  move]
 tick

 ;At the start of the simulation the blocking probability is very low since all callers are initally idle
 ;The block below resets the global varialbes until a simulation time is at least two times the mean idle time
 ifelse (ticks < idle_time * 2)[
  set tch_request_attempt 0
  set tch_request_success 0
  set sig_request_attempt 0
  set sig_request_success 0]

  [update_plots]
 end


 to make_callers [num]
```

```
;this procedure creates the caller agents at the beginning of each simulation

 create-callers num [
  setxy random-xcor random-ycor            ;set callers position to a random point in simulation area
  set color white                       ;set initial state to idle
  set time_left idle_time_distrib              ;spread initial idle time so that callers do not start calling at once and cause congestion at initial stages
  set speed (random 70) / 100                   ;set speed of agent
  set base_station min-one-of stations [distance myself]] ;determine base station
end


to monitor_state
;this procedure modifies the time_left variable.
;when it reaches zero the callers changes state

  let my_color word "color_" color
  ifelse(time_left = 0)
  [run my_color]
  [set time_left time_left - 1]
 end

 to color_105
 ;current colour is blue ==> currently using signalling channel
 ;This procedure is run at the caller has finishe occupying a signalling channel

  ifelse(request_tch_channel base_station)    ;request signalling channel
```

```
  [go_green]                 ;channel request granted
  [ifelse(redials_distrib?)  ;channel request not granted, decide whether to redial or go into the idle state
    [go_grey]                ;redial
    [go_white]]              ;go into the idle state
end

to color_55
;current colour is green ==> currently using a traffic channel
;this procedure is run after the caller has successfully occupied a signalling channel

  go_white                   ;go into the ilde state
 end

to color_9.9
;current colour is white ==> currenlty idle
;this procedure is run at the end of the idle period

 ifelse(flash = 0)                      ;Have there been any previous flashes ?
  [ifelse(random 100 < Flashing_Prop)         ;(NO- previous flashes)Is this attempt a flash?
    [set flash flash + 1                ;(YES - attempt is a flash) increase counter
    ifelse(request_sig_channel base_station)     ;Is a signalling channel available?
      [go_blue]                         ;(YES - signalling available) change state accordingly
      [go_yellow]]                      ;(NO - signalling no available) change state accordingly
    [ifelse(request_sig_channel base_station)    ;(NO - attempt not a flash)Is a signalling channel available?
      [go_blue]                         ;(YES - signalling available) change state accordingly
      [go_yellow]]]                     ;(NO - signalling no available) change state accordingly
```

```
[ifelse(flash_distrib?)                 ;(YES- previous flashes) flash again?
 [set flash flash + 1                   ;(YES - flash again) increase counter
 ifelse(request_sig_channel base_station)      ;Is a signalling channel available?
  [go_blue]                             ;(YES - signalling available) change state accordingly
  [go_yellow]]                          ;(NO - signalling no available) change state accordingly
 [set flash 0                           ;(NO - do not flash again) increase counter
 go_white]]                             ;go idle

end

to color_45
; current colour is yellow ==> retrying
; this procedure is run during the automatic redial state

set retrials retrials + 1               ;increase retrial counter
ifelse(retrials <= 3)                   ;is counter less than maximun allowed
 [ifelse(request_sig_channel base_station)     ;(YES)request signalling channel
  [go_blue]                             ;(signalling channel is granted), change state
  [set time_left 1]]                    ;(signalling channel not granted), reset timeleft counter
 [set retrials 0                        ;(NO)reset retrial counter
 ifelse(redials_distrib?)               ;redial?
  [go_grey]                             ;(YES)redial
  [go_white]]                           ;(NO)go into the idle state
end

to color_5
```

```
;current colour is grey ==> waiting to redial
;this procedure is run at end of brief prediods between redial attempts

set redials redials + 1                    ;increase redial counter
ifelse(request_sig_channel base_station)                  ;request signalling channel
 [go_blue]                                 ;signalling channel granted
 [go_yellow]                               ;automatically retry
end

to go_blue   ;change color to blue ==> signalling channel has been allocagted
  set color blue                 ;change colour to blue
  set retrials 0                 ;clear the retrials counter
  set time_left 2                ;set time_left counter
 end

 ;original go_green procedure
 to go_green   ;change colour to green ==> moving to active state with tch allocated
  set color green                              ;change colour to green
  set retrials 0                               ;reset retrials counter
  set redials 0                                ;reset redials counter
  ifelse(flash != 0)                           ;is this a flash?
    [set time_left flash_time_distrib]                    ;(YES)set timer accordingly
    [set time_left (flash_time_distrib + call_time_distrib)]   ;actual call -set timer accordingly

 end
```

```
to go_yellow    ;change colour to yellow ==> moving into retrial state
  set color yellow                          ;change colour to yellow
  set retrials 0                          ;reset retrial counter
  set time_left 1                          ;set time left
end

to go_white    ;change colour to white ==> change into the idle state
  set retrials 0                        ;reset retrials counter
  set redials 0                         ;reset redials counter
  ifelse(color = green)[                 ;check current colour ==> green implies traffic channel allocation just ending
   ifelse(flash = 0)                     ;flash = 0 ==> last traffic channel allocation was not a flash
    [set time_left idle_time_distrib]           ;set time left counter accordingly
    [ifelse(flash_distrib?)                ;last channel allocation was flash set time left accordingly
     [set time_left inter_flash_time_distrib]             ;engage in another call attempt
     [set time_left idle_time_distrib              ;go idle for long period time
     set flash 0]]                      ;reset flash counter as well
  ][
   set time_left idle_time_distrib             ;current colour not green ==> giving up after automatic retrys, manual and manual retrys. Go idle for a long
  period of time
  ]
  set color white                       ;finally change colour to white
end

to go_grey                              ;change colour to grey ==> waiting to redial manually
  set color grey                          ;set color to grey
  set retrials 0                        ;reset retrials counter
```

```
 set time_left redials_time_distrib              ;reset time left counter
end

to make_stations
;create base stations
let r 78                          ;radius of cell taken to be 500 meters
let angle (atan 1 (3 * sqrt (3)))
foreach [0 30 90 150 210 270 330] [
   create-stations 1[
     set heading ?
     set size 3
     if(? != 0)[jump r * sqrt (3)]
    set color red
  ]]
 end

 to-report request_sig_channel [bs]
 ;this produre to used by callers to request a signalling channel from the associated base station
 ;each base station has four signalling channels

 ;inputs: bs => ref. to associated base station
 ;outputs: true => caller granted signalling channel, false => caller not granted channel

   let ans false
   set sig_request_attempt sig_request_attempt + 1                 ;increase variable
   without-interruption[
```

```
  ifelse(count callers with [base_station = bs and color = blue] < 4)  ;are there free signalling channels?
  [set sig_request_success sig_request_success + 1                    ;(YES) increase variable
   set ans true]                                     ;return true
  [set ans false]]                                   ;(NO) return false
  report ans
end

to-report request_tch_channel [bs]
;this produre to used by callers to request a traffic channel from the associated base station
;each base station has 16 traffic channels

;inputs: bs => ref. to associated base station
;outputs: true => caller granted signalling channel, false => caller not granted channel

  let ans false
  set tch_request_attempt tch_request_attempt + 1                ;increase variable
  without-interruption[
   ifelse(count callers with [base_station = bs and color = green] < channels) ;are there free traffic channels?
   [set tch_request_success tch_request_success + 1                  ;(YES) increase variable
    set ans true]                                    ;return true
   [set ans false]]                                  ;(NO) return false
   report ans
 end

 to-report call_time_distrib
 ;this procedure is called when the caller moves into the speech state
```

```
;output: exponential distributed random number with mean equal to mean call distribution
;       the return value is used to set the time_left variable of the caller
;       this determines how long the caller spends in the specifed state

 report round (random-exponential Call_Duration)
end

to-report idle_time_distrib
;this procedure is called when the caller moves into the idle state

;output: exponential distributed random number with mean equal to mean idle time
;       the return value is used to set the time_left variable of the caller
;       this determines how long the caller spends in the specifed state

 report round (random-exponential idle_time)
end

to-report redials_distrib?
 ifelse(((0.5) ^ (redials + 1)) * 100  < random 100)
   [report true]
   [report false]
end

to-report redials_time_distrib
;this procedure is called when the caller moves into the redial state
```

```
;output: exponential distributed random number with mean equal to mean 5 sec
;       the return value is used to set the time_left variable of the caller
;       this determines how long the caller spends in the specifed state

 report round (random-exponential 5 )
end

to-report flash_time_distrib
;this procedure is called when the caller moves into the ringing state

;output: uniformly distributed random number with mean equal to mean idle time
;       the return value is used to set the time_left variable of the caller
;       this determines how long the caller spends in the specifed state

 report round (random (mean_flash_time * 2) )
 end

 to-report flash_distrib?
 ;this procedure determines whether a new call attemp is a flash or one that involves speech

 ;output: true => attempt is a flash. false => attempt is not a flash

 ifelse(((0.5) ^ (flash)) * 100  < random 100)
   [report true]
   [report false]
```

```
end

to-report inter_flash_time_distrib
;this procedure is called when the caller moves into the idle state after a flash

;output: exponential distributed random number with mean equal to mean 10 secs
;      the return value is used to set the time_left variable of the caller
;      this determines how long the caller spends in the specifed state

 report round (random-exponential 10)
 end

 to move
 ;this procedure is run every simulation cycle to modify the callers position

    set heading (heading + random 20 - 10)      ;change current heading
    forward speed                               ;move forward
    update_base_station
 end

 to update_base_station
   let new_base_station min-one-of stations [distance myself]    ;determine nearest base station
   if (new_base_station != base_station)                      ;has base station changed?
    [                                      ;(YES - base station has changed)
    ifelse (color = green)                          ;is caller active?
     [ifelse(retrials < 3)[                         ;(YES - caller active)is maximum number of retrials exceeded?
```

```
ifelse(request_tch_channel new_base_station)             ;(NO)request  new traffic channel
 [                                               ;channel granted
  set retrials 0                                      ;reset retrials counter
  set base_station new_base_station                            ;re associate with new base station
 ][                                              ;channel not granted
  set retrials retrials + 1                              ;increase retrial counter
]][                                              ;(yes - max retrials exceeded)==>handover failure, drop the call
 set base_station new_base_station                             ;re associate with new base station
 if(redials_distrib?)[go_grey]                              ;treat failed handover as failed call attempt
]][                                             ;(NO - caller not active)
 ifelse(color = yellow or color = blue)                   ;is caller in retrial state?
  [                                              ;(YES - retrial state)
   set base_station new_base_station                         ;re associate with new base station
   if(redials_distrib?)[go_grey]                         ;treat failed handover and failed call attempt
  ][                                             ;(NO - not in retrial state)==> caller in idle
   set base_station new_base_station                         ;re associate with new base station
 ]]]
end

to update_plots
 set-current-plot "states"
 set-current-plot-pen "yellow"
 plot count turtles with [color = yellow]
 set-current-plot-pen "green"
 plot count turtles with [color = green]
 set-current-plot-pen "blue"
```

```
  plot count turtles with [color = blue]
    set-current-plot-pen "grey"
  plot count callers with [redials > 0]
  if (plot-x-max > 1000)[
    set-plot-x-range (plot-x-max - 850) plot-x-max]
end
```

A.2 Simulation results

The results of the simulation presented below along with the calculated results obtained by applying s equations 3-1 to3-5. They are repeated below for reference.

$$P_s = \frac{No.Sig\ Ch.Grants}{No.Sig\ Ch.Requests} \quad \text{------------ 3-1}$$

$$P_t = \frac{No.tch\ Ch.Grants}{No.tch\ Ch.Requests} \quad \text{------------ 3-2}$$

$$P_{bs} = 1 - P_s \quad \text{------------ 3-3}$$

$$P_{bt} = 1 - P_t \quad \text{------------ 3-4}$$

$$P_b = 1 - P_t P_s \quad \text{------------ 3-5}$$

Table A-1 Results from simulations with basic model

#	Prop of Flashing	Erlang/ user	Mean Call Duration/sec	# TCH Channel requests	# TCH Channel grants	# Sig Channel requests	# Sig Channel grants	P_{bt}	P_{bs}	P_b
1	0	20	30	10132	10001	8860	8844	0.012929	0.001806	0.014712
2	0	20	60	10034	10000	8116	8115	0.003388	0.000123	0.003511
3	0	20	90	10050	10000	7414	7412	0.004975	0.00027	0.005244
4	0	20	120	10021	10000	6784	6784	0.002096	0	0.002096
5	0	25	30	10715	10000	9435	9365	0.066729	0.007419	0.073653
6	0	25	60	10162	10000	8114	8110	0.015942	0.000493	0.016427

7	0	25	90	10158	10000	7577	7575	0.015554	0.000264	0.015814
8	0	25	120	10165	10001	6983	6983	0.016134	0	0.016134
9	0	30	30	11912	10001	10476	10314	0.160426	0.015464	0.17341
10	0	30	60	10623	10000	8628	8617	0.058646	0.001275	0.059846
11	0	30	90	10573	10000	7814	7812	0.054195	0.000256	0.054437
12	0	30	120	10551	10000	7319	7318	0.052223	0.000137	0.052352
13	0	35	30	13060	10000	11836	11394	0.234303	0.037344	0.262897
14	0	35	60	11765	10000	9489	9450	0.150021	0.00411	0.153515
15	0	35	90	11373	10001	8468	8458	0.120637	0.001181	0.121675
16	0	35	120	11238	10001	7852	7849	0.110073	0.000382	0.110413
17	0	40	30	15309	10002	14409	13385	0.346659	0.071067	0.39309
18	0	40	60	13003	10000	10604	10507	0.230947	0.009147	0.237982
19	0	40	90	12563	10000	9411	9388	0.204012	0.002444	0.205957
20	0	40	120	12099	10000	8418	8409	0.173485	0.001069	0.174369
21	10	20	30	11505	11113	10384	10312	0.034072	0.006934	0.04077
22	10	20	60	11175	11113	9529	9519	0.005548	0.001049	0.006592
23	10	20	90	11147	11113	9048	9047	0.00305	0.000111	0.00316
24	10	20	120	11140	11112	8876	8875	0.002513	0.000113	0.002626
25	10	25	30	12403	11114	11308	11077	0.103926	0.020428	0.122231
26	10	25	60	11449	11112	9736	9721	0.029435	0.001541	0.03093
27	10	25	90	11423	11115	9212	9210	0.026963	0.000217	0.027174
28	10	25	120	11343	11112	8860	8858	0.020365	0.000226	0.020586
29	10	30	30	13655	11112	12695	12166	0.186232	0.04167	0.220142
30	10	30	60	12218	11113	10489	10445	0.09044	0.004195	0.094256
31	10	30	90	11743	11113	9502	9494	0.053649	0.000842	0.054446

32	10	30	120	11557	11112	8812	8807	0.038505	0.000567	0.03905
33	10	35	30	15748	11113	15499	14182	0.294323	0.084973	0.354287
34	10	35	60	13067	11113	11103	11012	0.149537	0.008196	0.156507
35	10	35	90	12532	11113	10046	10023	0.11323	0.002289	0.11526
36	10	35	120	12387	11112	9365	9358	0.10293	0.000747	0.103601
37	10	40	30	17564	11112	18127	15767	0.367342	0.130193	0.44971
38	10	40	60	14664	11112	12667	12446	0.242226	0.017447	0.255447
39	10	40	90	14053	11113	11383	11322	0.209208	0.005359	0.213446
40	10	40	120	13947	11113	10635	10617	0.203198	0.001693	0.204546
41	20	20	30	13407	12502	12624	12315	0.067502	0.024477	0.090327
42	20	20	60	12705	12500	11233	11203	0.016135	0.002671	0.018763
43	20	20	90	12578	12501	10655	10646	0.006122	0.000845	0.006961
44	20	20	120	12541	12501	10259	10258	0.00319	9.75E-05	0.003287
45	20	25	30	14711	12500	14078	13404	0.150296	0.047876	0.190976
46	20	25	60	13127	12500	11520	11449	0.047764	0.006163	0.053633
47	20	25	90	12847	12501	10939	10929	0.026932	0.000914	0.027822
48	20	25	120	12607	12500	10526	10523	0.008487	0.000285	0.00877
49	20	30	30	16763	12501	16957	15234	0.25425	0.10161	0.330026
50	20	30	60	14164	12500	12623	12476	0.117481	0.011645	0.127758
51	20	30	90	13334	12500	11350	11325	0.062547	0.002203	0.064612
52	20	30	120	13352	12500	10813	10798	0.063811	0.001387	0.065109
53	20	35	30	18607	12502	19911	16996	0.328102	0.146401	0.426469
54	20	35	60	15401	12502	13766	13499	0.188235	0.019396	0.203979
55	20	35	90	14633	12501	12284	12232	0.145698	0.004233	0.149314
56	20	35	120	14249	12501	11733	11685	0.122675	0.004091	0.126264

57	20	40	30	20954	12500	25079	19272	0.403455	0.231548	0.541584
58	20	40	60	16462	12503	14902	14470	0.240493	0.028989	0.262511
59	20	40	90	15504	12501	13060	12956	0.193692	0.007963	0.200113
60	20	40	120	15270	12502	12454	12408	0.18127	0.003694	0.184295
61	30	20	30	15960	14286	15645	14776	0.104887	0.055545	0.154606
62	30	20	60	14894	14286	13484	13373	0.040822	0.008232	0.048718
63	30	20	90	14453	14288	12769	12741	0.011416	0.002193	0.013584
64	30	20	120	14377	14286	12486	12476	0.00633	0.000801	0.007125
65	30	25	30	18328	14289	19016	16837	0.220373	0.114588	0.309709
66	30	25	60	15514	14288	14061	13870	0.079025	0.013584	0.091536
67	30	25	90	15095	14287	13159	13122	0.053528	0.002812	0.056189
68	30	25	120	14767	14286	12744	12716	0.032573	0.002197	0.034698
69	30	30	30	19962	14287	21812	18214	0.28429	0.164955	0.40235
70	30	30	60	16651	14287	15266	14881	0.141973	0.025219	0.163612
71	30	30	90	15676	14288	13816	13730	0.088543	0.006225	0.094217
72	30	30	120	15401	14286	13031	12984	0.072398	0.003607	0.075744
73	30	35	30	23106	14292	30091	21131	0.381459	0.297763	0.565638
74	30	35	60	18109	14287	16837	16214	0.211055	0.037002	0.240248
75	30	35	90	17096	14286	15128	14919	0.164366	0.013815	0.175911
76	30	35	120	16309	14286	13836	13766	0.124042	0.005059	0.128474
77	30	40	30	25247	14295	35717	23315	0.433794	0.34723	0.630398
78	30	40	60	19995	14288	18781	17724	0.285421	0.05628	0.325638
79	30	40	90	18392	14287	16020	15782	0.223195	0.014856	0.234735
80	30	40	120	17823	14286	15186	15070	0.198451	0.007639	0.204574
81	40	20	30	19962	16669	20753	18563	0.164963	0.105527	0.253082

82	40	20	60	17738	16670	16615	16261	0.06021	0.021306	0.080233
83	40	20	90	17187	16667	15397	15334	0.030255	0.004092	0.034223
84	40	20	120	16914	16668	15028	14983	0.014544	0.002994	0.017495
85	40	25	30	22283	16667	25630	20650	0.252031	0.194304	0.397364
86	40	25	60	19060	16668	18007	17329	0.125498	0.037652	0.158425
87	40	25	90	18174	16667	16438	16248	0.082921	0.011559	0.093521
88	40	25	120	17488	16667	15363	15300	0.046946	0.004101	0.050855
89	40	30	30	25562	16669	34788	23754	0.347899	0.317178	0.554731
90	40	30	60	20043	16668	18973	18096	0.168388	0.046224	0.206828
91	40	30	90	19409	16669	17560	17233	0.141172	0.018622	0.157165
92	40	30	120	18409	16667	16207	16077	0.094628	0.008021	0.10189
93	40	35	30	28023	16667	45575	25974	0.405239	0.430082	0.661035
94	40	35	60	22482	16667	22161	20377	0.258651	0.080502	0.318331
95	40	35	90	20894	16672	18842	18378	0.202068	0.024626	0.221717
96	40	35	120	19508	16670	17094	16917	0.145479	0.010355	0.154327
97	40	40	30	30649	16673	65178	28588	0.456002	0.561386	0.761395
98	40	40	60	24452	16667	25028	22108	0.318379	0.116669	0.397903
99	40	40	90	22363	16670	20591	19804	0.254572	0.038221	0.283063
100	40	40	120	21058	16669	18549	18251	0.208424	0.016066	0.221141
101	50	20	30	26190	20002	31314	24428	0.236273	0.219902	0.404218
102	50	20	60	22433	20001	21584	20668	0.108412	0.042439	0.14625
103	50	20	90	21027	20001	19433	19146	0.048794	0.014769	0.062842
104	50	20	120	20670	20000	18709	18586	0.032414	0.006574	0.038775
105	50	25	30	29118	20001	40097	27180	0.313105	0.322144	0.534384
106	50	25	60	23676	20001	23357	21802	0.15522	0.066575	0.211462

107	50	25	90	22260	20002	20651	20135	0.101438	0.024987	0.12389
108	50	25	120	21561	20000	19489	19264	0.072399	0.011545	0.083108
109	50	30	30	31855	20004	56147	29715	0.37203	0.470764	0.667656
110	50	30	60	25946	20002	26508	23764	0.229091	0.103516	0.308893
111	50	30	90	23592	20002	22136	21315	0.15217	0.037089	0.183615
112	50	30	120	22297	20000	20134	19869	0.103018	0.013162	0.114824
113	50	35	30	34196	20008	75021	31968	0.414902	0.573879	0.750678
114	50	35	60	28804	20002	31205	26393	0.305583	0.154206	0.412666
115	50	35	90	25996	20000	25098	23460	0.230651	0.065264	0.280862
116	50	35	120	24401	20001	21970	21434	0.18032	0.024397	0.200318
117	50	40	30	35895	20003	103524	33612	0.442736	0.675322	0.819068
118	50	40	60	31881	20003	37132	29037	0.372573	0.218006	0.509356
119	50	40	90	27930	20000	27445	25081	0.283924	0.086136	0.345604
120	50	40	120	26768	20006	24769	23773	0.252615	0.040212	0.282669
121	60	20	30	35920	25002	56571	33709	0.303953	0.404129	0.585246
122	60	20	60	29065	25003	29419	26930	0.139756	0.084605	0.212537
123	60	20	90	27191	25002	25892	25118	0.080505	0.029893	0.107991
124	60	20	120	26282	25000	24429	24076	0.048779	0.01445	0.062524
125	60	25	30	39149	25002	82094	36785	0.361363	0.551916	0.713837
126	60	25	60	31839	25001	34307	29496	0.214768	0.140234	0.324884
127	60	25	90	29254	25000	28369	26886	0.145416	0.052275	0.19009
128	60	25	120	27594	25003	25782	25112	0.093897	0.025987	0.117444
129	60	30	30	40839	25001	114157	38352	0.387816	0.664042	0.794332
130	60	30	60	35403	25002	41981	32763	0.293789	0.219576	0.448855
131	60	30	90	31943	25006	32093	29201	0.217168	0.090113	0.287711

132	60	30	120	29776	25000	27845	26803	0.160398	0.037421	0.191817
133	60	35	30	41904	25004	148006	39450	0.403303	0.733457	0.840954
134	60	35	60	38481	25002	51663	35668	0.350277	0.309603	0.551433
135	60	35	90	34054	25001	34838	31036	0.265842	0.109134	0.345964
136	60	35	120	31585	25001	30504	28547	0.208453	0.064156	0.259235
137	60	40	30	42522	25001	193670	40085	0.412046	0.793024	0.878308
138	60	40	60	41125	25000	64815	38308	0.392097	0.408964	0.640708
139	60	40	90	37009	25004	41524	34046	0.324381	0.180089	0.446052
140	60	40	120	34513	25002	34603	31300	0.275577	0.095454	0.344726

Table A-2 Results from simulations with alternate model (Alternate Channels)

#	Prop of Flashing	Erlang/ user	Mean Call Duration/sec	# TCH Channel requests	# TCH Channel grants	# Sig Channel requests	# Sig Channel grants	P_{bt}	P_{bs}	P_b
1	0	20	30	10163	10000	8918	8899	0.016039	0.002131	0.018135
2	0	20	60	10019	10001	8131	8129	0.001797	0.000246	0.002042
3	0	20	90	10033	10000	7545	7545	0.003289	0	0.003289
4	0	20	120	10008	10000	6957	6956	0.000799	0.000144	0.000943
5	0	25	30	10479	10000	9923	9838	0.04571	0.008566	0.053885
6	0	25	60	10176	10001	8565	8561	0.017197	0.000467	0.017656
7	0	25	90	10106	10001	7638	7638	0.01039	0	0.01039
8	0	25	120	10097	10001	7324	7323	0.009508	0.000137	0.009643
9	0	30	30	10658	10000	11316	11129	0.061738	0.016525	0.077243
10	0	30	60	10299	10002	9644	9635	0.028838	0.000933	0.029744
11	0	30	90	10147	10000	8837	8833	0.014487	0.000453	0.014933
12	0	30	120	10138	10000	8205	8205	0.013612	0	0.013612
13	0	35	30	10936	10000	12703	12246	0.085589	0.035976	0.118486
14	0	35	60	10502	10002	10648	10609	0.04761	0.003663	0.051098
15	0	35	90	10287	10000	9671	9665	0.027899	0.00062	0.028502
16	0	35	120	10285	10002	8851	8849	0.027516	0.000226	0.027736
17	0	40	30	11256	10000	14334	13498	0.111585	0.058323	0.1634
18	0	40	60	10712	10000	11453	11393	0.066468	0.005239	0.071358
19	0	40	90	10427	10000	10120	10108	0.040951	0.001186	0.042089
20	0	40	120	10480	10000	9563	9553	0.045802	0.001046	0.046799

Table A-3 Results from simulations with alternate model (Call deferment)

#	Prop of Flashing	Erlang/ user	Mean Call Duration/sec	# TCH Channel requests	# TCH Channel grants	# Sig Channel requests	# Sig Channel grants	Pbt	Pbs	Pb
1	0	20	30	10094	10000	8855	8836	0.009312	0.002146	0.011438
2	0	20	60	10026	10001	8033	8031	0.002494	0.000249	0.002742
3	0	20	90	10016	10000	7436	7435	0.001597	0.000134	0.001732
4	0	20	120	10014	10000	6988	6988	0.001398	0	0.001398
5	0	25	30	10364	10000	9112	9057	0.035122	0.006036	0.040946
6	0	25	60	10132	10000	8145	8138	0.013028	0.000859	0.013876
7	0	25	90	10072	10000	7426	7424	0.007149	0.000269	0.007416
8	0	25	120	10090	10000	7012	7012	0.00892	0	0.00892
9	0	30	30	10366	10000	9060	9020	0.035308	0.004415	0.039567
10	0	30	60	10212	10000	8199	8195	0.02076	0.000488	0.021238
11	0	30	90	10119	10002	7579	7579	0.011562	0	0.011562
12	0	30	120	10114	10000	7066	7066	0.011272	0	0.011272
13	0	35	30	10611	10000	9397	9311	0.057582	0.009152	0.066207
14	0	35	60	10312	10000	8329	8317	0.030256	0.001441	0.031653
15	0	35	90	10205	10000	7571	7570	0.020088	0.000132	0.020218
16	0	35	120	10206	10000	7109	7108	0.020184	0.000141	0.020322
17	0	40	30	10728	10001	9467	9384	0.067767	0.008767	0.07594
18	0	40	60	10429	10000	8402	8394	0.041135	0.000952	0.042048
19	0	40	90	10344	10000	7674	7672	0.033256	0.000261	0.033508
20	0	40	120	10263	10000	7036	7036	0.025626	0	0.025626