TOURNAMENT ARENA SIMULATION FOR A WIRELESS ‘ECOSYSTEM’ IN UNLICENSED BANDS

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ABSTRACT OF THE THESIS

Tournament Arena Simulation for a Wireless 'Ecosystem' in Unlicensed Bands

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The FCC has been allocating sections of the radio spectrum as unlicensed bands over the period of last decade with the motivation of promoting diversity and novelty of wireless systems, services and technologies. The most recent in this series is the Unlicensed National Information Infrastructure (U-NII), a 300 MHz of radio spectrum at 5 GHz, providing promising avenues for modern multimedia applications in 3G systems and beyond.

No license is required to operate in the unlicensed band, though there could be some minimal rules that the systems need to conform to. Due to the significant cost involved in bandwidth acquisition through licensing, the unlicensed bands provide an attractive alternative to service providers in terms of time and cost of development and deployment. This latitude, however comes at the price of enhanced mutual interference because now there are multiple wireless systems, autonomous and non-cooperating, competing for common media resources. WINLAB proposes the novel concept of simulating '*tournaments*' between these competing systems as a way of looking at this problem from the simulation and modeling angle.

This thesis describes the TOURNAMENT ARENA SIMULATOR (TAS), a simulation environment, developed for staging these tournaments between different autonomous wireless systems. The TAS involves modules for radio channel, mobility, geography and the mobile station transceiver to accurately portray all aspects of the real unlicensed band scenario. The transceiver module has the added capability of reconfigurability and dynamic class loading. This endows the TAS with the facility to dynamically reconfigure or rewrite the transceiver module in order to implement different autonomous systems and then make them compete with each other simultaneously. The fundamental system level assumption is that the environment supports only synchronous DS-CDMA systems in a mobile ad-hoc network scenario with point-to-point connections. The implementation is done in the Java binding of the Scalable Simulation Framework (SSF), a new public domain discrete event simulator. The thesis also goes on to demonstrate the utility and the operability of the TAS through performance evaluation of several standard systems and staging of sample tournaments between specific systems of interest.

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Dedication

To my mother, and my father.

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Chapter 1

Introduction

The Federal Communications Commission (FCC) is responsible for managing the electromagnetic frequency spectrum in the US. Wireless service providers who intend to operate and transmit signals in a particular frequency band participate in auctions to acquire radio spectrum, paying the specified license fee to the FCC. Thereafter that specific band of radio spectrum is exclusively owned by that service provider for its sole operative purposes. This is the premise of the licensed bands.

Unlicensed bands are special bands set aside by the FCC and are specified by minimal controls on spectrum usage. No federal license is required to operate in these bands as long as certain minimal rules are obeyed. The premise of unlicensed bands opens up an entirely new gamut of research issues, as described in the following sections, requiring exhaustive analysis and evaluation. Modeling and simulation is an integral part of communications research today because most often, realistic system models are too complex to analyze and too expensive to implement. This thesis focuses on the simulation and modeling aspect of the unlicensed band research at WINLAB by providing a simulation suite to augment the analytical research.

1.1 Context

This work is based on this backdrop of unlicensed band. Over the period of about last decade the FCC has allocated different sections of the radio spectrum as unlicensed bands. Setting aside radio spectrum, free of licensing, has two principal direct consequences. Firstly, the spectrum acquisition becomes much simpler in terms of time and cost. Secondly, operation in the band is more unrestricted and hence less complicated. This has the possibility of promoting diversity and novelty of wireless communication technologies and services and their rapid deployment. The most recent addition to this list of unlicensed bands is the 300 MHz (3 bands of 100 MHz each) of radio spectrum allocated at 5 GHz called the Unlicensed National Information Infrastructure (U-NII). The most exciting feature of the U-NII is the significant amount of bandwidth available for the first time under this category, which opens up promising prospects for modern multimedia applications in Third Generation (3G) wireless communications systems and beyond.

WINLAB research goals for the U-NII

As indicated in the opening paragraphs, the scenario that the premise of unlicensed band presents is radically different from that of licensed bands. Since the operation of the systems in the licensed bands is controlled by the spectrum owner, it implies that the interference faced by one user of the system from the other users of the same system is regulated and hence its characteristics can be controlled. On the other hand, in unlicensed bands, the case is of autonomous systems, possessing possibly different modulation schemes, multi-access methods and traffic characteristics, competing for common radio resources, most probably in a non-cooperative manner. This implies that though the purpose of making radio spectrum free of license and specifying it with minimal rules is to encourage multitude of new and varied wireless systems, if not implemented prudently, it is actually possible that a particular system could preclude the existence of any other system.

This thesis proposes a framework of a *wireless ecosystem* where different service providers and their wireless systems compete for customers and media resources [5]. Each of the wireless systems operating in this *ecosystem* would be evaluated on the basis of two metrics, namely it's *robustness* and it's *fairness*. These metrics define, firstly, the capability of the system to survive in the extreme interference environment and at the same time let other systems co-exist too. The result of these evaluations would give indications about the type of systems and technologies which can cohabit the unlicensed bands in a mutually cooperative fashion. The ultimate goal of the exercise is to make recommendations for robust modulation schemes, media access mechanisms and adaptation strategies that would foster *peaceful coexistence* of service providers, while not overtly restricting and limiting the diversity of possible applications.

The research approach is three-pronged, comprising simulation, modeling and theory. The emphasis is on distillation of useful analytic models from detailed simulations of wireless systems. The proposed methodology to achieve this is to simulate *tournaments* between the varied autonomous systems wherein they compete for the common radio resources. The comparative performance of the individual systems in such scenario would give indications about the types of systems likely to further the goal of a *wireless ecosystem* and would help crystallize the *principles of peaceful co-existence.* A wireless simulation environment is required to serve as the *arena* for holding these tournaments.

1.2 Objective

This thesis addresses design and development of the simulation environment which would serve as that arena to stage the tournaments between the autonomous systems operating in the unlicensed band. This is the Tournament Arena Simulator (TAS). It has been written in the Scalable Simulation Framework (SSF) developed by the S3 consortium [4]. SSF is a relatively new public-domain standard for discrete-event simulation of large, complex systems. SSF models are compact, flexible, portable, and transparently parallelizable. The SSF Application Programming Interface (API) has both C++ and JAVA bindings, with high-performance serial and scalable parallel implementations available. The thesis uses the JAVA binding of the API.

The specific objectives of the thesis are as stated below:

- Design and implement the tournament arena simulation environment JAVA SSF, which includes the radio channel and mobility modeled on a mobile ad-hoc network scenario.

- Implement reconfigurable and dynamically loadable class for transceiver models, which could be coded and configured independently and integrated with the environment dynamically to provide the functionality of creating different participants for the tournaments.

- Demonstrate the operation and utility of the simulator by staging sample tournaments.

1.3 Organization

Chapter 2 discusses the premise of unlicensed bands in general and U-NII in particular. Chapter 3 describes the system model, along with the assumptions involved in detail. Chapters 4 and 5 deal with the specific details of implementation. The former overviews the SSF fundamentals while the later goes into the details of the design of the system model using SSF. Chapter 6 examines the details of dynamic modeling and loading of the transceiver module to implement different wireless systems. Chapter 7 describes performance evaluation of some standard systems, sample tournaments between the transceivers of selected systems and the results thereof. Chapter 8 presents the conclusions and identifies some future trails which could be explored building on this work.

Chapter 2

Unlicensed bands

This chapter performs a detailed study of the unlicensed bands, in general and some of specific examples of the same, in particular.

2.1 Definitions

No license is required to transmit in the unlicensed bands. Further, these bands are characterized by minimal rules pertaining to spectrum usage in terms of radio emission or media access. The motivation behind their allocation is to promote rapid development and deployment of new and diverse wireless systems and technologies. This is fostered by the elimination of the expensive and time consuming process of spectrum acquisition. It also encourages smaller service providers to enter the playing field, increasing the novelty and diversity of ideas and implementation. This latitude, however, comes at the expense of susceptibility to excessive mutual interference. The interferers in this scenario are now not only other transmitting stations of the same system but also those of other systems operating in the same frequency bandwidth. The interference, hence, is unregulated and therefore more difficult to analyze or characterize.

2.2 Examples of unlicensed bands

Following up on the principle stated above, FCC has specified different sections of the radio spectrum as unlicensed bands for specific purposes. The following subsections list three prominent examples of the same.

2.2.1 ISM band

The ISM (Industrial Scientific and Medical) bands were set aside by the FCC in 1989 [1]. There are three distinct ISM bands. The first is a 26 MHz band between 0.902-0.928 GHz, the second is a 83.5 MHz band between 2.4000-2.4835 GHz, and the third is a 125 MHz band at 5.7250-5.8500 GHz (This band now actually overlaps with the U-NII as described in 2.2.3. The ISM band typically refers to only the first two bands.) The ISM bands are open for both voice and data communications. There are restrictions on the maximum allowable transmit power, in-band and out-of-band emission levels and channel definitions. The other fundamental rule for devices operating in this band is that they must use spread spectrum (either Direct Sequence or Frequency Hopping) scheme for media access. However there are no rules pertaining to actual usage of spectrum in terms of scheduling and timing. This band is typically used by applications related to medical telemetry, security systems, industrial and domestic microwave ovens, bar-code scanning devices, PDAs, printers and also wireless LANs. IEEE 802.11 and Bluetooth are recent WLAN standards which operate in the 2.4 GHz ISM band [6], [3]. Devices operating in these bands typically support bit rates of up to 11 Mbps. These are the most populated of the unlicensed bands. These specifications are summarized in table 2.1.

Freq. Band (GHz)	Max. Transmit Power (mW)	Max. EIRP (mW)	Bandwidth (MHz)
0.902-0.928	1000	4000	26
2.4000-2.4835	1000	4000	83.5
5.725-5.850	1000	4K or 200K (*)	100
** 4K (mW) for point-to-point communications. 200K (mW) for point-to-multi-point communications*			

Table 2.1: ISM band specifications

2.2.2 U-PCS band

The U-PCS stands for Unlicensed Personal Communications Services. U-PCS band was allocated by the FCC in 1993 for promoting new personal communications services. It provides a 20 MHz band from 1.910 GHz to 1.930 GHz. It is divided into two bands of 10 MHz each. The band from 1.910 GHz to 1.920 GHz is reserved for asynchronous (data) applications like wireless LANs and the band from 1.920 GHz to 1.930 GHz subband is reserved for isochronous (voice) applications like cordless telephones. In addition, in 1995, FCC augmented this band by allocating another 10 MHz band from 2.390 GHz to 2.400 GHz for personal data communications. Typically devices operating in these U-PCS bands support an information rate of about 2Mbps. These devices, however, are required to obey a certain spectrum etiquette. Reference [25] focuses on this in detail. This etiquette is based on three basic principles, namely,

1. Listen-Before-Transmit protocol (LBT)

2. Limited transmitted power

3. Limited time duration of transmission

Freq. Band (GHz)	Max. Transmit Power (mW)	Max. Antenna Gain (dBi)	Max. PSD (mW/Hz)	Band-Width (MHz)	Traffic Type
1.910-1.920	100 $\sqrt{B}$ (*)	3	1	10	Asyn-chronous
1.920-1.930	100 $\sqrt{B}$	3	1	10	Iso-chronous
** B is the emission bandwidth in MHz of the transmission where the power level is 26 dB below the level of peak transmission.*					

Table 2.2: U-PCS band specifications

The etiquette is designed to impart some predictability to the mutual interference between different systems. This band is mainly used by devices such as wireless LANs, cordless phones and PDAs. Table 2.2 summarizes these specifications.

2.2.3 U-NII band

U-NII stands for Unlicensed National Information Infrastructure. Looking at the growth of applications in the ISM bands and the general trend in devices and applications towards higher bandwidth, the FCC set aside the U-NII in 1997 [2]. The U-NII is 300 MHz of radio spectrum between 5.150-5.825 GHz, comprising three bands each of 100 MHz, 5.15-5.25 GHz, 5.25-5.35 GHz and 5.725-5.825 GHz. These bands are differentiated on the basis of their prospective application and also on the basis of geography where they are intended to be used. The rules governing operation in these bands are bare minimal and pertain mainly to in-band and out-of-band radio emission levels. Apart from these, though, there are no restrictions on the transceiver mechanism or media access scheme or the type of traffic supported. Furthermore, each of the three bands offers 100 MHz of bandwidth, which is a substantial enhancement over any of

Freq. Band (GHz)	Max. Transmit Power (mW)	Max. Antenna Gain (dBi)	Max. EIRP (mW)	Max. PSD (mW/Hz)	Location Restriction
5.15-5.25	50	6	200	2.5	Indoors
5.25-5.35	250	6	1000	12.5	None
5.725-5.825	1000	6	4000 or 200K	50	None
** 4K (mW) for point-to-point communications. 200K (mW) for point-to-multi-point communications*					

Table 2.3: U-NII band specifications

the other unlicensed bands. These two factors make the U-NII band a very promising avenue for deployment of high data rate 3G applications. Each of the bands can possibly support data rates in the region of 20 Mbps. The allocation has not been made with any particular application in mind, but rather to promote diversity and novelty of wireless services in its true sense without any restriction. The specifications are outlined in table 2.3.

2.3 Comparison

As is evident from the specifications of different unlicensed bands tabulated in the previous sections, each of the bands have their own advantages and disadvantages which make their employment more application sensitive. Moreover these allocations are only for the United States. Other regions of the world have their own versions of these bands which in general are comparable to the allocations here, but still some variations and incompatibilities exist. This makes the employment of these bands location specific too. U-PCS band was envisioned to compete with cellular telephone market but the main deterrent, with the current thrust towards multimedia applications, has been its low bandwidth and correspondingly low supportable data rates. The 900 MHz ISM

CHARACTERISTICS	*ISM*	*U-PCS*	*U-NII*
Max. Power Constraint	YES	YES	YES
Mod. Scheme Constraint	YES	NO	NO
Traffic Type Constraint	NO	YES	NO
Power Control	NO	NO	NO
Access Control	NO	YES (ETIQUETTE)	NO
Predictability of Interference	Low	Moderate	None

Table 2.4: Comparisons of unlicensed band features- Charcteristics

SPECS	*ISM*	*U-PCS*	*U-NII*
Max. Power (mW)	4K/200K (*)	$100\sqrt{B}$ (-)	4K
Max. Bandwidth (MHz)	83.5/125 (+)	10	100
Average Max. Throughput	2	11	20+
** 4K (mW) for point-to-point communications. 200K (mW) for point-to-multi-point communications*			

Table 2.5: Comparisons of unlicensed band features- Specifications

is very densely populated by the first generation unlicensed band applications, which include inventory control in stores and warehouses, point-of-sale terminals and rental car check-in. More recent wireless LAN standards like IEEE 802.11 and Bluetooth use the 2.4 GHz ISM band. The 3G multimedia applications of today are based in the 5.7 GHz ISM band and the U-NII. U-NII has the strong advantage of providing high bandwidth per band accompanied by least restrictions on usage, which makes it possible to have throughput of more than 20 Mbps. A comparison of the relevant characteristics of different unlicensed bands is presented in Tables 2.4 and 2.5.

Chapter 3

System Model

The following sections describe the system model adopted for the Tournament Arena Simulator. This is the first simulation project in WINLAB implementing the concept of *tournaments* and based on the unlicensed bands. Therefore the selected model and the associated assumptions are aimed at implementing the most elementary version which could capture the essence of the concept.

3.1 Overview

The physical or geographical setting is that of an mobile ad hoc network. It implies a collection of mobile hosts dynamically forming a temporary network without the aid of any standardized administration or standard support services [16]. These mobile hosts or mobile stations are the only physical communication entities in the environment. There are no base stations, switching centers or hubs for centralized control. Communication links can exist from the one mobile station (MS) to another. Theoretically, any two MS can communicate with each other. The model can be further specified in terms of its three main characteristics, namely,

- Radio propagation

- Mobility
- Transceiver scheme

3.2 Radio propagation

The physical layer air interface in this model is characterized only by long scale gain. This includes purely distance losses. The effects of short scale and long scale fading are not considered. The long scale gain is treated constant in time. For a transmitter i and a receiver j, the long scale gain, $G_{i,j}$, would be a function of the distance, $d_{i,j}$ between them and can be represented as,

$$G_{i,j} = G_D(d_{i,j}) \tag{3.1}$$

The distance loss is due to the attenuation suffered by a signal as it travels through the air from the transmitter to the receiver. This is proportional to the inverse power of distance between the transmitter and the receiver i.e. $G_D(d_{i,j}) \sim d^{-\alpha}$, where α is the propagation constant. The value of α ranges from 1 to 4 and depends on the air interface and the geography. For a free space propagation environment, $\alpha = 2$. However, for propagation close to the earth's surface, which is generally the case in wireless network models, the terrain features become more significant and $\alpha = 4$ is more typical [24]. Accordingly, this simulation employs the fourth power of distance loss rule.

The noise in the system is additive, white and Gaussian with a constant double sided power spectral density N_0 at a noise variance $\sigma^2 = N_0/2$. This noise variance is a property of the receiver.

3.3 Geography and Mobility

Geography characterizes the terrain over which the MSs move and the mobility defines the fashion in which the MSs move. The geography of this model is a rectangular area on which a MS can take up any position. The mobility model used is a modified version of *random waypoint* model, which is widely used for mobile ad hoc network modeling [14].

Random waypoint model

Various versions of this mobility model are employed depending on the application. For the model used in this simulation, each MS is randomly initialized at some position on the geography. It stays stationary in that position for an exponentially distributed time t with mean $1/\mu'$. Thereafter it generates three mobility co-ordinates $[\theta, \nu, \tau]$, where θ is angular direction of motion uniformly distributed between $[0,2\pi]$; ν is the speed of motion uniformly distributed between $[\nu_{\min}, \nu_{\max}]$; and τ is the time duration of motion with speed ν and in the direction θ. The random variable τ is exponentially distributed with some mean $1/\mu$. The MS moves as specified by these co-ordinates. On reaching the new position, it again pauses for an exponentially distributed time t. These two steps occur repeatedly.

The special case of this model, as used in this simulation, is that the MS does not pause at any stage. It generates an initial mobility co-ordinate set $[\theta_1, \nu_1, \tau_1]$ and starts moving to the position specified by those co-ordinates, moving with speed ν_1, in the direction θ_1, for time τ_1 . On reaching that position, it generates a new co-ordinate set $[\theta_2, \nu_2, \tau_2]$ and begins to move according to this new specification without a pause.

The geography also has wrap-around. This ensures uniform loading of the entire geographical grid so that each point on the grid is identical in terms of the radio resource distribution. Further details are described in chapter 5.

3.4 Transceiver mechanism

The basic tenet of the transceiver scheme is that all MSs operate in a mode similar to synchronous Direct Sequence - Code Division Multiple Access (DS-CDMA). To simplify the implementation of the experiment, the channel is modeled to be frame synchronous as well as chip synchronous. Also, all MSs transmit using Binary Phase Shift Keying (BPSK) modulation. There is no implementation of a quadrature channel. The operating bandwidth of all mobiles, W, is constant. The signal waveform is sampled once per chip time.

The implication of this transceiver model is that in every frame duration, each of the transmitters generates a vector of chips corresponding to a frame. The number of chips per frame for each transmitter are equal and constant. At each receiver in the system, these frames perfectly line up, during every frame time, with chip level resolution.

This system model can be mathematically represented as below. Consider a system with K transmitter-receiver pairs. The receiver of pair i receives signal from the desired transmitter of the same pair and interference from the other undesired transmitting MSs of pairs $j \neq i$, at the same time. The received signal vector at receiver i would be given as,

$$r_i = \sqrt{h_{ii}E_i}b_i\mathbf{s}_i + \sum_{j \neq i} \sqrt{h_{ij}E_j}b_j\mathbf{s}_j + \mathbf{n}_i \tag{3.2}$$

where h_{ij} is the link gain from transmitter of pair j to receiver of pair i, E_i is the transmit energy in a bit of user i, b_i is the transmitted bit, $\mathbf{s}_i$ is the signature vector of transmitter of i, and $\mathbf{n}_i$ is the additive white Gaussian noise vector.

The signature vectors are selected to have unit energy and hence satisfy,

$$\mathbf{s}_i^\top \mathbf{s}_i = 1, \qquad i = 1, 2, ..., K \tag{3.3}$$

At the receiver, the signal vector is demodulated using some receiving filter $\mathbf{c}_i$. The output of the filter denoted by y_i is given as,

$$\begin{aligned} y_i &= \mathbf{c}_i^\top \mathbf{r}_i \\ &= \sqrt{h_{ii}E_i} b_i \mathbf{c}_i{}^\top \mathbf{s}_i + \sum_{j \neq i} \sqrt{h_{ij}E_j} b_j \mathbf{c}_i{}^\top \mathbf{s}_j + \mathbf{c}_i^\top \mathbf{n}_i \end{aligned} \tag{3.4}$$

The Signal-to-Interference ratio (inclusive of filtered noise) is given by,

$$\gamma_i = \frac{h_{ii}E_i(\mathbf{c}_i{}^\top \mathbf{s}_i)^2}{\sum_{j \neq i} h_{ij}E_j(\mathbf{c}_i{}^\top \mathbf{s}_j)^2 + \sigma^2} \tag{3.5}$$

where $\sigma^2 = N_0/2$ is the variance of the receiver noice.

If the filter at the receiver is a matched filter then $\mathbf{c}_i = \mathbf{s}_i$, and the equation (3.5) can be expressed as,

$$\gamma_i = \frac{h_{ii}E_i}{\sum_{j \neq i} h_{ij}E_j\rho_{ij}^2 + \sigma^2} \tag{3.6}$$

where

$$\rho_{ij} = \mathbf{s}_i^\top \mathbf{s}_j \tag{3.7}$$

is the cross correlation between the signature sequences of user i and user j. The mathematical modeling of the system is based on these equations.

Chapter 4

SSF Domain Fundamentals

This chapter describes the Scalable Simulation Framework (SSF) which provides the platform for design and implementation of the TAS. The background and motivation for SSF development is first given along with a brief discussion on its salient features and advantages. The software implementation is then discussed.

4.1 Background

SSF is a public-domain standard for simulation of large and complex systems in C++ [10] and JAVA [8]. SSF has been developed by the S3 consortium, a collaboration of researchers in networking, parallel simulations and software engineering. The goal of the S3 consortium is to achieve radical improvements in speed, scalability and manageability involved in modeling and simulations of very large multi-protocol communication networks. Scalability and parallel performance of S3 software have been extensively tested on large scale models of Internet, ATM and mobile wireless and satellite networks [15].

The Scalable Simulation Framework Application Programming Interface (SSF API) is the single, core and unified interface which provides conformability and portability of code and models across different SSF -compliant simulation environments. This maximizes the potential for direct reuse of model code, while minimizing dependencies on a particular simulator kernel implementation. In addition to its concrete modeling applications, the API also functions as an abstract target for compilation of models specified in higher level modeling languages or graphical modeling environments. The framework's primary design goal is to support high performance simulation. SSF makes it possible to build models that are efficient and predictable in their use of space, able to transparently utilize parallel processor resources, and scalable to very large collections of simulated entities.

The reference development implementation on SSF is written in JAVA while its high performance version is written in C++. The TAS uses the JAVA binding.

4.2 Overview

Before going onto the syntax and semantics of the SSF API, this section first focuses upon the prominent features of the API. There are four main fundamentals on which the API is based, which provide a significant motivation for using it as a platform for the TAS . They are,

1. Separation of modeling and simulation
2. Object-oriented simulation framework
3. Event-driven simulation executive
4. Parallelization capability

4.2.1 Separation of modeling and simulation

Implementation of detailed simulations of large and complex systems involves a substantial effort in writing the 'simulator' itself along with all its functionality, in order for it to process the operations while maintaining the *causality.* Causality, here, in the context of simulations, refers to execution of operations in an ongoing simulation, in an order, which is in accordance with the logical (real) time associated with those operations so that the real-time dynamics of the actual physical system being simulated are maintained. Ensuring this causality in a simulation is an elaborate and intricate task [9, 21]. It, therefore, comes at the expense of the extent of detail achievable in actual system modeling within a constraint of time. SSF provides a way to separate domain specific modeling from the internals of the simulator so that the user can now spend more effort on modeling actual system details. Another added advantage is that with SSF no simulation-specific framework language like TeD [22, 23] is required as the API is written in standard high level programming language like JAVA and C++.

4.2.2 Object-oriented design

The SSF is implemented using an object oriented programming (OOP) software design. This provides the framework with all the advantages of OOP including encapsulation, inheritance, polymorphism, run-time binding and parameterized typing [8, 10]. The idea of OOP approach has great intuitive appeal in systems modeling because it is very easy to conceptualize real world applications as being composed of objects. The SSF API implemented as an object-oriented framework can be described as a layered design linked hierarchically. The concepts at each layer are 'encapsulated' so that a user at a particular layer need not be concerned about the concepts at the lower layers.

Each layer specifies the levels of abstraction, with the lowest being the most abstract and more concrete elements added in higher levels so that at the highest level, the final product maybe a specific simulation model. The lowest level construct is the general *OOP language*, either C++ or JAVA in which SSF is implemented. The OOP language is used to construct certain *Foundation Classes* which implement objects of varied pattern and functionality. These foundation classes are used to construct more specific *Simulation Classes*. These simulation classes provide for more specific simulation-related objects and operations. The SSF API occurs at this level. The simulation classes are further specified into *Domain modeling packages* which make the framework more pertinent to the model being implemented such as either a protocol or some network element etc. SSFNet includes such packages. The topmost level is the *Simulation Model* which implements the actual real world system. The end user of SSF can operate in the top two levels of the hierarchy. These hierarchical levels of the framework are illustrated in figure 4.1. A generic form of this type of design is discussed in [17]

4.2.3 Event-driven executive

The key component of a simulator is the simulation executive. The executive is responsible for controlling the time advance of the central simulation clock. This clock keeps track of the logical time relationship between the various simulation entities to ensure causality, as defined earlier in subsection 4.2.2 . There are two main methods of time

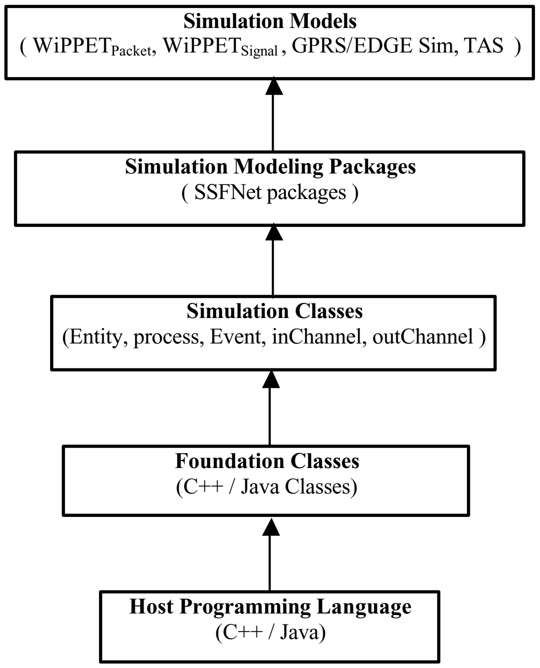

Simulation Models
(WiPPET$_{Packet}$, WiPPET$_{Signal}$, GPRS/EDGE Sim, TAS)
Simulation Modeling Packages
(SSFNet packages)
Simulation Classes
(Entity, process, Event, inChannel, outChannel)
Foundation Classes
(C++ / Java Classes)
Host Programming Language
(C++ / Java)

Figure 4.1: *Hierarchy of abstraction in* SSF

advancement by the executive, namely,

1. Fixed-increment time advancement

2. Next-event time advancement.

The former involves advancing the simulation time periodically with a fixed time increment irrespective of the state of the simulation. It is suitable for *continuous* or *exhaustive* simulations in which the system is likely to change continuously so that the simulation needs to be sampled regularly at a sufficient frequency. However, if that is not the case, then this form of time advancement involves a significant computational overhead. The later method involves advancing the simulation time at instances of new activity. This means that the simulation clock advances in an irregular fashion with unequal increments from one instant of activity to the other. In the intermittent instants of inactivity the simulation clock remains idle or in other words the simulation is not sampled. Here *activity* or *event* implies an occurance leading to the change in the *state variables*, of the simulation.

SSF utilizes the next-event time advancement mechanism. It therefore falls under the category of a *discrete event simulator* (DES). Figure 4.2 shows the components of a DES. The simulator utilizes three principal data structures:

- The *state variables* which specify the state of the system;
- The *event queue* containing all pending events that have been scheduled but have not yet taken effect;
- The *simulation time*, a global variable which keeps track of the progression of the simulation in terms of logical time.

Each event possesses a time stamp and some payload data. The payload data defines the operation to be performed upon execution of the event. It would lead to the change in the state variables of the simulation. The time stamp defines the simulation time at which that change has to come into effect. The event queue has a scheduler attached to it which performs the job of operating the event queue as a First In First Out (FIFO) priority queue. The scheduler arranges the events joining the queue in the increasing order of their time stamps, so that the event with the least time stamp is at the head of the queue and is executed first. The event processing changes the state variable/s and could lead to more events being generated which again get queued according to their time stamps. After the execution of the event at the head, it is removed from the queue and the next event in the queue becomes the head and is executed when the

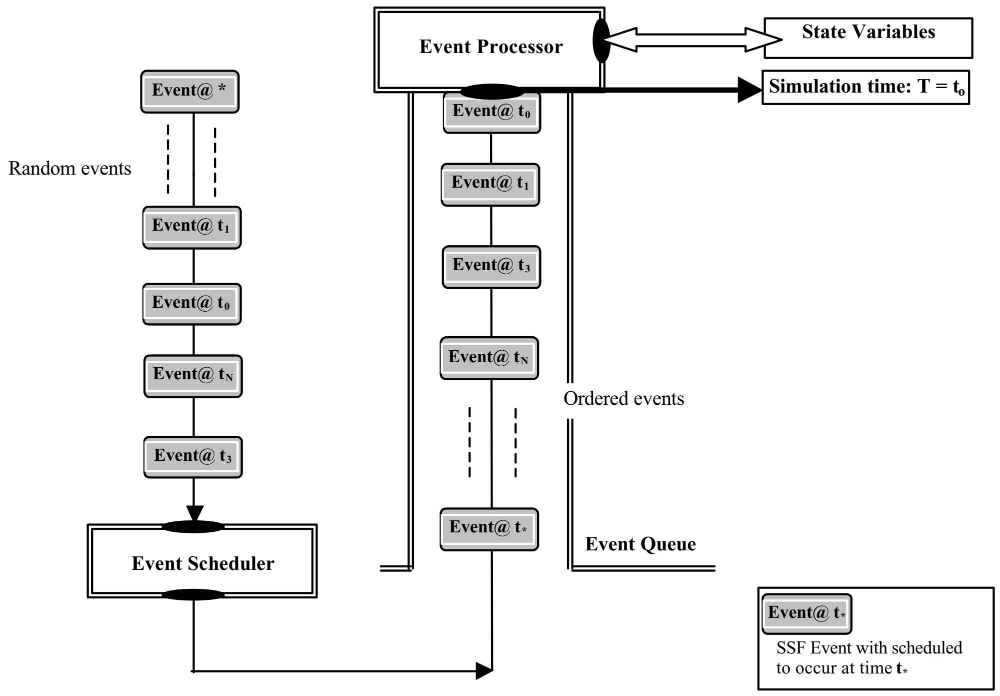


Figure 4.2: *Discrete event simulator*

simulation time is equal to time stamp of that event. The run time of the simulation is equal to the time stamp of the last event in the queue. This operation paradigm of the DES simulator is essential to ensure causality.

The time precision of the simulation, implying the logical time equivalent to one tick of the simulation clock or the least count of the logical time resolution, is user-dependent and could be set to any value. For this TAS implementation, one simulation tick equals one CDMA chiptime.

4.2.4 Parallelization Capability

One of the main bottlenecks of a large and complex simulation is the speed. As explained in the previous sub-section, the DES operates on the basis of an event queue. The events in a queue are identified by a single timeline or thread and are executed sequentially by the processor based on the time-stamp associated with the event. However, not all events actually share a sequential relationship with each other, so that some events could be executed totally independent of the other as long as the overall causality is maintained. This implies that if the programming platform of the framework supports multi-threading, meaning creating multiple event queues out of events with independent timelines, then these queues could be processed concurrently on multiple processors to gain substantial advantage in speed. Theoretically if the simulation work is distributed between two processors, then the simulation time should be half of the time when it was carried out on a single processor. SSF supports this type of parallelization. JAVA is inherently a multi-threaded language while for the C++ binding, additional foundation classes have been written in the framework to support parallelization.

Parallelization with the C++ bindings is profusely experimented with in [18]. The TAS in the current version consists of a single thread. The radio channel which is modeled in this simulation is quite basic and simple. The simulation is not so computation-intensive. The simulation in the single threaded version is sufficiently fast. However, for future versions with more complex radio channel models, the JAVA SSF platform does provide the option of parallelization.

4.2.5 Dynamic Modeling

SSF supports modeling of the simulation dynamically at the time of execution. This is essential for run-time self organization of very large heterogeneous models, run-time aggregation of sub-models and other similar novel techniques. This provides dynamic reconfigurability to the simulation.

The TAS utilizes this feature in providing the facility to the user to code and configure one's own transceiver models and let the environment load and aggregate them dynamically. This is explained in detail in chapter 6.

4.3 SSF Model Abstractions

This section specifies and explains the relevant syntax and semantics of SSF [7]. As discussed, SSF is written as an object-oriented simulation, with JAVA and C++ serving as the host language. The following explanation uses common OOP terminologies. The reader may refer to [19] for more details. The SSF syntax comprises of five base class interfaces,

1. Entity
2. process
3. Event
4. inChannel
5. outChannel

These five classes form a self-contained design pattern for constructing operation-oriented, event-oriented and hybrid simulations. They are sufficient to model any system which could be described as a collection of different communicating objects each implementing some distinct functionality.

An entity is a formulation of a physically or conceptually tangible object found in the real system. It possesses processes which implement the dynamic behavior of objects that are being modeled. From the point of shared computer memory, entities are non-contiguous and independent blocks. The only means of interaction between different entities is through inChannels and outChannels. These are conduits for exchanging information between the entities. The information unit which traverses across the channels is called event. While implementing a specific system, these base classes can then be extended to have their derived classes implement more specific objects. Figure 4.3 illustrates this basic frame work. There are three entities in the TAS environment. Each possesses one or more processes which implement its functionality. Instances of inChannels and outChannels create communication links between two different entities. The in and out channels are not differentiated in the figure. Events are exchanged between the processes. It is important to note that the inChannels and outChannels exist between the processes owned by the same entity or different entities.

4.3.1 Entity

The Entity base class serves as the blue print for implementation of system objects. Tangible physical objects like a MS or a switching center or conceptual objects like

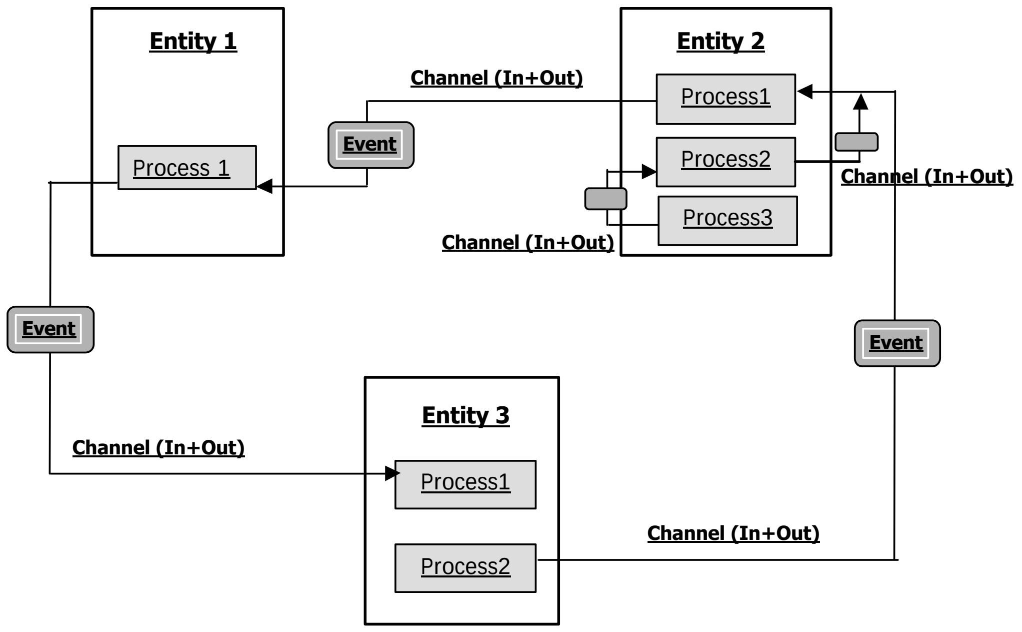


Figure 4.3: *SSF platform with* Entities *possessing* processes *and exchanging* events *through* inChannels *and* outChannels

the radio channel or a protocol are implemented as entities, extending the base class Entity. These entities specify the data structure and the functionality of the object. The derived entity possesses instances of inChannel, outChannel and process which help in achieving the same.

4.3.2 process

The process base class describes the dynamic behavior of an entity and implements its functionality. Instances of process are defined within the entity as inline methods. These inline methods are encompassed within a special SSF method called `action()`. Conceptually, processes are similar to native programming language methods, JAVA methods in this case, which execute a particular group of instructions upon being called by the execution thread of the main program. However the difference lies in the way they are called. The instances of processes are initialized and activated only once at the beginning of the simulation. Thereafter they remain ‘live’ throughout the simulation. They may alternate between an active and a dormant state but they never become ‘dead’. Hence explicit and regular calls are not required for executing them. This is achieved by the `action()` method of each process which serves as an implicit callback method.

The processes are dynamic threads of computation owned by their host entity . The instances of inChannel and outChannel also owned by the the host entity, actually serve as input stream to and output stream from the process. Derived events travel on these channels and affect the state of the process. The activation (active state) or deactivation (dormant state) of processes is controlled by certain characteristics categorizing them. Accordingly processes are of two types,

- Time-driven process
- Event-driven process

There is another special SSF method, `wait()`, used in the process in varied versions. All versions of the `wait()` method suspend the process into a dormant state. The re-activation is then regulated by the version of `wait()`, which is used as the terminating statement of the process code. A time-driven process calls a `waitFor()` version, which forces the process to go into a dormant state for a particular period of simulation time which is specified as an argument to the method call. An event-driven process, on the other hand uses a `waitOn()` version. It also suspends the process into dormancy, but now the re-activation is dependent on the arrival of an event on the inChannels of the process. The process keeps on listening onto the inChannel and until an event is received on it, it stays in an inactive state. There are other versions of `wait()` that perform slightly modified actions. However the above two are the most frequently used ones.

The types of actions performed in the process during execution can be categorized as

- Computation
- Synchronization

Computation actions are coded in the host language, JAVA in this case, and they take-up zero elapsed simulation time. They are related to the actual operations and functioning of the process. Synchronization actions are necessary to reflect the simulation time advancement with the progression of the simulation. They are effected through the various versions of `wait()` method. They take-up non zero simulation time.

4.3.3 Event

The Event base class provides the framework for the structure of the information unit that is exchanged between the entities through the inChannels and the outChannels. Depending on the application or the nature of the end-to-end process and entity between which the information exchange is taking place, the unit may have to be modified in its structure and data typing. This is achieved by specifying derived classes extending the Event base class. All derived classes of Event must provide their own copy constructors. The management of event storage is the responsibility of the framework, which may release the storage of an event anytime after its last recipient process has suspended, unless the modeler explicitly instructs otherwise. The events are written onto to its outChannel by a process at one end and received at the inChannel of the recipient process at the other end. A specific SSF method, `write()`, and its versions are used for this. This traversal of events could be intra-entity or inter-entity. The receipt of the events is non-destructive. Each designated process is allowed to receive, exactly once, each of the events scheduled for delivery on all of its coaligned inChannels in the current instant of the simulation time. However if no process receives an event at its time of delivery (possible due to mismatch in inChannel and outChannel mapping), the event is lost. The framework does not buffer it for retrospective delivery.

4.3.4 inChannel and outChannel

The inChannel and the outChannel are the base classes which provide the implementation for input and output conduits between entities. These base classes are directly instantiated without any extensions or derived classes unlike the previously described base classes. The instances of the inChannel and the outChannel belong to a process and are owned by the host entity. Depending on the relationship between the different entities in the simulation, the inChannels and the outChannels are linked by a combinational mapping. An inChannel of a process would be mapped to one or more outChannels of another process in the same or a different entity. Vice versa for the outChannel. In effect, the SSF supports unicast (one-to-one) as well as multicast (one-to many) in both inChannels and outChannels in addition to bus-style mappings (many-to-many). The channels also have a certain channel delays associated with them specified by the modeler. A *minimal channel delay* can be associated with an outChannel if specified by the modeler at the time of constructing them. A *minimal mapping delay* can be associated with a channel mapping between an inChannel and an outChannel, again if specified by the modeler. Finally, each outChannel can also have a *per-write delay* or *transmission delay* associated with it. For JAVA SSF there is an inherent per-write delay of one simulation tick associated with each outChannel. This could be compensated by passing a negative delay argument to the `write()` method or it could be projected using a non-negative delay argument by the modeler.

This completes the description of the SSF relevant to comprehending the essence of the design as described in the following chapter. Detailed specification of the API is given in [7].

Chapter 5

Design and Implementation

This chapter describes the design of the TOURNAMENT ARENA SIMULATOR (TAS) and its implementation in the JAVA SSF domain. The focus is on functionality of the system design and the SSF modules and structures involved in implementing the same.

5.1 Design Overview

As discussed in section 4.3, the physical and conceptual objects in a communication system are modeled as an entity in the SSF domain. For a mobile ad-hoc network model supporting point-to-point connections, the only physical communication objects are the *mobile stations* (MS) occuring as transmitter-receiver pairs. Additionally, for implementing the radio propagation aspects, a *radio channel* module and a *mobility* module are required. These are the other conceptual objects in the simulation. These modules get modeled as extensions or in object-oriented progamming terminology, as a derived class of the SSF base class Entity. These derived classes are also referred to as 'entities' in the following discussion for generality.

The TAS entities are itemized below.

1. Master : `Simulation` Entity

2. Radio channel : `RadioChannel` Entity

3. Mobility module : `Mobility` Entity

4. Mobile station : `MobileTerminal` Entity

The interactions of the different SSF simulation classes were described in chapter 4. They are reiterated here in brief for ease of understanding. Each of the entities possess instances of the SSF base class process. They are referred to as processes, too, in further discussion for generality. Encapsulated within the processes are JAVA methods which implement the functionality of their host entity. The entities communicate with each other through instances of SSF base classes inChannel and outChannel. The inter-networking between the entities is achieved by combinational mapping of these inChannels and outChannels.

These SSF channels could be broadly differentiated into two types depending on their logical function in the simulation.

- *data channel*
- *info channel*

Data channels act as conduits for transmitting actual communication system data between the transmitting and the receiving MSs. They can be further specified as *real data channels*, which either enter or exit the `RadioChannel` so that the data these conduits carry is affected by channel effects and *fake data channels*, which bypass the `RadioChannel` and hence the data carried by these conduits has no channel effects incorporated. *Data channel*s have direct analogy to actual air interface in a communication system. However in the simulation the forward channel, from the transmitter MS to the receiver MS, is implemented as *real* while the reverse channel, from the receiver MS to the transmitter MS, is implemented as *fake*. The second type of SSF channels are the *Info Channels* which carry information pertaining sustenance of simulation, like the state of different simulation variables or triggers for initiating and terminating different operations in the simulation.

The information is exchanged over these channels by encompassing it within instances of extensions of SSF base class Event. Different extensions or derived classes of Event are employed depending on the type of information to be carried, such as real data (class `DataEvent`) or feedback information about link resource (class `ResourceEvent`) or information about the different entity variables (class `InfoEvent`) or simply triggers for initiating any of the processes (class `TriggerEvent`). Figure 5.1 provides an approximate system map of the entities involved in the simulation.

5.2 `Simulation` Entity

The `Simulation` entity does not have any physical relation to the communication system being implemented. It simply provides the environment in which all other entities exist and interact with each other. It creates the instances of each entity and performs the mapping of their inChannels and outChannels. It also contains the `main()` method to initiate the simulation.

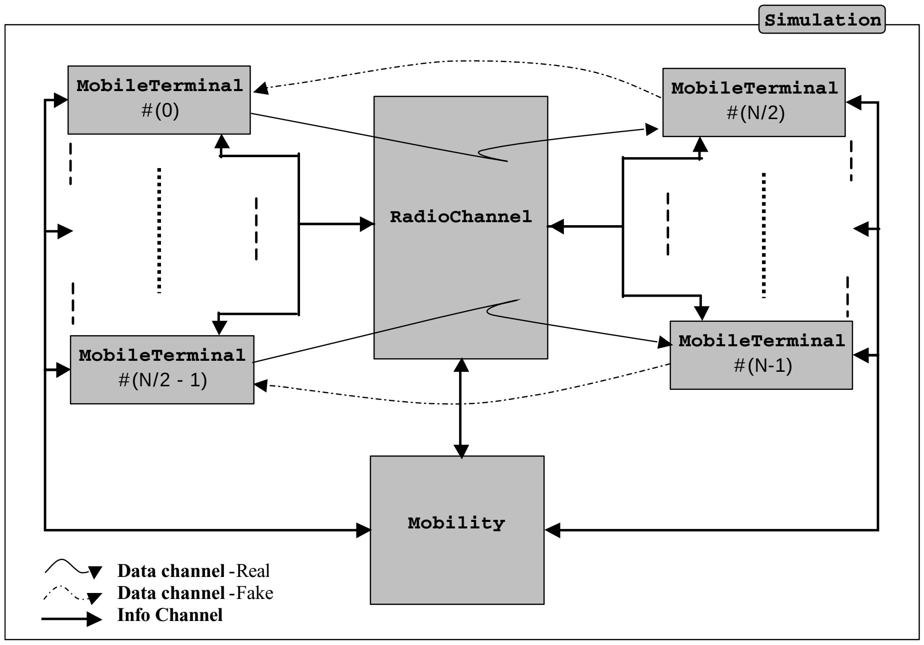


Figure 5.1: *System Entity Map*

5.3 `MobileTerminal` **Entity**

The `MobileTerminal` entity implements the internals of a mobile station (MS) transceiver. The following section describes the default version of the MS implemented in the `MobileTerminal`. The transceiver scheme assumed as the default is a DS-CDMA transmitter and a corresponding matched filter based receiver. The MSs are created as as instances of the `MobileTerminal` class and occur as transmitter-receiver pairs. The radio channel is frame synchronous and chip synchronous. So in each frame duration, T_f, a transmitting MS transmits a vector of chips corresponding to a frame. The receiving MS receives this vector post channel degradation and processes it to detect the data. The `MobileTerminal` entity contains methods, encapsulated within processes to perform the operations prior to transmission of the frame of data and post the reception of frame. The default transceiver scheme is depicted in the figure 5.2.

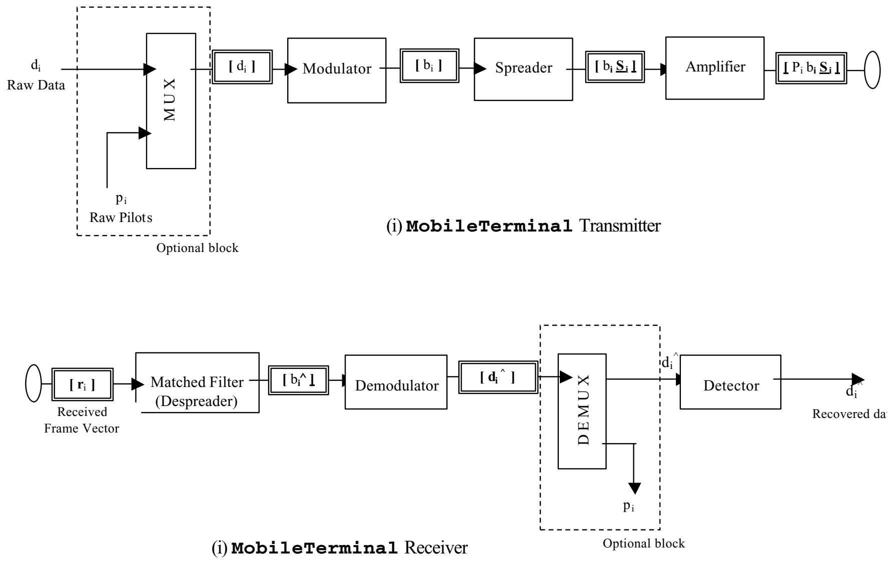


Figure 5.2: *Transceiver scheme in the `MobileTerminal`*

The MSs and `RadioChannel` entity are connected through *data channels* and *info channels.* The channels of both type are bidirectional. The MSs are connected to the `Mobility` entity through *info channels.* This connection is unidirectional originating from the MS. There exists a direct *fake data channel* from the receiving MS of a pair to the transmitting MS. MSs are also connected to `Simulation` entity through *info channel.*

There are four processes in the `MobileTerminal` entity implementing four main functions. They are described in brief here, focusing on their functionality.

- **Initialization and Activation**

  The first action to be taken in a MS before starting communication is its activation. This is done by the `MobileTerminal` process `TriggerTranceptionProcess`.

The activation of the MS is accompanied by initialization of its system parameters like transmit power, data rate etc. There is a local data structure which maintains these values.

- **Data Transmission**

  The process `TransmissionProcess` performs this function of data transmission. This is done one frame at a time. Since the system is synchronous upto the precision of a chip, an integer number of chips would be transmitted in the frame time, T_f. Let this number be N_c. These N_c chips form a *frame*. The frame length of all the MS in the simulation is constant and equal.

  The MS first generates raw data bits corresponding to a frame. These data bits are then modulated and placed in the frame. If, suppose, the processing gain used by the transmitting MS i is N_i, then the number of bits in the frame would be $N_b = N_c/N_i$. This corresponds to the framed bits. The MS also generates a pseuda-random (PN) long code sequence corresponding to the entire frame, meaning a vector of N_c chips. The chips of this PN long code are generated in a random fashion, by default. The raw data is spread by this long code. Each chip is then multiplied by the amplitude of the transmit power. This frame is then transmitted.

  This set of operations is performed regularly at time interval T_f by this process. The process has a self triggering mechanism to achieve this. Specific JAVA methods are written to achieve each of these functions. The calling of these methods is controlled by flags. These flags enable the user to specify the exact dynamics of the simulation, such as whether the long code sequences are fixed or generated randomly; or whether pilot bits are present or absent in a frame and so on.

- **Data Reception**

  The `process ReceptionProcess` performs the functions associated with receiving the data at the receiver MS. At the interval of frame time T_f, a vector of N_c chips is received at the input *data channel* of this `process`. It is the transmitted frame post channel effects in the `RadioChannel`. The channel effects include distance loss and interference from other transmitting MSs. Additive white Gaussian noise is added to this received frame at the receiver. The receiving MS locally generates the same long code as its transmitting counterpart using a common seed to feed the long code generator. This long code is used by the receiver MS to despread the received frame. The frame is then demodulated and the data bits are detected. Based on the detected frame, two resource statistics, namely the bit error rate (BER) and the signal to interference ratio (SIR) are calculated. BER calculation is straight forward, as the receiver MS also has the capability to generate, locally, the same raw data bits as the transmitter MS every frame using a mechanism similar to localized long code generation. The SIR calculation is more complicated and is explained below.

SIR Calculation

The MS in the default implementation in `MobileTerminal` does not use any form of SIR estimation using pilots or any other blind estimation schemes. The exact value of the SIR is calculated using actual channel gain values supplied directly from the `RadioChannel` over the *real data channel* itself, coupled with the channel data vector.

The SIR for a matched filter based receiver, at receiving MS, i, is given by the equation 3.6.

- **Resource Feedback and Control**

  There exists a mechanism for a receiver MS to feedback radio resource information or instructions based on that information to the transmitter MS. This ensures that MS utilizes the system resources optimally so as to exploit the link condition to its best advantage. This system resource in question could be transmitter power or transmitter rate or the signature sequences used, to name some. Based on the information about these, the MSs could use power control or rate adaption or codeword adaptation schemes for optimal resource management. The decisions would be based on some metric calculated at the receiver. This metric could be BER or SIR or some other statistic.

  This functionality is achieved by the `ResourceControlProcess` of `MobileTerminal`. There exist a *fake data channel* from every receiver MS to its transmitter. This process uses this *data channel* to feedback resource control information from the receiver to the transmitter at the end of every frame time T_f. It is triggered after the execution of the `ReceptionProcess` during every frame execution loop. The execution of this process is controlled by user specified process flag. The type of resource to be controlled is also user defined. This is explained further in chapter 6 as a part transceiver reconfigurability options.

5.4 `RadioChannel` Entity

The `RadioChannel` entity models the air channel. The air channel involves waveform level interactions. These are modeled by a sampled time system with sampling interval Δ. In general, T_c, the duration of one CDMA chip, is a multiple of Δ; however, to reduce the computational requirements, the simulation employs one sample per chip. Also, the air channel is assumed to be synchronous and the channel effects include only distance losses and additive white Gaussian noise. Short scale and long scale fading channels are not considered. Also only the in-phase channel exists. There is no quadrature channel.

*Real data channel*s connect the each of the transmitter MSs to the `RadioChannel` and the `RadioChannel` to each of the receiver MSs. The `RadioChannel` is also closely coupled with the `Mobility` through an *info channel* to incorporate MS motion effects in channel calculations. The operations modeling the air channel are implemented in the `RadioChannel`. This is depicted in figure 5.3. During every frame duration, the `RadioChannel` receives the transmitted frame vectors from all the transmitter MS in the simulation. Each frame is a vector of real numbers. The frame corresponding to transmitter i can be written as,

$$\mathbf{q}_i = P_i b_i \mathbf{s}_i \tag{5.1}$$

Assume that there are M transmitter and M receiver MS in the system. Then the link gains to each receiver from the M transmitter form a $M \times M$ link gain matrix,

$$\mathbf{H} = \begin{pmatrix} h_{00} & h_{01} & \cdots & h_{0(M-1)} \\ h_{10} & h_{11} & \cdots & h_{1(M-1)} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M0} & h_{M1} & \cdots & h_{(M-1)(M-1)} \end{pmatrix}$$

where h_{ij} represents the link gain from the transmitter j to the receiver i. The channel vector received at the receiver MS i after incorporating the channel effects is given as,

$$\mathbf{r}_i = \sum_{j=0}^{M-1} h_{ij}\mathbf{q}_j = \sum_{j=0}^{M-1} h_{ij}P_j b_j \mathbf{s}_j \tag{5.2}$$

The `RadioChannel` calculates this channel vector corresponding to each of the M receiver MSs and sends it to each of them respectively.

These functions are achieved in the `RadioChannel` through three processes. Their functional aspects are described below.

- **Initialization**

  The `ActiveMobileRegistrationProcess` performs the task of initializing this entity. MSs use *info channels* to convey their initial state to the `RadioChannel`. The `RadioChannel` records this information into a local data base. The initialization procedure is considered complete when this initialization information corresponding to all the active mobiles in the simulation is recorded. The local data base associated with `RadioChannel` is called the `ChannelMatrix`.

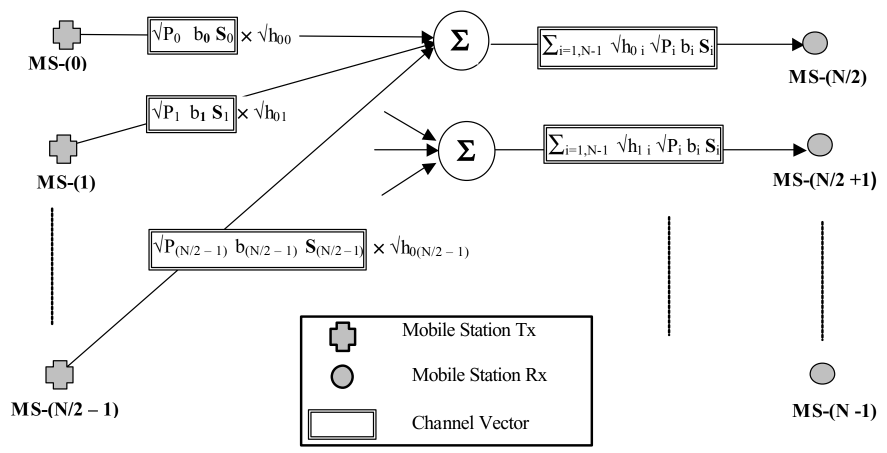

MS-(0)
$\sqrt{P_0}\ b_0\ S_0 \times \sqrt{h_{00}}$
MS-(1)
$\sqrt{P_1}\ b_1\ S_1 \times \sqrt{h_{01}}$
$\sqrt{P_{(N/2-1)}}\ b_{(N/2-1)}\ S_{(N/2-1)} \times \sqrt{h_{0(N/2-1)}}$
MS-(N/2 – 1)
Σ
$\sum_{i=1,N-1} \sqrt{h_{0i}} \sqrt{P_i}\ b_i\ S_i$
MS-(N/2)
$\sum_{i=1,N-1} \sqrt{h_{1i}} \sqrt{P_i}\ b_i\ S_i$
MS-(N/2 +1)
MS-(N -1)
Mobile Station Tx
Mobile Station Rx
Channel Vector

Figure 5.3: Radio Channel Calculations

`ChannelMatrix`

The data structure for the `ChannelMatrix` is designed to support multiple channels and dynamic activation and deactivation of MS during the run of the simulation. Though the present version of the environment deals solely with physical level DS-CDMA implementation and hence requires only a single channel and static initialization of MS at the beginning of the simulation, the design is amenable to overlaying of higher level Medium Access Control (MAC) or Call Admission Control (CAC) on top of it. From a data structure viewpoint, the `ChannelMatrix` is an array of linked lists. The array index specifies the active channel and the linked list at that index represents the list of active MSs on that channel. Each node of the list stores the MS initialization information relevant to the channel calculations described previously, like transmit power, position and the other MS in the connection pair. Figure 5.4 shows this structure.

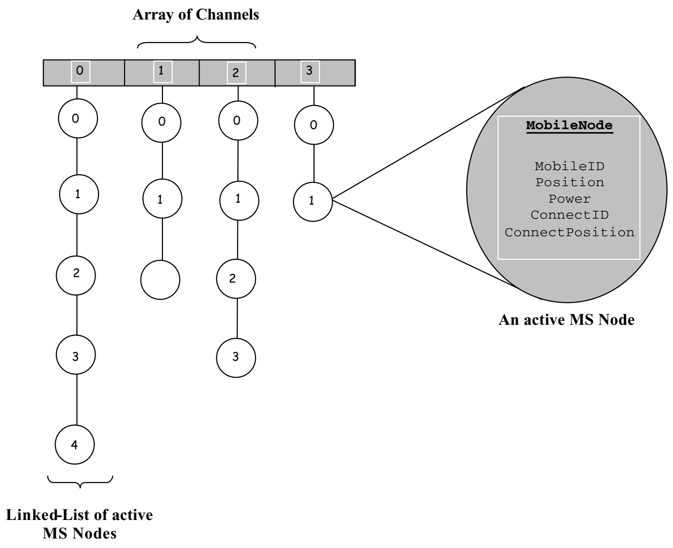


Figure 5.4: `ChannelMatrix` Data Structure

- **Channel calculation**

  The task of performing the channel calculations and determining the channel taps corresponding to each receiver MS has been described here. It is done by the `ChannelCalculationProcess`. Every T_f, this process receives the transmitted frames corresponding to each transmitting MS. Using the position information corresponding to each active MS stored in `ChannelMatrix` it calculates the link gain matrix $\mathbf{h}$ and generates the channel vector corresponding to each of the receiver MS. These channel vectors are sent to respective receivers. Additionally, the link gain array $\mathbf{h}_i = [h_{i0}h_{i1}...h_{i(M-1)}]$ corresponding to receiver i is also sent along with the channel vector to enable actual SIR calculation as described in section 5.3 at the receiver MS.

- **Position update**

  As is evident from the description of the channel calculations, the `RadioChannel` needs to constantly update the `ChannelMatrix` with the latest position of the MS so that it can perform precise link gain calculations. Therefore it needs to communicate with the `Mobility` entity and retrieve the position updates with the motion of each and every active MS. This is done by process `PositionUpdateProcess`, which constantly listens on the *info channel* from the `Mobility` for new positions of the MS. Upon receiving the information it updates the relevant fields in the `ChannelMatrix`.

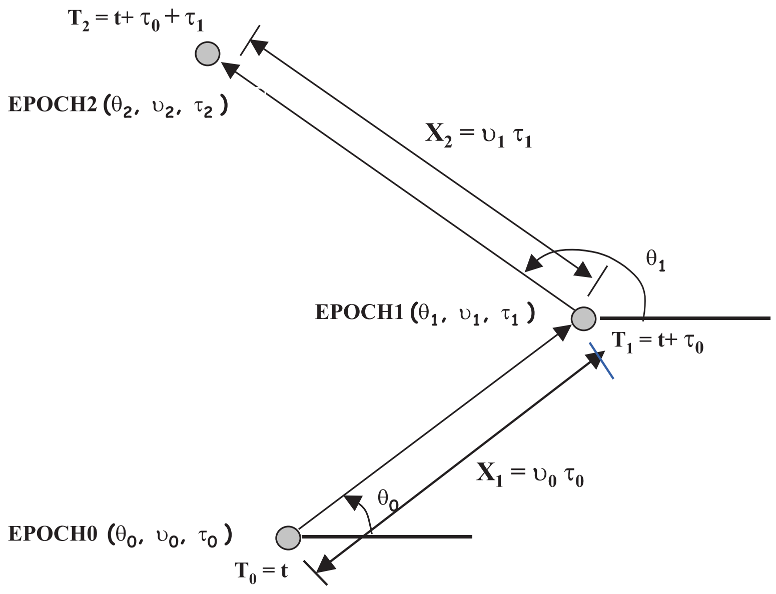
5.5 `Mobility` Entity

The `Mobility` is a derivative of Entity. It performs the function of providing mobility to the MSs in the simulation. Based on the mobility model adopted, the `Mobility` generates the new position values for each of the active MS at the end of the time interval defined by the speed of the mobile and the distance resolution of the mobility module. There exist *info channel*s going from the `Mobility` to the `RadioChannel` that convey these updates to the `RadioChannel` . There are further *info channel*s from the MS to the `Mobility` to provide initialization information of the MS to the `Mobility`.

Modified random waypoint model

As mentioned in section 3.3 the mobility model used is a modified *Random Waypoint* model over rectangular geographical area. There is no concept of a grid because the position which the MS can occupy are continuous valued. These two initial assumptions make the new position calculations in the `Mobility` fairly complicated.

When the simulation is initiated, the MSs are randomly initialized on the geography at different positions. These positions are specified in terms of rectangular co-ordinates



$T_2 = t + \tau_0 + \tau_1$
EPOCH2 $(\theta_2, \upsilon_2, \tau_2)$
$X_2 = \upsilon_1 \tau_1$
θ_1
EPOCH1 $(\theta_1, \upsilon_1, \tau_1)$
$T_1 = t + \tau_0$
$X_1 = \upsilon_0 \tau_0$
θ_0
EPOCH0 $(\theta_0, \upsilon_0, \tau_0)$
$T_0 = t$

Figure 5.5: *Random Waypoint* Mobility Trail of a MS

- x and y. These positions are also registered in the `Mobility` in a local data base. Each MS is identified by its *mobility coordinates set* defined as [θ, ν, τ], where θ is the direction of motion uniformly distributed between [0,2π]; ν is the speed of motion uniformly distributed between [$\nu_{\min}$, $\nu_{\max}$]; τ is the time duration of motion with the previous two values for speed and direction. The random variable τ is exponentially distributed with some mean $1/\mu$. The actual computation is in fact significantly more complicated. Consider the example below. Corresponding to the initial position, identified as *EPOCH 0* in figure 5.6, a MS generates an initial *mobility coordinate set* [θ_0, ν_0, τ_0] and starts moving to the position specified by that. On reaching that position, identified as *EPOCH 1* in this case, it generates a new co-ordinate set [θ_1, ν_1, τ_1] and begins to move according to this new mobility specification to this new position. However the number of position updates that actually comprise this motion of the MS from position identified by *EPOCH 0* to that identified by *EPOCH 1* depends on the distance resolution of the mobility. Suppose the distance resolution is d and the distance between the two positions is, say X, where,

$$X = \nu_0 \tau_0 \tag{5.3}$$

The position updates, hence, need to be sent at distance step of d. This translates to a time step between position updates, τ' given by,

$$\tau' = d\nu_0 \tag{5.4}$$

The number of such updates required to describe the traversal of the MS from position identified as *EPOCH 0* th that identified as *EPOCH 1*, m, would be given as,

$$m = \lceil X/d \rceil \tag{5.5}$$

This is illustrated in figure 5.6.

Wrap-around geography

The other feature of the `Mobility` is wrap-around geography. Wrap-around model ensures uniform loading of the geography without any bias to boundary points. This ensures that that interference seen by any given MS is totally independent of its absolute position on the geography, and only dependent on its position relative to other MS. From the implementation point of view, this entails further detail in calculations.

Say the geography is specified by the co-ordinates [0,0] to [X_{max}, Y_{max}]. Referrng to figure 5.7, the transmitter MS is on the boundary point [x, Y_{max}] at position update

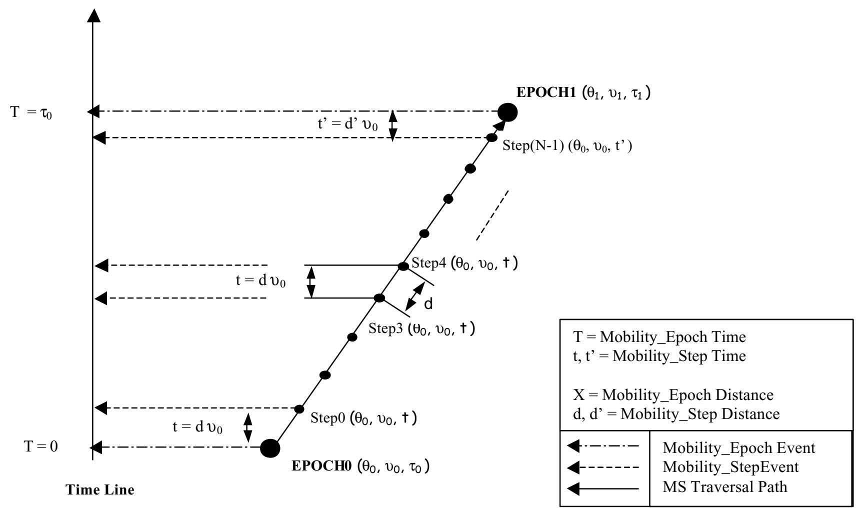


Figure 5.6: *Mobility Update Process for a MS*

time step t and its mobility coordinate set is $[\theta', \nu', \tau']$. Then according to the wrap-around definition, at next position update time step $t+1$, it would move to the position specified by the position co-ordinates $[x, 0]$ continuing with the same *mobility coordinate set* as at the previous position. This is illustrated in figure 5.7, where the transmitter MS is wrapping around. These functions are performed through instances of processes defined within `Mobility`. A brief description of the functionality of the processes follows.

- **Initialization**

  The `ActiveMobileReistrationProcess` performs the task of initializing this entity like in `RadioChannel`. MSs use *info channel* to convey their initial state to the `Mobility`. The `Mobility` records this information into a local data base. The initialization procedure is considered complete when this information corresponding to all the active MSs in the simulation is recorded. The local data base associated with `Mobility` is called the `ConnectionRegistry`.

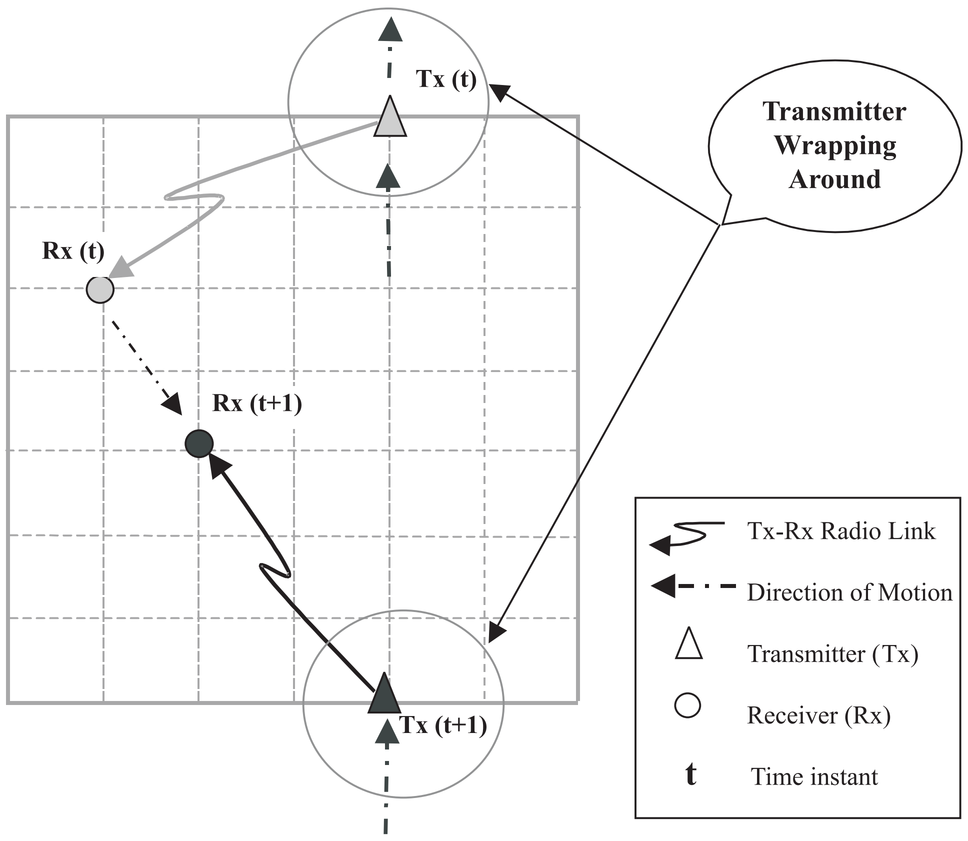


Figure 5.7: Illustration of *Wrap-Around*

`ConnnectionRegistry`

The data structure implementing this data base is a linked list. Again the use of a linked list provides the option of dynamic activation and deactivation of MS in the simulation for future overlaying of a MAC and CAC on top of this physical layer. Each node on the list represents an active MS and is identified by it's unique id. Each node stores the MS initialization information relevant to the mobility calculations such as position, speed, angular direction of the MS and the id of its connection partner. Figure 5.8 depicts this data structure.

- **Mobility management**

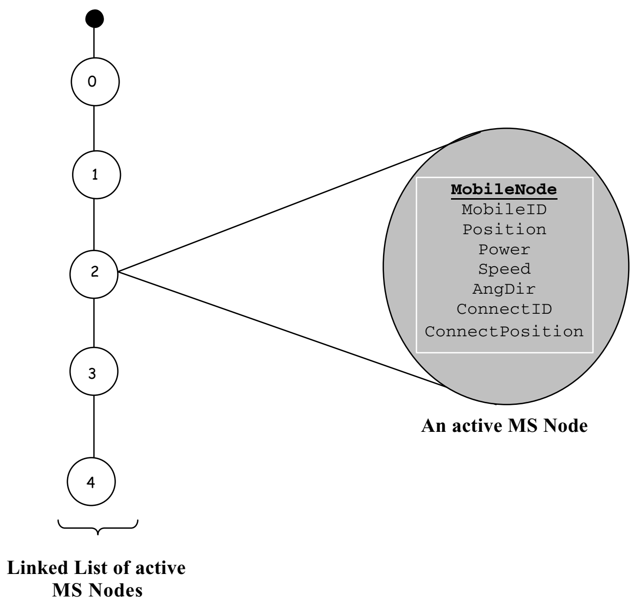


Figure 5.8: `ConnectionRegistry` Data Structure

The calculations pertaining to mobility for determining the next position of a MS are performed by two `processes InitiateMobilityManagementProcess` and the `MobilityManagementProcess`. Once triggered, the mobility calculations are done for each MS according to the description above. The next position of MS is determined as also the time, t, when it would reach that position. This information is passed onto the `RadioChannel` through the *info channel* and self queued in this process. At time t, the position in `ChannelMatrix` as well `ConnectionRegistry` for this MS get updated. At the same time this process again performs the calculations and determines the next position of the MS and the new time, t', when it would reach that position and again `RadioChannel` and `Mobility` are intimated; and so on. This process occurs repetitively for each of the MS to simulate mobility as defined by the mobility and geography models.

This concludes the design and implementation of the system model as specified in chapter 3 according to the SSF platform as detailed in chapter 4.

Chapter 6

Transceiver Reconfigurability

The TAS is a 'tournament arena' for comparison of different wireless systems in a particular radio environment, rather than being a 'conventional testbed' geared towards the performance evaluation of a specific wireless system. This implies that the simulation environment should be able to support the simultaneous existence of different wireless systems, which use their own unique transceiver mechanisms. The transceiver module which implements a MS needs to have the critical capability of 'seamless dynamic reconfiguration' essential to implementing a tournament arena simulation. This chapter focuses on explaining the same.

6.1 Transceiver module requirements

The 'seamless dynamic reconfiguration' capability of the SSF transceiver module could be crystallized as three individual characteristics. They are itemized below.

- **Code remodeling**

  The most important feature of the transceiver class is the ability to support remodeling of the code. This is essential to allow the implementation of distinct wireless systems having different transceiver schemes and even different media access mechanisms. For the above function to be achieved most efficiently, remodeling needs to include the ability to modify, rewrite as well as reuse the code. At the same time all of this needs to be relatively uncomplicated so that modelers unfamiliar with the intricacies of the platform can still model their own versions of the transceiver.

- **Module encapsulation**

  The module implementing the MS and its transceiver scheme needs to be self-contained, independent and isolated from the other modules. All interactions of this module with the other modules should be generic. This is extremely essential to ensure that the modifications in this module don't warrant consequent changes in the other modules. Seamless integration of the newer versions of this module in to the simulation environment is critical.

- **Dynamic class loading**

  This feature is closely related to the previous two items. The TAS is envisaged to allow modelers to submit their distinct transceiver modules to participate in a tournament. These modules could be written by different modelers in different formats. The lesser the number of rules they need to conform to, the greater the flexibility in modeling. The simulation environment, hence, needs to be able to dynamically scan and locate these modules and load them dynamically at run-time such that they continue to exhibit their individual features while seamlessly integrating with the environment.

These three characteristics define the 'seamless dynamic reconfiguration' capability of the transceiver module.

6.2 Transceiver module implementation

This section goes into the implementation details of the transceiver module necessary to explain how the above design requirements are satisfied.

As discussed in chapter 4, all the different modules in the TAS exist in form of JAVA SSF classes. The class `MobileTerminal` implements the transceiver module and performs the functions of a MS. The transceiver implemented in `MobileTerminal` is the scheme assumed as the default for the MSs in the TAS. The default transmitter is a DS-CDMA transmitter and the default receiver is a matched filter. The `MobileTerminal` contains the methods realizing these functionalities. It also contains the basic data structures needed for a MS. The `MobileTerminal` is derived from JAVA SSF base class Entity. It further acts as the base class for all other transceiver models. The classes implementing specific transceiver models and hence individual wireless systems are derived classes extending `MobileTerminal`. The hierarchy of this class inheritance is shown in figure 6.1. Inheritance implies that these derived transceiver classes retain all characteristics of the default transceiver class `MobileTerminal`, while possessing newer individual traits which make them distinct from the other. A modeler wanting to implement a new transceiver model, thus, simply writes a new JAVA SSF class extending the `MobileTerminal` and possessing methods implementing the capabilities of the new model. For example, the `MobileTerminal` uses the JAVA random number generator for generating the random signature sequences. Now suppose the new model uses Gold sequences [11,12] instead. The modeler in this case would write a new JAVA SSF class in which the only modification is in the method generating signature sequences. Since this class is derived from the base class `MobileTerminal` all of its other

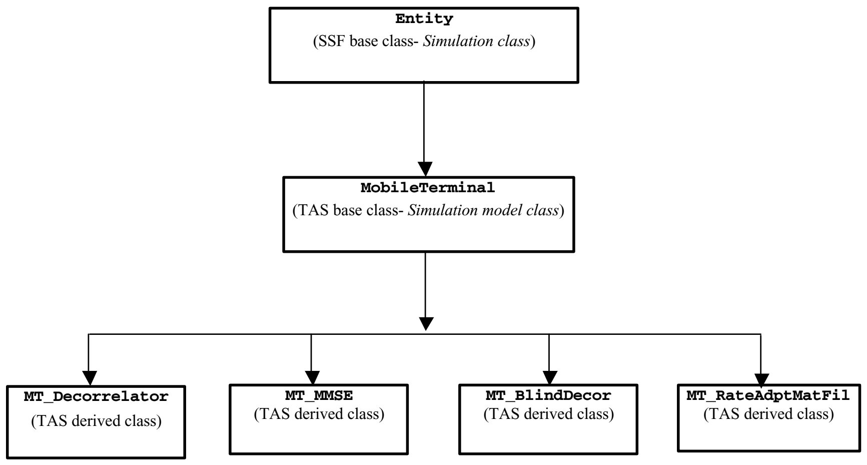


Figure 6.1: *Hierarchy of class inheritance*

functionalities that are not different from the base class are simply inherited without the need for recoding. There are *readme* and *configuration* files provided to facilitate the above process. This is discussed in detail appendix B.

This form of design accounts for the three requirements highlighted in section 6.1. The fact that new transceiver models are implemented in form of new classes, gives complete flexibility in terms of any new capabilities they have to be imparted with. At the same time, class inheritance ensures that there is code reusability so that there is no duplication of effort. This takes care of the code remodeling requirement. Seamless integration of these new classes is ensured by the fact that all new classes are derivatives of `MobileTerminal`. Therefore, to the simulation environment and the other modules therein, the new classes and their objects are still instances of `MobileTerminal`. The other modules are oblivious to the individual features of each of the derived transceiver classes. For run-time aggregation of these classes into the environment, the dynamic class loading feature of the JAVA language is utilized. The new transceiver classes are specially marked through a *configuration* file and this helps environment identify and load these classes dynamically.

6.3 Transceiver Feedback Mechanism

The other significant aspect of the transceiver module, necessary for understanding its operation is the reverse channel feedback mechanism. The simulation environment provides a reverse channel connection from every receiver MS to its transmitter MS. The purpose is to allow the MS pair to alter their transceiver and media access method according to the link condition. The operation of reverse channel feedback mechanism is closely linked with transceiver reconfigurability. It is achieved through the `ResourceControlProcess` of the `MobileTerminal` entity.

The reverse channel is implemented as a *fake data channel* . This means that it is a direct SSF channel- conduit - from the receiver MS to the transmitter MS and does not include any actual radio channel effects. The payload of this reverse channel is left unspecified in the `MobileTerminal`. It is simply declared as a void array of real numbers and is encapsulated within the derivative of JAVA SSF class Event. The resource control option is controlled by a switch. The `MobileTerminal` in its default mode has the resource control option switched off. So no payload event is sent across the reverse channel. A modeler wanting to use this reverse feedback channel needs to switch the option on. Further he needs to define the payload that is going to be fed back from the receiver to the transmitter and also define the processing or action that is to be taken at the transmitter consequent to receiving the feedback. This is achieved through two methods which are declared in the `MobileTerminal` but defined in the new transceiver class by the modeler. This design gives the modeler the flexibility to define his own unique resource control mechanism. This includes flexibility in the resource being controlled, the metric used for exercising the control at the receiver and the follow-up action undertaken at the transmitter. For example, the resource being controlled could be the transmitter power or the transmitter rate, the metric used could be either SIR or BER, the action taken could be increase or decrease the transmit power or rate or simply switch off the transmission, and so on.

This completes the discussion of the transceiver module from its reconfiguration capability viewpoint, which is critical to the simulation environment functioning as a tournament arena. The exact syntactical details for implementing this are given in appendix B.

6.4 Environment Reconfigurability

It has been stressed so far that the key to operation of the 'tournament arena' is the reconfiguration capability of the transceiver module. In addition to this, though, the environment itself has some reconfiguration capability of its own. This facilitates setting up specific system scenarios within the broad purview of the original system model as defined in chapter 3. The simulation environment has two other modules apart from the transceiver module, namely, the radio channel module, `RadioChannel` and the mobility module, `Mobility`. Reconfiguration in each is discussed below.

- **Radio Channel module reconfiguration**

  The default radio channel model is defined in chapter 3, as a flat channel comprising of only distance losses and additive white Gaussian noise. All the processes of the `RadioChannel` are controlled by boolean flags- switches. So there exists the flexibility to modify the radio channel to suit a more specific model. For example, there does exist a method in `RadioChannel generateShadowFade()`, which generates the shadow fade values according to the Gudmundsson model [13]. However, since model parameters such as the standard deviation of the log normal process and the correlation distance are geography dependent, this option is switched off as a default. Similarly the noise addition is operated by a switch, and the noise variance value is also configurable. The `RadioChannel` is actually designed to support multiple radio channels. This is also configurable.

- **Mobility module reconfiguration**

  The mobility module, which also specifies the geography, is defined as mobile adhoc environment with random waypoint mobility. The most important flexibility that is available is that instead of purely ad-hoc mobility scenario, one could actually move to a *cellular-like* scenario supporting multiple cells and both uplink and downlink communication. Here '*cellular-like*' implies that though though the system still consists of only MSs, it is given a *cellular* nature by fixing all the transmitting MSs (downlink) or all the receiving MSs (uplink) at one location on the geography. Though this type of '*cellular-like*' model cannot support higher layer functions like call admission and handoff, it is sufficient to capture the essence of radio propagation characteristics of an actual cellular system from the physical layer viewpoint. This capability is vital for validation of results against standard results which all happen to be mainly for cellular systems. It also provides the possibility of tournaments between cellular and non-cellular systems. This entire mechanism is again controlled by a single configuration flag. Apart from this, other mobility related parameters like speed of MS, size, dimension and distance resolution of the geography or even whether mobility exists or not are configurable.

6.5 Reconfiguration parameters

The previous sections described the reconfiguration capabilities of the different modules of the simulation environment. This section tabulates the specific parameters which are open to modifications in each module. The configuration parameters of the transceiver are listed in the table 6.1, and the simulation environment configuration parameters are listed in the table 6.2, which also includes those of the radio channel and the mobility modules. The exact configuration files which are used to achieve this are explained in appendix B.

A. Transceiver Configuration			
Process Flag		*Range*	*Definition*
a	FixCodeOn	0 or 1	Fixed long code: 0 => absent (random code) / 1 => present
b	OrthCodeOn	0 or 1	Orthogonal code: 0 => absent / 1 => present
Process Parameter		*Range*	*Definition*
c	iNoChipsPerFrame	Any power of 2	Transmission bandwidth. Constant and equal for all MSs.
d	iNoBitsPerSymbol	1	Index of the modulation. BPSK=1
e	iNoBitsPerFrame	Any power of 2 from 1 to c	Data rate of the MS in bits/frame
f	iNoSymbolsPerFrame	d * e	Number of symbols in a frame
g	iNoDataBitsPerFrame	Any power of 2 from 1 to c from 1 to c	Number of data bits in a frame
h	iNoPilotBitsPerFrame	e - g	Number of pilot bits in a frame
i	iSpreadFactor	c / f	Processing gain of this MS
j k	iChipRate dMaxTxPwr	Any power of 2 Any real value in W	Chip rate of the MS. Constant and equal for all MSs Max transmit power of the MS.
l	dMinTxPwr	Any real value in W	Min transmit power of the MS.
m	dMaxSpeed	Any real value in m/s	Max speed of the MS
n	dMinSpeed	Any real value in m/s	Min speed of the MS
o	dMeanSpeed	Any real value in m/s	Mean speed of the MS

Table 6.1: Transceiver configuration table

B. Environment Configuration			
Process Flag		*Range*	*Definition*
a	MobilityOn	0 or 1	MS motion: 0 => absent / 1 => present
b	RadioChannelOn	0 or 1	Radio channel effects: 0 => absent / 1 => present
c	NoiseOn	0 or 1	AWG Noise: 0 => absent / 1 => present
d	DistCompOn	0 or 1	Perfect power control: 0 => absent / 1 => present)
e	ShadowFadeOn	0 or 1	Shadow fading: 0 => absent / 1 => present
f	ResourceControlOn	0 or 1	Resource control: 0 => absent / 1 => present
g	RangeCalcOn	0 or 1	Range calculation between connected tx-rx pair: 0 => absent / 1 => present
Process Parameter		*Range*	*Definition*
h	dSimTime	Any +ve real value	Run time of the simulation
i	dConstNodB	Any value in dB	System noise specified in terms of the noise variance N_0 in dB
j	dConstEbNodB	Any value in dB	System noise specified in terms of the SNR(E_b/N_0) in dB, with $E_b = 1$ at the rx
k	dMaxX	Any real value	Maximum value of X-coordinate of the geography
l	dMaxY	Any real value	Maximum value of Y-coordinate of the geography
m	dDistRes	Any real value < k,l	Distance resolution of the geography
n	dIntraRange	Any real value < k,l	Maximum distance range between the tx-rx of a connection pair
p	dInterRange	Any real value < k,l	Maximum distance range between the 'BS' of two different 'cellular-like' systems
q	dLgNrmlSigma	Any real value in dB	Standard deviation of the log-normal shadow fading process (Gudmundsson's model)
r	dCorrDist	Any real value < k,l	Correlation distance of the log-normal shadow fading process (Gudmundsson's model)

Table 6.2: Environment configuration table

Chapter 7

Sample Transceivers and Tournaments

Different tournaments have been staged in the TAS as a part of the thesis to demonstrate the capabilies of the simulation platform as also to highlight the possible avenues where this could be used for future research.

7.1 Transceivers

The most salient feature of the TAS is the ability to simulate, simultaneously, different autonomous wireless systems with diverse, and independent tranceiver schemes. There are some basic guidelines, though, specified based on the system model as described in section 3.4. The most relevant point is that all mobile stations (MSs) operate in a mode similar to DS-CDMA within a radio channel that is frame synchronous as well as chip synchronous. Within this premise, the diversity in the tranceivers can be exercised in a two-pronged fashion:

- **Transceiver Structure**

  The simplest means of implementing transceiver diversity is by employing different tranceiver structures like the matched filter, the Rake receiver, the decorrelator, some other the multiuser detector etc in the mobile stations (MS).

- **Resource Control Scheme**

  The second part of implementing tranceiver diversity is control and adaptation of the radio resources. There are three main parameters that could be classified as radio resource, (a) the transmit power of the mobiles, (b) rate or the number of bits transmitted per frame and (c) the signature sequences used for spreading the signal.

Using these as the building blocks several different transceiver schemes can be implemented. Schemes largely different than these can also be tried as long as these follow the basic guidelines of DS-CDMA in a frame synchronous and chip synchronous radio channel. The details of this type of reconfiguration have already been explained in chapter 6.

7.1.1 Transceiver Implementation

For the tournaments staged here as a part of this thesis and the experiments done within, three different transceiver structures have been selected. These are (a) the Matched Filter, (b) the Decorrelating Detector and (c) the Blind Adaptive Decorrelator. Additionally, rate adaptation while keeping the transmit power and the signature sequences fixed is employed. This subsection describes these transceiver schemes in greater detail. It also provides results that compare these transceivers against the theory to demonstrate the correctness of the implementation.

(a) Matched Filter

The first transceiver structure implemented is the conventional matched filter receiver as described by equation 3.6. The probability of bit error for a single connection matched filter is given by equation 7.1.

$$P_k^m(\sigma) = Q\left(\sqrt{\frac{E_k}{\sigma^2}}\right) \tag{7.1}$$

where E_k is the bit energy of the transmitter k and $\sigma^2 = N_0/2$ is the power spectral density of the AWGN. The BER vs. SNR performance of the implemented matched filter in comparison to the theory for a single connection, or a single transmitter-receiver pair, matched filter system with additive white gaussian noise (AWGN) is shown in figure 7.1. The simulation environment is set up with 2 mobile stations (MSs) initialized randomly on the geography grid and connected to each other as a transmitter-receiver pair. The MSs remain stationary once initialized. The system signal-to-noise ratio (SNR) is varied from 0 to 16 dB, for each value the simulation is allowed to run so that the transmitter has transmitted 100,000 bits, and system BER is noted. The figure 7.1 shows that the implemented match filter performance matches the theory closely.

(b) Decorrelating Detector

The next transceiver implemented is the decorrelating detector as described in [20]. In simple words, a decorrelating detector is a linear multiuser detector that decodes the desired user by suppressing the multiaccess interference completely at the cost of increasing the system noise. For this the decorrelator needs to know the signature sequences of all the transmitter-receiver pairs in the system.

The probability of bit error of a decorrelating detector is as given in equation 7.2.

$$P_k^d(\sigma) = Q\left(\sqrt{\frac{E_k}{\sigma^2 R_{kk}^+}}\right) \tag{7.2}$$

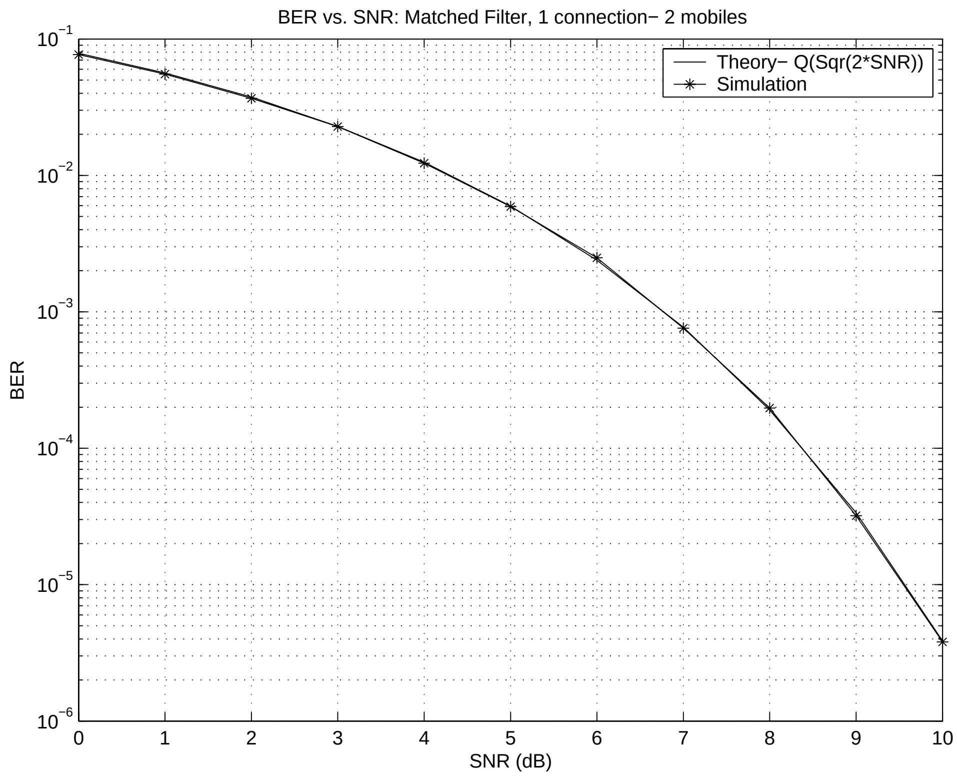


Figure 7.1: *BER vs SIR: Matched Filter Receiver*

where E_k and σ are as described for equation 7.1, $R^{+}_{kk} = [\underline{\mathbf{R}}^{-1}]_{kk}$ and $\underline{\mathbf{R}}$ is the cross correlation matrix for the signature sequences of the all the users in the system.

The performance of the implemented decorrelator filter in comparison to the theory for a single connection matched filter system as specified by equation 7.1, and a 10 connection decorrelating detector system as specified by equation 7.1 is shown in figure 7.2. The simulation environment is set up with 20 decorrelating detector MSs initialized randomly on the geography grid and connected to each other to form 10 transmitter-receiver pairs. The MSs remain stationary once initialized. The system signal-to-noise ratio (SNR) is varied from 0 to 16 dB, for each SNR value the simulation is allowed to run so that each transmitter has transmitted 100,000 bits, and system BER is noted. The figure 7.2 shows that the implemented decorrelator performance matches the theory

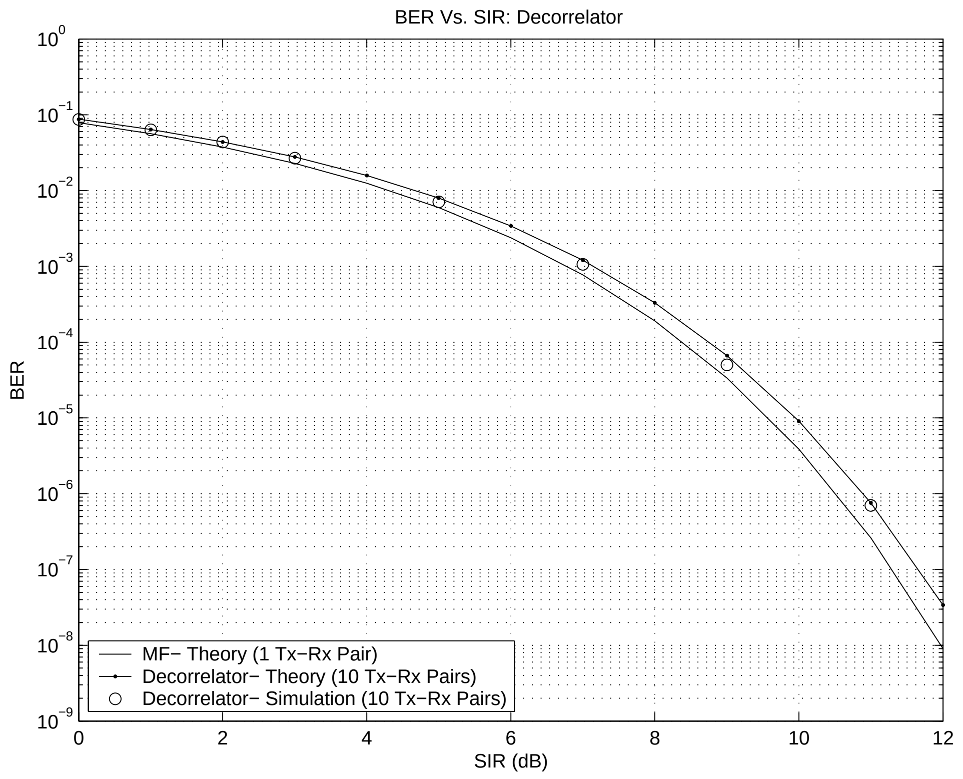


Figure 7.2: *BER vs SIR: Decorrelator*

closely.

(c) Blind Adaptive Decorrelating Detector (BADD)

The third transceiver implemented is the blind adaptive decorrelating detector as described in [26]. The BADD, like the decorrelating detector, uses the structure of the noise to suppress multiaccess interference. The detector is constructed through a local iterative algorithm that updates the filter coefficients, $\underline{\mathbf{c}}_n$, of a desired user by using the previous output of the filter under construction as follows.

$$\underline{\mathbf{c}}_{n+1} = (1 - \sigma^2 a_n)\underline{\mathbf{c}}_n - a_n(\underline{\mathbf{r}}_n y_n - \underline{\mathbf{s}}_1) \tag{7.3}$$

This filter converges to the decorrelating detector in the mean square energy (MSE) sense.

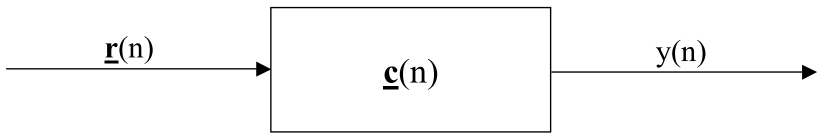


Figure 7.3: *BADD Filter Structure*

For iteration n, $\underline{\mathbf{c}}_n$ is a vector of filter taps, $\underline{\mathbf{r}}_n$ is the received vector at the filter input, y_n is the output of the receiver filter, σ^2 is the variance of the AWGN, $\underline{\mathbf{s}}_i$ is the signature sequence of the desired user i, and a_n is the iteration step size in iteration n. This is shown diagramatically in Figure 7.3. The iteration step size could be fixed or time-dependent. The time-dependent step size has been selected here as it is optimal from the point of view of convergence time as well as the MSE, as detailed in [26, page 10]. The time-dependent step size a_n is specified in 7.4.

$$a_n = \frac{1}{n_0 + n} \tag{7.4}$$

where $n_0 = 5$ is a constant and n is the iteration number.

It should be noted here that $\underline{\mathbf{r}}_n$ and y_n are readily available at the input and the output of the receiver filter. The only other system parameter that needs to be known in advance at the receiver filter are the variance of the AWGN and the signature sequence of the desired user. It is fairly reasonable to assume that a receiver filter will be

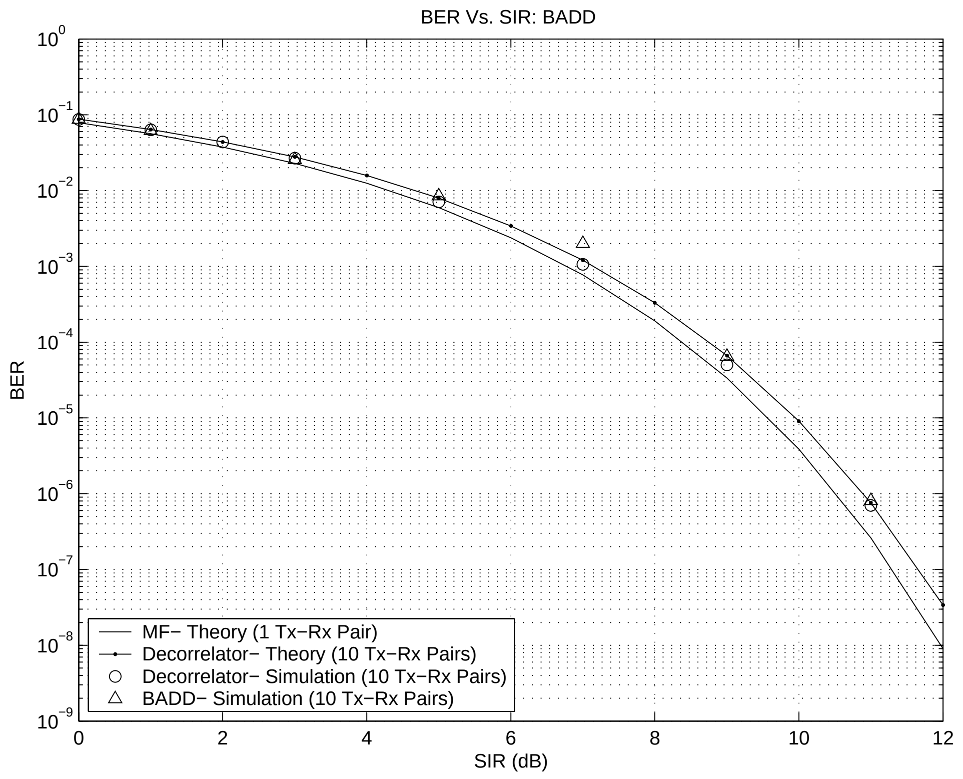


Figure 7.4: *BER vs SIR: BADD*

able to have the prior knowledge of these two parameters. Thus, the BADD provides performance comparable to the decorrelating detector in the BER sense, without the necessity for each of the receivers to have the knowledge of the signature sequences of all the users in the system. In an autonomous, diverse and possibly non-cooperative multiuser scenario, the BADD proves to be an attractive receiver option.

The simulation environment is set up with 20 MSs initialized randomly on the geography grid, configured as BADD transceivers, and connected to each other to form 10 transmitter-receiver pairs. The MSs remain stationary once initialized. The system signal-to-noise ratio (SNR) is varied from 0 to 16 dB, for each SNR value the simulation is allowed to run so that each transmitter has transmitted 100,000 bits, and system BER is noted. Figure 7.4 essentially superimposes the system BER values for this BADD system over the figure 7.2. It can be seen that the BADD transceiver implemented here to be almost as good as decorrelating detector in BER-performance sense.

7.2 Tournaments

Several different experiments and tournaments have been conducted with the transceivers and the transceiver schemes defined above. It has been shown in [26, pages 7-10] that if the simulation is allowed to run for a sufficient number of iterations, the BADD converges to a decorrelating detector. This is also seen from figure 7.4 in a BER sense. Therefore, in all the tournaments below, the participants are the matched filter and the BADD. The tournaments are staged in a flat square geographical grid, 10,000m x 10,000m in area.

7.2.1 Tournament 1: Single Transceiver System in the Arena

This tournament has two participant transceivers, a matched filter transceiver and a BADD transceiver. At a time, all the mobile stations (MS) in the system have the same transceiver structure.

Round A comprises all the MSs with matched filter transceivers. The MSs (transmitter-receiver pairs) are randomly initialized on the grid such that distance between the transmitter and the receiver of a pair is not more than a pre-determined range. This is done using a simple iterative loop in the code wherein after intializing the transmitter MS of the transmitter-receiver pair, the receiver MS is initialized iteratively and its distance from the transmitter calculated each time till the distance is lesser than the pre-determined range. This pre-determined distance is called the Tx-Rx range from here on. Once initialized, the MSs don't move from their positions. This is to ensure that the results are not affected by the geographical distance losses. The radio channel is chip synchronous and frame synchronous. The transmitter transmits 1 bit per frame. The spreading gain is 128, and the signature sequences are randomly generated and then kept fixed with every frame. The distance loss of the transmitted signal at the receiver is compensated by setting the transmit power so that received signal strength at the receiver is equal for all receivers. Since the MSs don't move once initialized, the transmit power once set also remains fixed. The bit rate is also kept fixed at 1 bit per frame. The two parameters that are variable in these experiments are the number of MSs in the system and the Tx-Rx range. Several sets of experiments are run. For each set, the Tx-Rx range is fixed, and then the number of MSs in the system are varied with different iterations. For every iteration or run of the simulation, each MS transmits 100,000 bits. The Signal-to-Noise ratio, with one transmitter-receiver pair and no multiuser interference, is set to 7 dB.

The resuts are averaged over 10 runs of this experiment, i.e. for 10 different mobile position initializations.

Round B comprises of exact same experiment as above, except that now all the MSs have BADD transceivers as described by the equation 7.3.

The performance of these two systems are quantified in terms of the system goodput, the system throughput and the system bit error rate (BER). The system throughput is defined as the total number of bits transmitted in the system, the system goodput is defined as the total number of error-free bits transmitted in the system and the system BER is defined as the ratio of the total number of bits in error and the total number

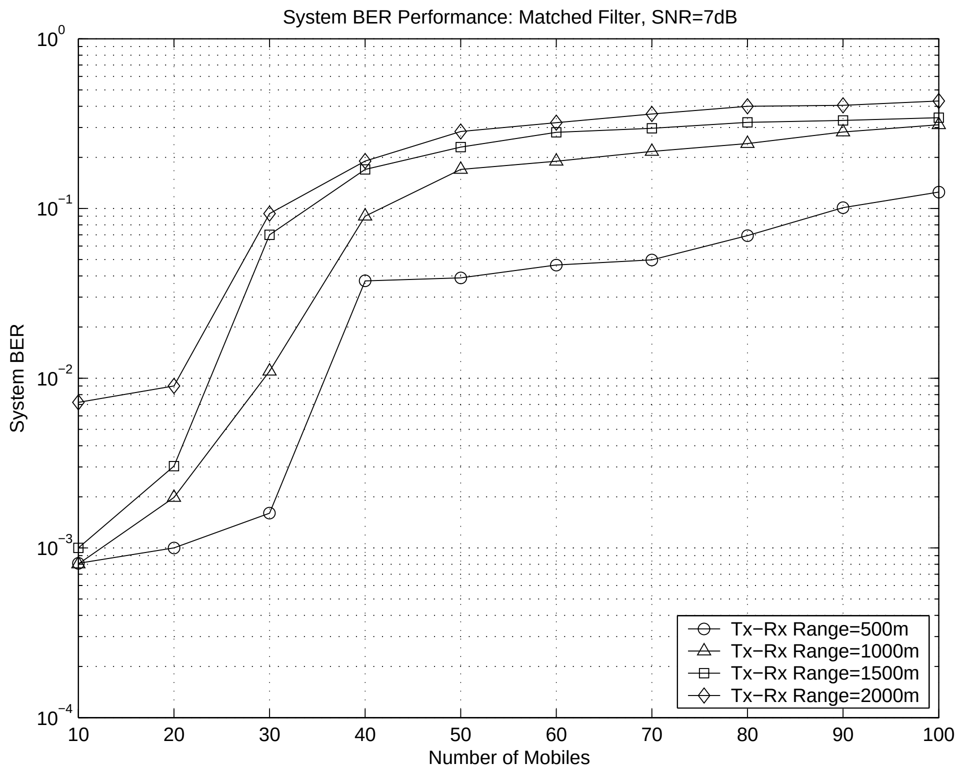


Figure 7.5: *System BER Performance: Tournament 1A, Matched Filter, SNR = 7dB*

of transmitted bits.

The figure 7.5 shows the plot of the the system BER versus the number of MSs in the system at different Tx-Rx range values for the system with all matched filter transceivers. This emphasizes the obvious fact that as the number of MSs in the system increases, the system BER increases. In addition it also shows the effect of the Tx-Rx range on the BER performance. If we consider BER $= 10^{-2}$ to be a performance threshold, then it is seen from the figure that the number of MSs that the system can support without exceeding the threshold decreases with increasing Tx-Rx range.

Figure 7.6 provides the same statistics for a system where all the MSs have BADD transceivers. The figure 7.7 compares the system with all matched filter transceivers with the system with all BADD transceivers, on the basis of the same system BER vs.

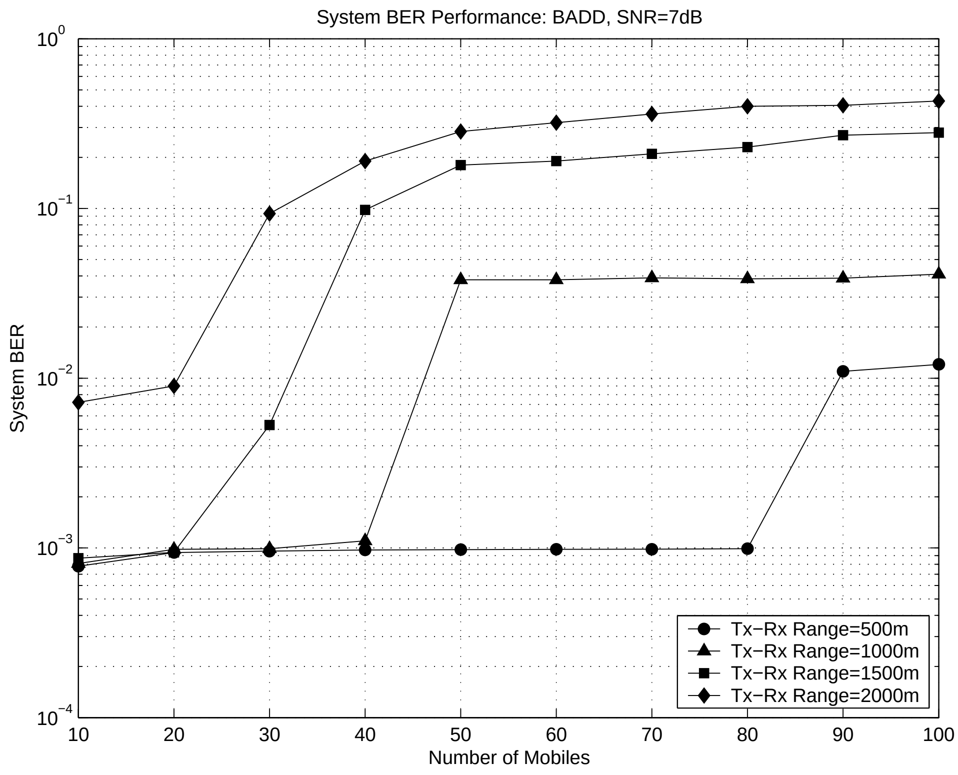


Figure 7.6: *System BER Performance: Tournament 1B, BADD, SNR = 7dB*

number of Mobiles statistic, at two different Tx-Rx range values. Again if we consider $BER = 10^{-2}$ to be the BER performance threshold value, then the plot shows that for a Tx-Rx Range = 500m, the maximum number of connections that can be supported in the system without exceeding the performance threshold is approximately 18 (36 MSs) for a system with matched filter transceivers, while it is approximately 44 (88 MSs) for a system with all BADD transceivers. For a Tx-Rx Range = 1500m, the same is approximately 11 (22 MSs) for a matched filter system, and is approximately 17 (34 MSs) for a BADD system. Figure 7.8 also compares the two type of systems, but shifts the attention on performance of individual transmitter-receiver pairs. It shows the scatter-plot of the average BER versus the average SIR seen at the receiver of each transmitter-receiver pair for both the matched filter system and the BADD systems.

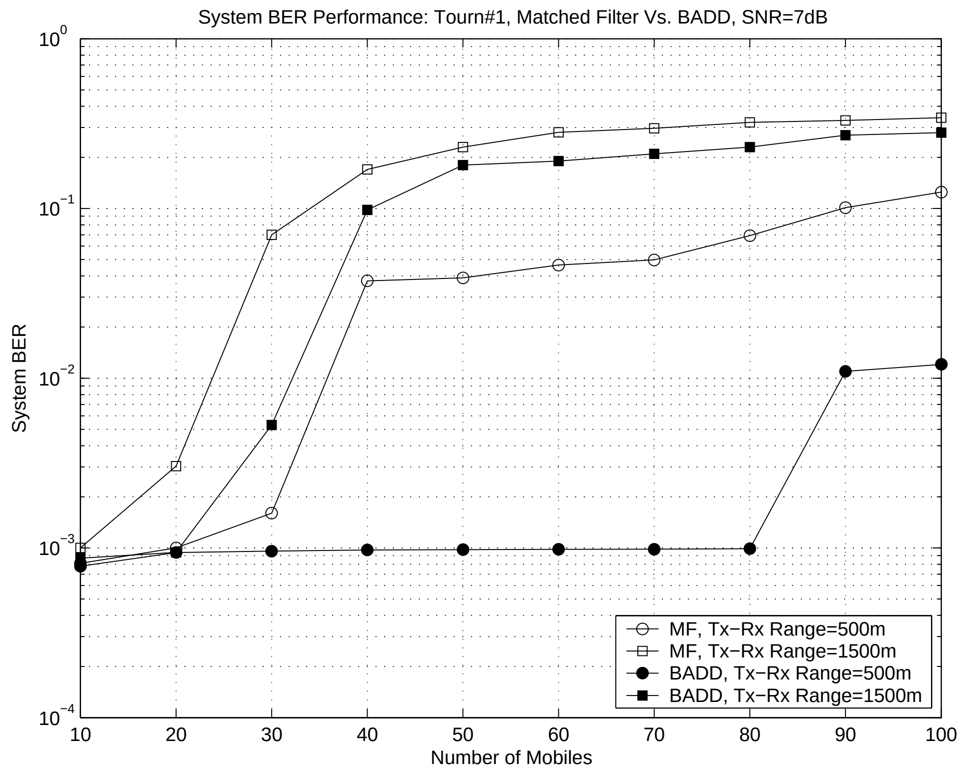


Figure 7.7: *System BER Performance: Tournament 1, Matched Filter vs. BADD, SNR = 7dB*

The BER vs. SNR Q-curve, as specified by the equation 7.1, for a single matched filter transmitter-receiver pair with only AWGN is also give for reference. This helps quantify the number of 'bad connections' in a system, for particular system BER performance statistic. It clearly shows difference in performance of a BADD system with 0 bad connections as compared to a matched filter system with 5 bad connections, out of a total of 20 connections, with the Tx-Rx Range = 500 m. Here a 'bad connection' is defined as a connection where the system BER is less than 10^{-2}.

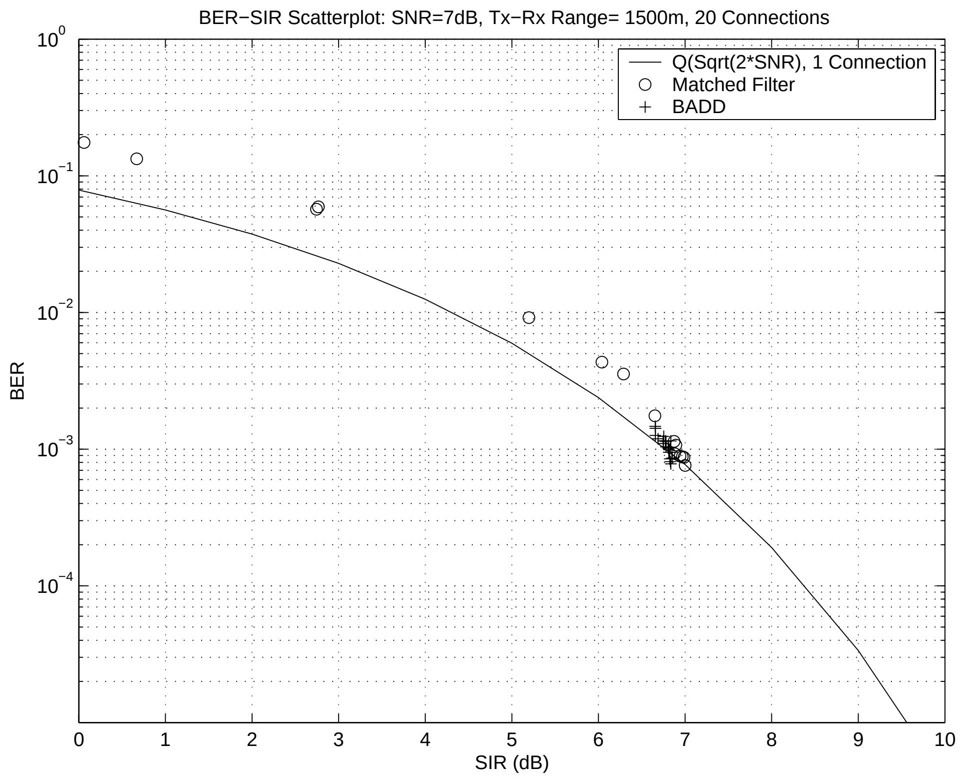


Figure 7.8: *System BER Performance: Tournament 1, Matched Filter vs. BADD*

7.2.2 Tournament 2: Two Equal-sized Transceiver Systems in the Arena

Similar to the first tournament, this tournament also has two participant transceivers, the matched filter transceiver and the BADD transceiver. However, here the MSs with matched filter transceiver and the MSs with BADD transceiver co-exist in the environment simultaneously.

Other than the fact that two types of transceivers exist simultaneously, all other system setup parameters are same as tournament 1. These are restated again below for the reference. The MSs (transmitter-receiver pairs) are randomly initialized on the grid such that Tx-Rx range is not more than a pre-determined distance; a simple iterative loop in the code is used to achieve this as described in section 7.7. Once initialized, the

MSs don't move from their positions. This is to ensure that the results are not affected by the geographical distance losses. The radio channel is chip synchronous, and frame synchronous. The transmitter transmits 1 bit per frame. The spreading gain is 128, the signature sequences are randomly generated and then kept fixed with every frame. The distance loss of the transmitted signal at the receiver is compensated by setting the transmit power so that received signal strength at the receiver is equal for all the receivers. Since the MSs don't move once initialized, the transmit power is set once and then remains fixed. The bit rate is also kept fixed at 1 bit per frame. The two parameters that are variable in these experiments are the number of MSs in the system and the Tx-Rx range. Several set of experiments are run. For each set, the Tx-Rx range is fixed, and then the number of MSs in the system are varied with different iterations. For every iteration or run of the simulation, each MS transmits 100,000 bits. The Signal-to-Noise ratio, with one transmitter-receiver pair in the system and no multiuser interference, is set to 7 dB.

The fact that matched filter and BADD transceivers co-exist in the system leads to some interesting changes in the signal vs. interference dynamics. For the matched filter receiver, only the transmitter of the Tx-Rx pair is the desired user, and it has prior knowledge of the signature sequence of the transmitter. All other transmitters, including the BADD transmitters, are interferers. For the BADD, for a given set of signature sequences, the performance is independent of the transceiver structure of the other MSs in the system.

There are three statistics that we will consider while comparing the performance of these wireless systems.

- **Matched Filter System BER** : The system BER of the matched filter transceivers is calculated by taking the ratio of the total error-free bits to the total bits transmitted by the matched filter transmitters. The effect of the additional BADD transmitters in the system is captured in the increased system interference and consequently decreased goodput.

- **BADD System BER**: The system BER of the BADD transceivers is calculated by taking the ratio of the total error-free bits to the total bits transmitted by the BADD transmitters. The effect of the additional matched filter transmitters in the system is captured in the increased system interference and consequently decreased goodput of the BADD system.

- **Total System BER**: The total system BER of receiver MS is calculated by taking the ratio of the total error-free bits to the total bits transmitted by all the transmitters in the system, including both the matched filter and the BADD transmitters.

With the matched filter and the BADD transceivers coexisitng in the environment, two different rounds of the experiment are conducted.

In round A, for the first set of experiments, the Tx-Rx range is set to 500m, the system is initilized with 4 mobiles, half of which are matched filter transceivers and the other half are BADD transceivers. The experiment is allowed to run until each mobile transmitter transmits 100,000 bits, and the BER statistics are noted. Subsequent sets are performed increasing the total mobiles in the system up to 100 mobiles, keeping all other parameters the same, and again the BER statistics are noted. In round B, this same series of experiments is repeated with the Tx-Rx range set to 1000m.

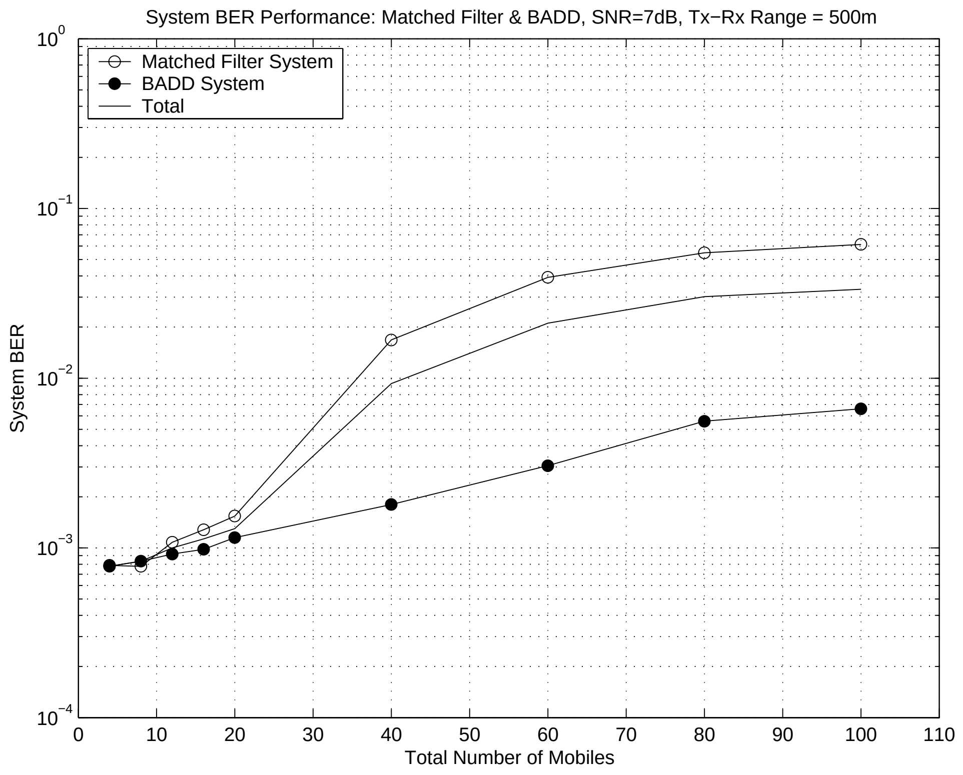


Figure 7.9: *System BER Performance: Tournament 2A, Matched filter Vs. BADD, SNR = 7dB*

The resuts are averaged over 50 runs of each experiment, i.e. for 50 different mobile position initializations.

The figure 7.9 shows the plot of the the system BER for both the transceiver systems versus the total number of MSs in the system at Tx-Rx range value of 500m. Apart from emphasizing the obvious fact that as the number of MSs in the system increases, the system BER increases, the plots clearly shows that the BADD system performs much better as compared to the matched filter system. If we consider $BER = 10^{-2}$ to be a performance threshold, then it is seen from the plot that the matched filter system can sustain that system BER with up to 17 connections (34 mobiles) in the environment, while the BADD system is well below the threshold even with up to 50 connections (100 mobiles) in the environment. Another way of looking at this is that

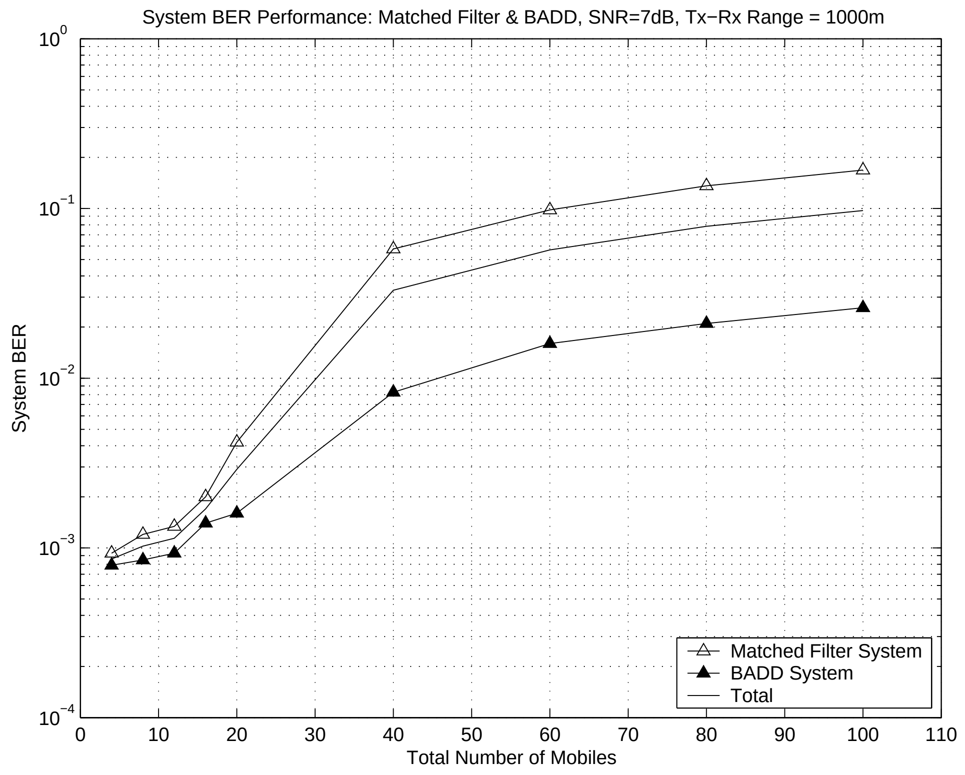


Figure 7.10: *System BER Performance: Tournament 2B, Matched Filter Vs. BADD, SNR = 7dB*

with a total of 80 mobiles in the system, 40 matched filter transceivers and 40 BADD transceivers,the matched filter system BER is of the order of 10^{-2} while the BADD system BER is approximately 10^{-3}.

The figure 7.10 shows similar results with the Tx-Rx range set to 1000m. It is seen that while the BADD has better performance, the advantage is diminished. Again considering $BER = 10^{-2}$ as the performance threshold, it is seen that the matched filter system can supports 13 connections (26 mobiles) while the BADD system can support 22 connections (44 mobiles).

The figures 7.11, and 7.12 show the system BER data points for the matched filter system and the BADD system, for this same tournament, but for each run, i.e. each of

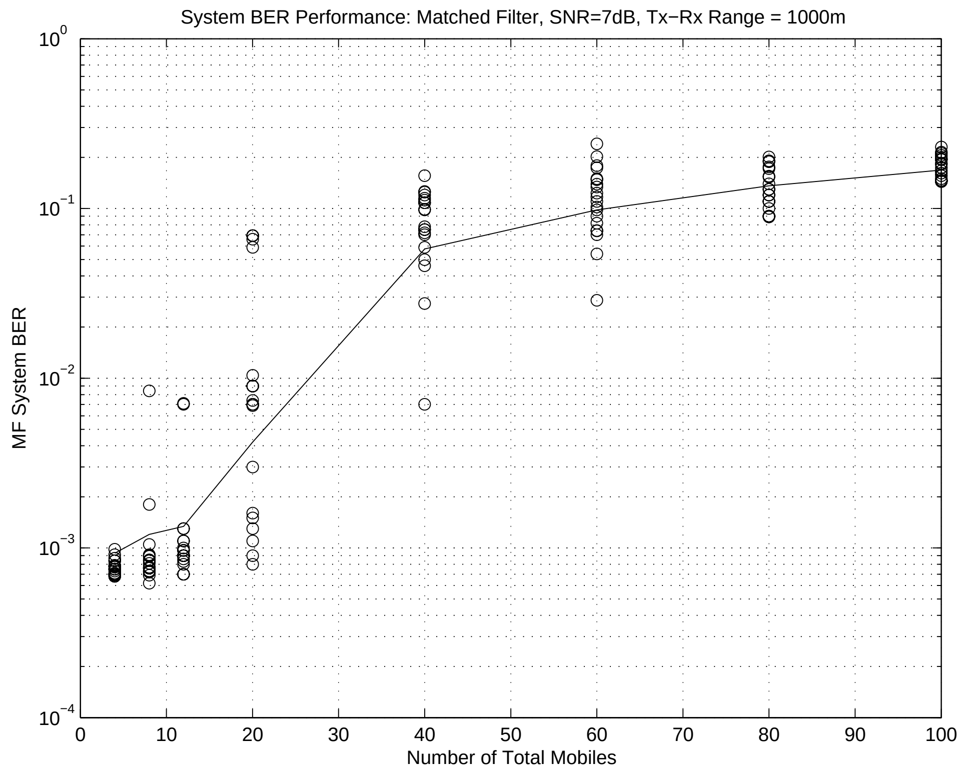


Figure 7.11: *System BER Performance (Per Run): Tournament 2C, Matched Filter Vs. BADD, SNR = 7dB*

the 50 mobile position initializations. It gives an idea about the variance in the system BER depending on the position of the transmitter-receiver pairs.

7.2.3 Tournament 3: Two Unequal-sized Transceiver Systems in the Arena

The experiments in tournament 3 are designed for understanding the impact of the different transceiver types in the environment on the total system BER. Here while the total number of mobiles in the system is kept fixed, the composition of those mobile

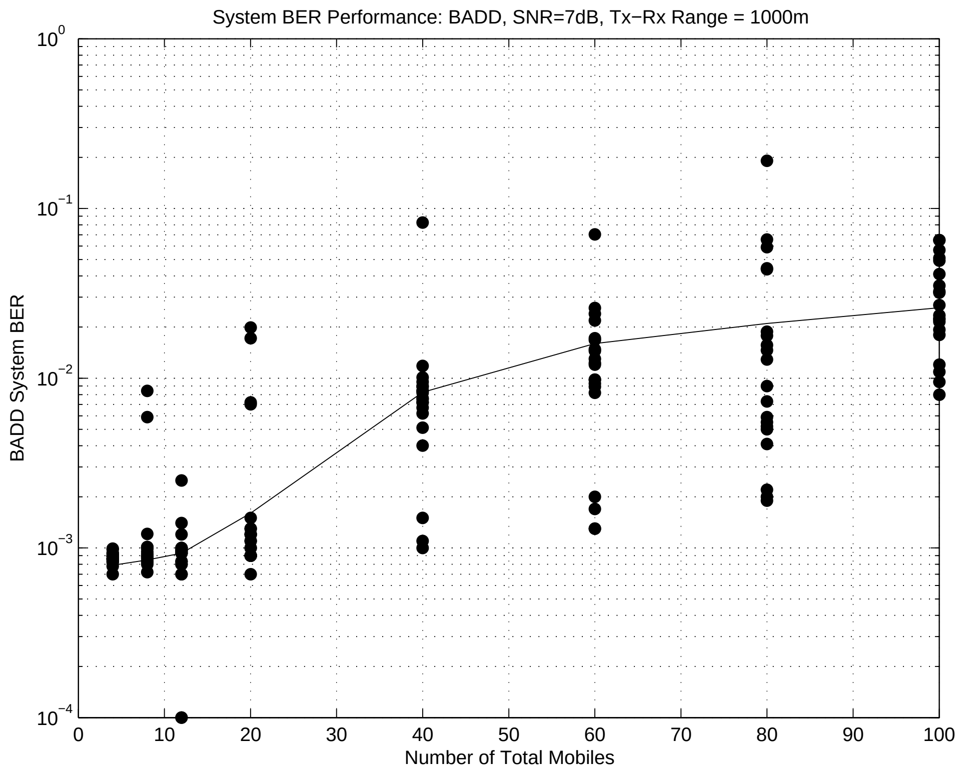


Figure 7.12: *System BER Performance (Per Run): Tournament 2D, Matched Filter Vs. BADD, SNR = 7dB*

stations in terms of number of matched filter transceivers and the number of BADD transceivers is altered, and the system BER statistics are noted. For round A, the Tx-Rx range is set to 500m, the system is initilized with 80 mobiles, all of which are matched filter transceivers. The experiment is allowed to run until each mobile transmitter transmits 100,000 bits, and the BER statistics are noted. In the next set of experiments the total number of mobiles is still kept fixed at 80, but now 70 of those mobiles are matched filter transceivers while the remaining 10 are BADD transceivers. All other parameters the same, and again the BER statistics are noted. Similarly, subsequent sets of the experiment are run, altering the arena composition while keeping the arena size constant. For round B, this entire series of experiments is repeated with the Tx-Rx range set to 1500m. The results are averaged over 10 runs of each experiment, i.e. 10

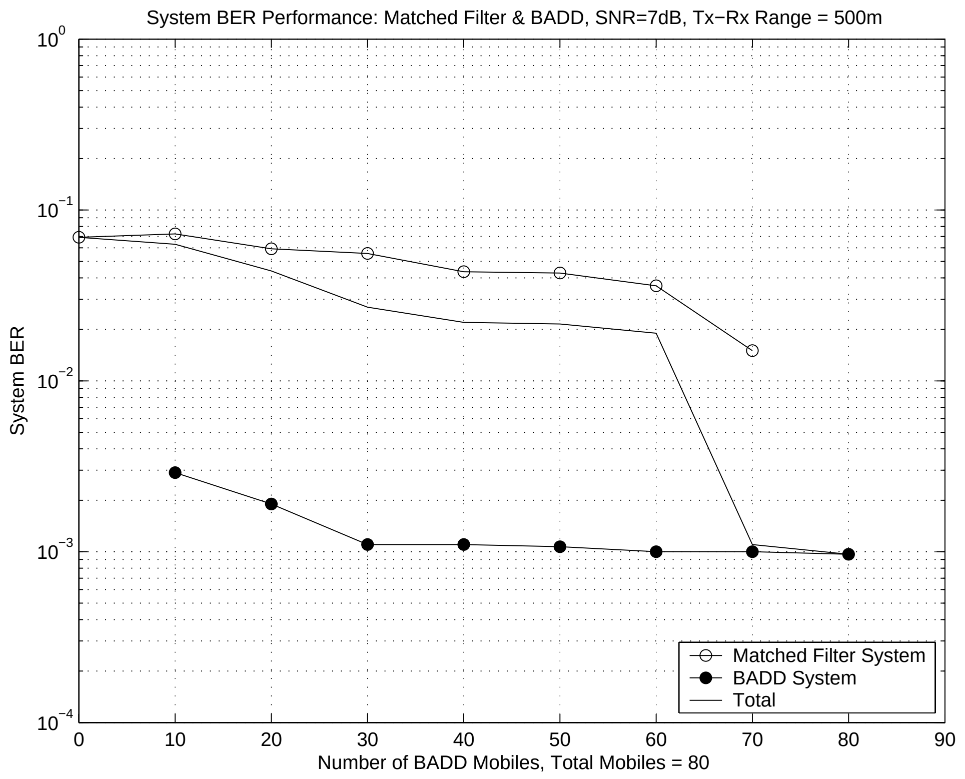


Figure 7.13: *System BER Performance: Matched Filter Vs. BADD, SNR = 7dB*

mobile position initializations.

The figure 7.13 shows the plot of the the system BER for each of the transceiver systems individually as well as the total system, versus the number of BADD transceivers in the system at Tx-Rx range value of 500m. The plot reiterates result of the previous round that the BADD system performs much better as compared to the matched filter system. In addition to this, an interesting result can be derived by noting the plot for the total system BER, which considers both the transceiver types. It clearly shows that total system BER improves (becomes numerically lower) as the number of BADD transceivers increase and the number of matched filter transceivers in the system decrease.

The figure 7.14 shows the plot of the the system with the Tx-Rx range set to 1500m. The results are similar to the previous set of experiment, but again the advantage gained

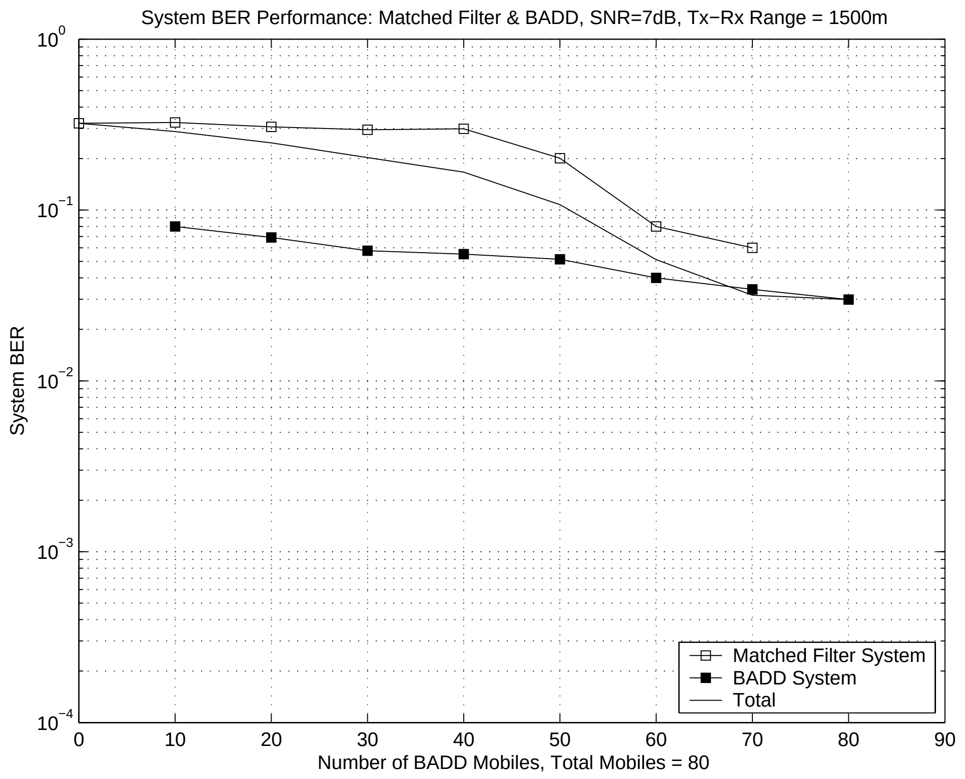


Figure 7.14: *System BER Performance: Matched Filter Vs. BADD, SNR = 7dB*

due to the more robust BADD transceiver gets eroded due to the greater Tx-Rx range.

7.2.4 Conclusion

Based on these three sample tournaments staged with the matched filter and the BADD transceivers, it can be concluded that for a system model as in the TOURNAMENT ARENA SIMULATOR , the BADD emerges as a clear winner for having the most robust transceiver scheme in BER sense. Additionally, we also get good insights in to the effect of the distance range between the transmitter and the receiver, and to what might be an optimum Tx-Rx range to achieve a required BER performance given a partcular system composition; or what might be the optimum size of the system in terms of the number of MSs, given the Tx-Rx range.

Chapter 8

Conclusion and Future Work

The thesis has described the Tournament Arena Simulator, a software simulation platform for performance evaluation of wireless systems in the unlicensed bands, based the Java binding of SSF. The concept of unlicensed band communication has been explained. The system model, which is a simplified derivation of an unlicensed band communication environment, is described conceptually, mathematically, and also from the implementation point of view. The thesis has also explained how the simulation platform can be configured to stage tournements between different wireless communications, and how meaningful statistics can be collected. The integrity of the Tournament Arena Simulator has been validated by comparing the BER performance statistics of some standard transceivers against theory. Some sample tournaments were staged to demonstrate the functioning of the platform, and its utility in evaluating the perfomance of different communications systems participating in the tournaments. Some simple inferences with regards to a robust transceiver scheme were derived based on the outcome of the sample tournamnents.

Tournament Arena Simulator has been shown to be a robust and versatile simulation platform for evaluating system performace in unlicensed band where multiple autonomous wireless communications systems are existing simultaneously. It can provide performance statistics at the level of an individual mobile station, or a specific transceiver system or for the entire wireless environment. It is possible to evaluate one system at a time or to simultaneously evaluate several different systems. There is adequate fexibility inherent in the platform at system parameter level as well as individual transceiver mechanism level to allow researchers implement very specific unlicensed band communications scenarios with very specific transceiver schemes to experiment with. The Tournament Arena Simulator is integrated with DATUM, WINLAB's Java SSF based viewer program, to enable viewing and run-time plotting of the graphs for different system and mobile statistics. As shown by these results and conclusions, the Tournament Arena Simulator can be used for exhaustive experimentation in the area of unlicensed band communications, and as evidenced by the sample tournaments and its results, it could serve as a useful tool for defining the etiquette for 'peaceful co-existence' of wireless systems.

Some avenues of future work include implementing fading in the radio channel, support of multiple-access schemes other than CDMA, defining higher level performance statistics, and staging tournaments involving rate adaptation strategies.

Appendix A

Java-SSF Example Program

The objective of this appendix is to provide a basic understanding of the Java SSF program. This is aimed at getting a better understanding of the functioning of the TAS so as to actually help the user in setting up and running different experiments. The main characteristic of a C++ SSF program are described in detail in [18]. The basic fundamentals of the Java binding of the SSF are similar. This section restates these and focuses on the functionalities that are specific to the Java binding.

We will describe the main characteristics of a SSF program by running through an example program. Source code has been provided and the functionality of statements has been detailed.

Consider a very basic communications system consisting of several MSs, wirelessly connected connection as Transmitter-Receiver pairs, in a radio system environment.

There are 2 types of JAVA SSF entities:

- `MobileStation` : This entity represents the mobile stations and sends out messages on its outChannel, and receives messages on its inChannel
- `RadioSystem` : This entity encompasses all the `MobileStation` entities and does the channel mapping

We now describe the system in more detail.

There are multiple `MobileStations` in the `RadioSystem`. Half of the `MobileStations` are transmitters and the other half are receivers. Each transmitter is connected to exactly one receiver. For this the transmitter `MobileStations` possess outChannels that are mapped to the inChannels of the respective receiver `MobileStations`. The transmitter and the receiver are represented by classes that extend the entity `MobileStation`, which in turn is an extension of JAVA SSF base class entity.

The information is exchanged between the transmitter and the receiver `MobileStations` over the outChannels and the inChannels˙

The entity `MobileStation` is described below. It specifies the basic parameters that specify a mobile station such as the *mobileID*, the *isTx* flag identifying whether this is a transmitter or not, and *Info*, the information it stores. `MobileStation` also has an inChannel and an outChannel. The constructor initializes the `MobileStation` setting the *mobieId*, defaulting it to a receiver, and resetting the *Inf* values to zero. The inChannel and the outChannel are also initialized. It should be noted here that the outChannel is initialized with a minimum delay of 1. This is a JAVA SSF requirement, and it implies that every time an event is sent over the outChannel a delay of 1 simulation time unit is added.

This is shown in the code block below.

`MobileStation` **Entity**

```
public class MobileStation extends Entity {

  int  mobileID;
  boolean isTx;

  class Info {
   double xVal;
   double yVal;
  }

  inChannel iCh_fromMobileStation;
  outChannel oCh_toMobileStation;

  public MobileStation ( int id ) {
    mobileID = id;
    isTx = false;
    Info.xVal = 0.0;
    Info.yVal = 0.0;

    iCh_fromMobileStation = new inChannel( this );

    oCh_toMobileStation = new outChannel( this );
    oCh_toMobileStation.setMinDelay( 1 );
  }

  inChannel getMSinChannel(){
    return iCh_fromMobileStation;
  }

  outChannel getMSoutChannel(){
    return oCh_toMobileStation;
  }
}
```

Msg Event

```
public class Msg extends Event {

  int sender;
  double valX;
  double valY;
  boolean isTx;

  public Msg ( in id, boolean isSender, double x, double y ) {
    if ( isSender ) {
      sender = id;
      valX = x;
      valY = y;
    }
  }
}
```

Information is passed from the msTransmitter entities to the msReceiver entity by encapsulating it into a JAVA SSF class Msg. Msg extends the JAVA SSF base class event. JAVA SSF base class Event acts as the medium of transferring information across entities through the mapped outChannels and inChannels˙

The transmitter and receiver entities are constructed extending the MobileStation entity as shown in the code blocks below. There is one-to-one mapping between the transmitters and the receivers.

msTransmitter **Entity**

```
public class MS_Transmitter extends MobileStation {

  int txID;
  int txCount;

  public MS_Transmitter ( int id ) {
    txID = id;
    isTx = true;

    Info.xVal = Math.pow( txID, 2 );
    Info.yVal = Math.pow( txID, 3 ) * Math.random();

    Transmit();
  }

  public void Transmit() {
    process Transmission = new SimpleProcess(this){
      public void action(){
              Msg myMessage;
              myMessage = new Msg( txID, Info.xVal, Info.yVal );
      oCh_toMobileTerminal.write( myMessage );
              txCount++;

             waitFor( 25 );
      }
    };
  }

}
```

In addition to identifying a `MobileStation` as a transmitter, the `msTransmitter` entity constructor assigns a transmitter id, *txID*, sets the *isTx* flag to TRUE value to identify the `MobileStation` as a transmitter, specifies information value in the *Info* field, and finally triggers the process *Transmit()*. This in turn calls the method *Transmission()*, which creates a message, transmits it on the outChannel of the `msTransmitter`, then waits for 25 SSF simulation ticks, and then again repeats the action. This time-controlled continuous loop is achieved by using the JAVA SSF methods *action()* and *waitFor()*.

`msReceiver` **Entity**

```
public class MS_Receiver extends MobileStation {

  int  rxID;
  int rxCount;

  public MS_Receiver ( int id ) {
    rxID = id;
    isTx = false;
    rxCount = 0;

    Receive();
  }

  public void Receive() {
    process Reception = new SimpleProcess( this ) {
      public void action(){

        SSF.Event[] events = in_fromMobileTerminal.activeEvents();
Msg[] RxMsg = new Msg[ events.length ];

for(int i=0; i < RxMsg.length; i++) {
              RxMsg[ i ] = (Msg) events[ i ];
              if( rxID == RxMsg[i].sender ) {
                Info.xVal = RxMsg[i].valX;
                Info.yVal = RxMsg[i].valY;
              }
              rxCount++;
        }
        waitOn( iCh_fromMobileterminal );
      }
    };
  }
}
```

In addition to identifying a `MobileStation` as a receiver, the `msReceiver` entity constructor assigns a receiver id, *rxID*, sets the *isTx* flag to FALSE value to identify the `MobileStation` as a Receiver, and initiates the process *Receive()*. This in turn calls the method *Reception*, which receives events encapsulated as *Msg*, extracts the *Info* sent in it from the `msTransmitter`, and then waits for on the inChannel for the new event. This event-driven continuous loop is achieved by using the JAVA SSF methods *action()* and *waitFor()*.

RadioSystem Entity

```
public class RadioSystem extends Entity  {

public static int mobileNum = 10;
public static int txNum = mobileNum / 2;
public static int rxNum = mobileNum / 2;

public MS_Transmitter[] Tx = new MS_Transmitter[ txNum ];
public MS_Receiver[] Rx = new MS_Receiver[ rxNum ];

  RadioSystem() {

    for( int i=0; i<Tx.length; i++ ) {
        Tx[i] = new MS_Transmitter(i);
Tx[i].alignTo(this);

        Rx[i] = new MS_Receiver(i);
Rx[i].alignTo(this);

Tx[i].getMSoutChannel().mapto(Rx[i].getMSinChannel());
    }
  }
}
```

The RadioSystem entity hosts the MobileStations. The number of MobileStations in the system are defined here. Half of those are designated as transmitters and the other half as receivers. The constructor initializes the corresponding msTransmitter and msReceiver entities by calling their respective constructors. The corresponding inChannels and outChannels also get initialized during the constructor call. The call to *align()* aligns the transmitters and the receivers with the RadioSystem entity and the call to the method *mapto()* maps the outChannel of the transmitter with the inChannel of the receiver. This essentially completes the simulation setup, and we are ready to run the simulation.

main() Function

```
public static void main(String[] args) throws
             IOException, InterruptedException {

   RadioSystem WiFi = new RadioSystem( );

    WiFi.startAll( 100,000);
    System.out.println( "+++++++++++++++++++++++++");
    System.out.println("  -SIMULATION INITIATED- ");
    System.out.println( "+++++++++++++++++++++++++");
    WiFi.joinAll();

    System.exit( 0 );

}
```

The *main()* function initializes `WiFi` as the `RadioSystem` entity. The *startAll()* statement passes the parameter that indicates the number of SSF ticks for which the simulation will run. The *joinAll()* statement starts all the processes aligned to the same timeline.

Appendix B

Transceiver Reconfiguration Primer

The objective of this appendix is to provide a step-by-step tutorial for achieving the reconfiguration of the transceivers defined in the wireless environment. This appendix should be treated as a complement to chapter 6 that talks about transceiver reconfigurability. The TOURNAMENT ARENA SIMULATOR provides the platform for simulating tournaments between different autonomous wireless communication systems. It also provides the flexibility to the users to define their own transceivers and hold tournaments amongst those. The code has been set up so that the above can be achieved with minimal knowledge of the existing code, and with only a basic working knowledge of JAVA and SSF.

The following are the files that may need to be modified for re-defining the transceiver:

- **./code/mtMyTransceiver.java**:

  This is a new file, where the new transceiver is to be implemented.

- **./code/SimSetup.java** :

  This is the simulation setup parameter file, where both system-level and mobilestation-level parameters are configured.

- **./code/Com.java** :

If the tournament output needs to be written in to a file, the file defnitions are done here.

- **./config/SysConfig.config**:

  This is the configuration file where the different autonomous wireless communication systems in the arena, and the number of mobilestations in each system are specified.

The actual process of introducing new transceivers in to the tournament arena can be explained through the following steps.

1. `mtMyTransceiver` **Entity Definition**

   As explained in 6.2, `MobileTerminal` is the base class implementing a generic MS. It contains all the necessary Java methods and JAVA SSF processes that provide the basic functionality to the MS to work as a matched filter transceiver in a chip-synchronous CDMA environment. Additional transceiver characterization can be done by extending this JAVA SSF entity, and re-defining some of the methods and processes. For example, in order to implement a BADD transceiver the derived JAVA SSF class `mtBADD` is defined; and the process `ReceptionProcess` of the `MobileTerminal` is over-written to include actions for filter-tap updates, and decoding using the filter under construction.

   Here we call the derived `MobileTerminal` class `mtMyTransceiver`. The sections of the code, which are available for modification and re-definition are clearly demarcated, as shown below. It should be noted that Java file containing the newly defined transceiver should have the same name as the derived `MobileTerminal`.

The naming convention followed is that all the derived `MobileTerminal` entities have a prefix 'mt' before the actual transceiver name.

The code blocks below, highlights the methods that can be modified to characterize the new transceiver.

`mtMyTransceiver` Entity - Transmitter process

```
public class mtMyTransceiver {

 //++++++++++++++++++++++++++++++++++++
 // SAMPLE CODE FOR THE TRANSMITTER
 // PROCESS 'initTransmission()'
 //++++++++++++++++++++++++++++++++++++

void initTransmission() {
  process Transmission = new SimpleProcess(this){
    public void action(){

     double[] Data, Pilot, RawFrame,
              ModFrame, SprdFrame, TxFrame;
     SSF.Event[] Events =
        in_toMobileTerminal_Transmission.activeEvents();
     TriggerEvent[] MyTrigger =
        new TriggerEvent[ Events.length ];

   for(int i=0; i .less than. MyTrigger.length; i++){

     MyTrigger[i] = (TriggerEvent)Events[i];
     FrameNum++;
   //--------------------------------------------------//
   //--- MODIFY THE CODE WITHIN "<-xxxxx->"
   //      TO WRITE YOUR TRANCEIVER ---//
   //-------------------------------------------------//

    // Continued below.
```

The section of the code till this point handles JAVA SSF standard operations. It shouldn't be changed. The section of the code that follows (between the '–xxxxx–') can be altered.

`mtMyTransceiver` **Entity - Transmitter process(continued)**

```
        <---xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx--->

        Data = generateRawBit( DataBitsPerFrame, DataRand );
        Pilot = generateRawBit( PilotBitsPerFrame, PilotRand );
        RawFrame = generateRawFrame( Data, Pilot, BitsPerFrame );
        ModFrame = generateModFrame( RawFrame, SymbolsPerFrame, 0 );
        // '0' is the modulation index for bpsk modulation.
        //No other scheme defined right now

        if(OrthSeqOn){
          LongCode = generateOrthCode(
                       ChipsPerFrame, ConnectID);
        }
        else {
          if( FixedCodeOn ){
            LongCode = generateFixedCode(
              SpreadFactor, ChipsPerFrame, LongCodeRand );
        }
          else{
      LongCode = generateRandomCode(
              ChipsPerFrame, LongCodeRand );
          }
        }
        SprdFrame = spreadModFrame(
             ModFrame, LongCode, SpreadFactor, ChipsPerFrame);
        TxFrame = generateTxFrame(
             SprdFrame, SpreadFactor, TxPwr );

        <---xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx--->
        //--------------------------------------------//
        //--------DONOT CHANGE ANYTHING BEYOND THIS------//
        //--------------------------------------------//

        out_fromMobileTerminaltoRadioChannel_Data.
             write( new DataEvent( MobileID, TxFrame, ConnectID ),
                                                              -1 );
        ich_out_fromtoTransmission.write( new TriggerEvent(),
             MUtility.SimTime( SimSetup.System.Time.dRsrcTmStep ) );
        }
        waitOn( in_toMobileTerminal_Transmission );
      }
    };
  }
```

The *initTransmission()* process contains Java methods that perform tasks pertaining to transmission of a frame such as generating the raw data bits, generating the pilot bits, generating the frame with the data bits and the pilot bits, modulating the frame, spreading the frame, amplifying the signal level using the transmit power and finally transmitting the frame. The functionality of any of these methods could be altered to suit a particular transmission scheme as long as the name of the method is kept the same.

The following code block continues further with `mtMyTransmitter` entity describing the receiver process.

`mtMyTransceiver` **Entity - Receiver process**

```
// ++++++++++++++++++++++++++++++++++++++
// --- SAMPLE CODE FOR THE RECEIVER
// PROCESS 'initReception()' ---
// ++++++++++++++++++++++++++++++++++++++

   public void initReception(){

    process Reception = new SimpleProcess(this){
      public void action(){

      double[] NoisyRxFrame, FilteredRxFrame;
      double[] DetRxData, NormRxData;
      double[] RxData = new double[ DataBitsPerFrame ];
      double[] RxPilot = new double[ PilotBitsPerFrame ];
      double AvgRxSigStr;

      SSF.Event[] events
       = in_fromRadioChanneltoMobileTerminal_Data.activeEvents();

      DataEvent[] RecDataEvent
       = new DataEvent[events.length];

      for(int i=0; i .less then. RecDataEvent.length; i++){
        FrameNum++;
        RecDataEvent[i] = (DataEvent)events[i];
        //------------------------------------------//
        //----- MODIFY THE CODE WITHIN "<-xxxx->"
        //---- TO WRITE YOUR TRANCEIVER ------//
        //------------------------------------------//

     // Continued below.
```

The section of the code till this point handles JAVA SSF standard operations.

It shouldn't be changed. The section of the code that follows (between the '–xxxxx–') can be altered.

`mtMyTransceiver` **Entity - Receiver process**(continued)

```
        // <---xxxxxxxxxxxxxxxxxxxxxxxxxxx--->

        Data = generateRawBit( DataBitsPerFrame, DataRand );
        Pilot = generateRawBit( PilotBitsPerFrame, PilotRand );
      if(OrthSeqOn){
           LongCode = generateOrthCode( ChipsPerFrame, ConnectID );
        }
        else {
          if( FixedCodeOn ){
      LongCode = generateFixedCode(
              SpreadFactor, ChipsPerFrame, LongCodeRand );
    }
          else{
       LongCode = generateRandomCode(
               ChipsPerFrame, LongCodeRand );
    }
        }
       if( NoiseOn ) {
          NoisyRxFrame =
            addWGNoise( RecDataEvent[i].AirData,
                                           SpreadFactor );
      }
       else {
          NoisyRxFrame =
            RecDataEvent[i].AirData;
        }

        FilteredRxFrame = filterRxFrame(
              NoisyRxFrame, LongCode, SymbolsPerFrame,
                                               SpreadFactor );

        extractPilot( FilteredRxFrame, RxPilot, RxData );
        AvgRxSigStr = Math.sqrt( getAvgPwr( RxData ) );
        NormRxData = normalizeData( RxData, AvgRxSigStr );
       DetRxData = detectData( NormRxData );
        calcBER( DetRxData, Data, DataBitsPerFrame );
        calcSIR( RxPilot, Pilot );

        if( PowerControlOn ){
          controlPower( ConnectID, SIR, SIRTarget);
        }

      // <---xxxxxxxxxxxxxxxxxxxxxxxxxxxxx--->
      //------------------------------------------//
      //-------- DONOT CHANGE ANYTHING BEYOND THIS -----//
      //------------------------------------------//
      }
      waitOn(in_fromRadioChanneltoMobileTerminal_Data);
    }
   };
  }
}
```

The *initReception()* process contains the Java methods for performing tasks related to the receiving and decoding of a signal by a matched filter receiver. These include filtering the received frame, extracting the pilot bits, decoding and detecting the desired bit and calculating the SIR and the BER statistics. The functionality of any of these methods can be altered as long as the name is kept the same.

2. **Simulation Setup Configuration**

   Once the `mtMyTransceiver` is defined, the next step is to set the simulations parameters in the Java file *SimSetup.java*. Some of the key parameters that are likely to be modified are the number of autonomous systems in the arena, the number of MS per the autonomous system, the maximum allowable distance between the transmitter and its receiver, and the simulation run-time. A comprehensive list of the simulation setup parameters is defined in 6.5.

3. **Output File Definition**

   If the simulation output statistics like SIR, BER etc need to be written in to a file for further analysis, the Java file *Com.java* needs to be modified. This file is already setup with methods that write the different parameters. The naming of the output file can be customized by specifying the *addIn* parameter value depending on the type of tournament.

4. **Configuration File Definition**

   The overall composition of the tournament arena needs to be summarized in the file *SysConfig.config*. This includes the names of the files that contain the updated transceivers, the number of MSs of each transceiver type, and the type of the system whether ad-hoc mobile or cellular. For example, if for a tournament the derived `MobileTerminal` entities are `mtMyTransceiver1` with 20 mobile stations (10 Tx-Rx pairs), and `mtMyTransceiver2` with 30 mobile stations (15 Tx-Rx pairs), the specification of the system configuration file will be as shown in the code block below. Additionally, the *SimSetup.java* file should be updated so that the parameter *System.Environ.iNoAutoSystem* has value 2, and the parameter *System.Environ.iNoMobile* has the value 50.

A sample configuration file is given as a part of the code block.

System Configuration Reference File - SysConfig.Config

```
# Format :
# ------

#
# System_Id System_Name System_Number System_type .
#

# Explanation: .
# -----------
# System_Id:
# Id of the system { 0, 1, 2, ... } .
# System_Name:
# Name of the java class file which implements your transceiver.
# System_Number:
# Number of mobile terminals of that system.
# System_Type:
# Type of the system. Type specifies the geographical environ.
#   Ad-Hoc  --->          0 .
#   Cellular_uplink --->  1 .
#   Cellular_downlink --->2 .

# Instructions:
# ------------
# List all the autonomous systems participating
# in the tournament in successive rows
# in the format described above. The different
# 'Format' fields are tab delimited.

# Example:
# -------
# 0 mtTranceiverA 4 0
# 1 mtTranceiverB 12 1
# 2 mtTranceiverC 2 0

# Specification (Specify your configuration below) :
# ------------------------------------------------

0 mtMyTransceiver1     20        0
1 mtMyTransceiver2     30        1
```

These 4 simple steps allows one to setup the Tournament Arena Simulator to support tournaments with customized transceivers as participants.

References

[1] FCC Report and Order 96-36: Amendments of Parts 2 and 15 of the Commission's Rules Regarding the Spred Spectrum Transmitters.

[2] FCC Report and Order 97-5: Amendment of the Commission's Rules to Provide Unlicensed NII Devices in the 5 GHz Frequency Range.

[3] Specification of the Bluetooth System.

[4] SSFNET website : http://www.ssfnet.org.

[5] U-nii: Winlab research goals and benefits. Internal Document.

[6] Wireless LAN Medium Access Control(MAC) and Physical Layer(PHY) Specifications.

[7] Scalable Simulation Framework API Reference Manual, 1999. Version 1.0.

[8] Ken Arnold and James Gosling. *The Java Programming Language.* Addison-Wesley, 1997.

[9] Kevin Gang Chen. Integrated Dynamic Radio Resource Management of Wireless Communication Systems. Masters thesis, Rutgers, The State University of New Jersey, New Brunswick, NJ, May 1996.

[10] M. Ellis and B. Stroustrup. *The annotated C++ reference manual.* Addison-Wesley, 1990.

[11] R. Gold. Optimal Binary Sequence for Spread Spectrum Multiplexing. *IEEE Transactions on Information Theory, Vol. IT-13)*, pages 619–627, October 1967.

[12] R. Gold. Maximal Recursive Sequences with 3-Valued Recursive Cross Correlation Functions. *IEEE Transactions on Information Theory, Vol. IT-14)*, pages 154–156, January 1968.

[13] M. Gudmundson. Correlation model for shadow fading in mobile radio systems. *Electron. Lett.*, 27(23):2145–2146, 1991.

[14] D. B. Johnson Y. Hu J. Broch, D. A. Matz and J. Jetcheva. A performance comparison of multi-hop wireless ad hoc network routing protocols. Oct 1998.

[15] Jason Liu David M. Nicol Andrew T. Ogeilski James Cowie, Hongbo Liu. Towards Realistic Million Node Internet Simulation. *Proceedings of International Conference on Parallel and Distributed Processing Techniques and Applications*, 4:2129–2135, 1999.

[16] David B. Johnson. Routing in ad hoc networks of mobile hosts. Dec 1994.

[17] Jeffery A. Joines and Stephen D. Roberts. Design of Object Oriented Simulations in C++. *Proc. of the 1995 Winter Simulation Conference.*

[18] Vikram Kaul. Multi-cell wcdma signal processing simulation testbed. Masters thesis, Rutgers, The State University of New Jersey, New Brunswick, NJ, Oct 2000.

[19] Robert Lafore. *Object-Oriented programming in Turbo C++.* Waite Group, 1999.

[20] R. Lupas and S. Verdú. Linear Multiuser Detectors for Synchronous Code-Division Multiple-Access Channels. *IEEE Transactions on Information Theory*, 35:123–136, Jan 1989.

[21] Jignesh Panchal. Wippet : Wireless propagation and protocol evaluation testbed. Masters thesis, Rutgers, The State University of New Jersey, New Brunswick, NJ, Sep 1998.

[22] K. Perumalla and R. Fujimoto. A C++ instance of TeD. TR GIT-CC-96-33, College of Computing, Georgia Institute of Technology, 1996.

[23] K. Perumalla, A. Ogielski, and R. Fujimoto. MetaTeD: A meta language for modeling telecommunication networks. TR GIT-CC-96-32, College of Computing, Georgia Institute of Technology, 1996.

[24] T. S. Rappaport. *Wireless Communications.* Prentice Hall, first edition, 1996. pages 69–192.

[25] David G. Steer. Co-existence and access etiquette in the united states unlicensed pcs band. *IEEE Personal Communications*, Fourth Quarter:36–43, 1994.

[26] S. Ulukus and R. Yates. A Blind Adaptive Decorrelating Detector for CDMA Systems. *IEEE Journal Selected Areas in Communications*, 16:1530–1541, Aug 1998.