KUNGL TEKNISKA HÖGSKOLAN
Royal Institute of Technology

Multihop Packet Radio Sytems in Rough Terrain

OSCAR SOMARRIBA

DEPARTMENT OF SIGNALS, SENSORS AND SYSTEMS
RADIO COMMUNICATION SYSTEMS

KUNGL TEKNISKA HÖGSKOLAN
Royal Institute of Technology

Multihop Packet Radio Sytems in Rough Terrain

OSCAR SOMARRIBA

Licentiate Thesis

October 95

TRITA-S3-RST-9506
ISSN 1400-9137
ISRN KTH/RST/R-- 95/06 --SE

DEPARTMENT OF SIGNALS, SENSORS AND SYSTEMS
RADIO COMMUNICATION SYSTEMS

Abstract

Multihop Packet Radio Networks (PRN:s) offer interesting possibilities for reliable rural data communications in areas where no "external" telecommunication infrastructure is present. One key design issue in PRN:s is the formulation of Medium Access Control (MAC) protocols. In this thesis, the performance for two MAC protocols, Slotted ALOHA (S-ALOHA) and Spatial TDMA (S-TDMA), is investigated in multihop PRN:s. A detailed radio propagation model, which takes the terrain shadowing into account is used. A finite number of buffered nodes were used in the evaluation of these two MAC protocols. Optimum network performance is achieved when the *average packet delay* is minimized.

For S-ALOHA, nodes transmit at random with some given probability q. For this protocol, we investigate the selection of q. An assignment for transmission probability is given in terms of the traffic load and the connectivity, which yields a near optimal network performance.

Furthermore, a novel systematic procedure to find *transmission schedules* in S-TDMA based on the gain matrix is described. The traffic-sensitive schedules show better performance in comparison to the classical S-TDMA. Also, the results from sample networks suggest that there is a favorable connectivity for this protocol, i.e., 3.2 -3.4 neighbors in a network with ten nodes. As expected, S-ALOHA works well with low traffic loads. For high loads, S-TDMA exhibits better performance.

Lastly, we explore how we can affect the connectivity by changing the transmitted power and the antenna height, and their respective influences on the network performance. It turns out that S-ALOHA is less sensitive to these changes than S-TDMA.

Ackowledgment

My debt is to my supervisor Professor Jens Zander, Radio Communicattions Systems, Royal Institute of Technology, for his guidance as well as inspiration and encouragement he has provided throughout this thesis work. Without his outsatanding support this work would not has been possible.

It has been an enriching experience to work at the Radio Communications Systems, because of that I would like to express my sisncere gratitude to my friends and colleagues in this Group. Especially, I would like to tahnk Dr. Bo hagerman for valuable discussion and sugestions. Lise-Lotte Walhberg should be thanked for all help in practical aspects regarding the completion of this work.

I also thank Dr. Magnus Frodigh at Ericsson Radio Systems AB for valuable comments on the manuscript.

The financial support from the Swedish Agency for Research with Developing Countries (SAREC) is gartefully ackowledged.

Lastly, I would like to express my gartitude to Virginia, for her love and support.

Stockholm, October 1995
Oscar Somarriba

Contents

Chapter 1

Introduction

Current wireless systems, such as cellular radio system, are supported by a tethered infrastructure of fixed base stations linked by a wired network. In some cases, such as with emergency disaster relief, the wired network is not available and this type of architecture is not feasible. Moreover, we might face the challenge of providing communications in rural areas or sparsely populated areas where no wired network exists.

A very attractive alternative for data communication in areas without a wired telecommunication infrastructure is to use autonomous radio networks. These networks allow for wireless communications between a ”changing” number of network entities in the situation were no ”external” infrastructure is present. Moreover, such wireless networks could be suitable for military and emergency applications, mobile users, low density personal systems, surveillance of critical signals and remote data acquisition.

1.1 Multihop Packet Radio Communication Systems

One type of autonomous radio networks is the multihop Packet Radio Networks (PRN:s). PRN:s emerged as applications of packet switching techniques to a shared radio channel and are intended to support communications between users over a wide-spread geographical area where a line connection is difficult or impossible. In addition, they also support mobile users and access to a mobile subnet. They usually carry packets of data between nodes equipped with radio transceivers and omnidirectional antennas [1]. With the decrease in the cost of a packet radio unit [2], PRN:s have become a practical way of providing communications. In many PRN:s, not all packet radio nodes can communicate directly because of interference, range limitations, or natural obstacles. In this situation, a packet transferred between two distant nodes may have to be relayed by intermediate stations or nodes. Major design issues in PRN:s involve the "path finding" methods, i.e. *the routing algorithms*, and *the protocols* that determine which nodes *share the channel* to transmit their packets (Figure 1.1). Also, the transmitted power and directional antennas have been addressed as important parameters in the design of PRN:s.

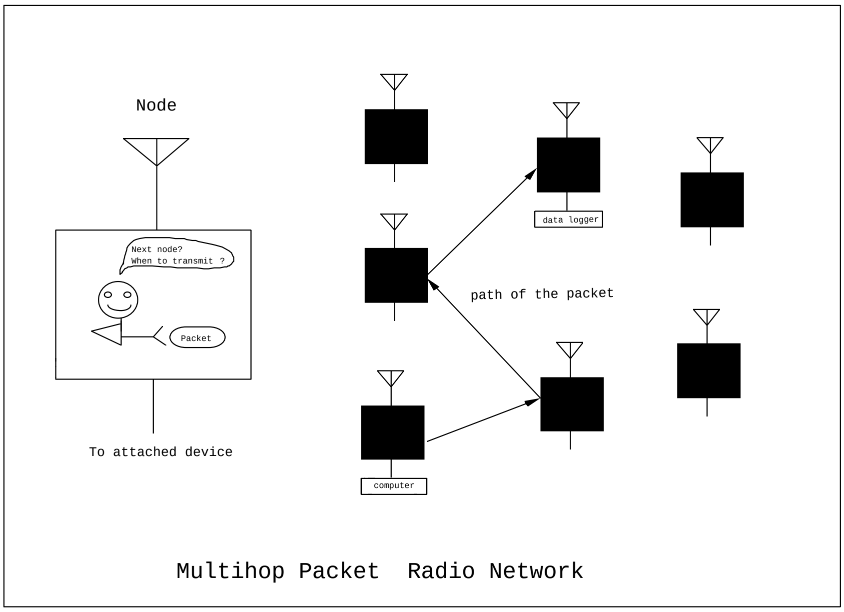

Figure 1.1 MAC protocols and Routing algorithms in PRN:s.

In a multihop network, a message may travel long distances by means of a store-and-forward mechanism: a node transmits to another node, which in turn forwards the packet. This procedure is repeated until the packet arrives at its final destination. In each retransmission phase, the node currently holding the message uses the network routing algorithm to determine the next node in the transmission chain. In an adverse environment where links and nodes may fail without prior warning, nodes cannot rely on routing information distributed from a central routing information distribution center ("station" [1]). Instead, nodes need to make their routing decisions based on limited knowledge about their immediate surroundings.

In addition to making a routing decisions, each node needs to determine when a message is to be transmitted to the neighboring node selected by the routing scheme. This decision is governed by the Medium Access Control (MAC) protocol (or multiple access protocol). Since transmissions in different links in the network may interfere with one another, the routing and access procedures are strongly interconnected [3,5,6]. The goal of the combined routing and access schemes is primarily to minimize the end-to-end packet delay, i.e., the time that it takes a packet to travel from the source station to the final destination station. Often (but not always), this goal coincides with maximizing the number of packets successfully transported through the network, the packet throughput.

1.2 Today’s applications of multihop PRN:s

Data packet technology was developed in the mid-1960’s and was put into practical application in the ARPANET in 1969. The first large-scale PR project, ALOHANET [7], based at the University of Hawaii became operational in 1970. Its principal objective was to allow user terminals in widely scattered locations to access the university computer system. Since ALOHANET, many PRN:s have been implemented, some of them in the multihop fashion such as:

1) DARPA PRNET. Since 1973, the US Defense Advanced Research Projects Agency (DARPA) initiated research on the feasibility of using packet-switched techniques, store and forward radio communications to provide reliable computer communications. As a result of these, the DARPA Packet Radio Network (PRNET) has evolved to provide computer communications in a mobile environment [22]. Also, in 1983, DARPA has sponsored the Survivable, Adaptive Networks (SURAN) program [23] to research and develop network technology capable of supporting communication between computers and their users in the modern battlefield. In the last program, spread spectrum techniques are used. To support experimentation with and demonstration of the advance, adaptive channel capability, the Low-cost Packet Radio Unit (LPR) was developed [2], with 180 LPR:s having been produced up until 1990 [23]. This constitutes a PRN for military communication.

2) AMATEUR PRN. It is worthwhile mentioning the experiments of the radio amateurs which has lead to a standard for the level-link protocol suitable for packet radio networks known as AX.25 [24-25] sponsored by the American Radio Relay League (ARRL). An ARRL-type network is a distributed network organized into clusters of stations connected by repeaters with fixed routing. Amateur PRN began in Montreal, Canada in 1978. This was followed by the Vancouver Amateur Digital Communications Group (VADG) development of a Terminal Node Controller (TNC) in 1980. The improved versions of this TCN provide the ”work horses” of today’s amateur PRN:s. This technology is used all around the world and provides an experimental platform for the amateur community. Also, PRN of this kind have been suggested as ”cheap” means of studying digital radio communications and an attractive possibility for providing emergency communication in case of natural disasters.

1.3 Literature review

Several MAC protocols have been proposed in the literature, and in [4] an overview of the existing multiple access protocols is given. They can be grouped into at least four classes:

- Fixed assignment protocols
- Random access protocols

- Demand assignment protocols
- Adaptive assignment protocols.

The protocols in the first class, fixed assignment protocols, dedicate a fixed portion of the available channel capacity to each user. Examples of this type of protocol are the FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access). Conversely, in random access (contention) protocols, the entire bandwidth is presented to the users as a single channel to be accessed randomly. This means that collisions (an overlapping in time of messages sent by two or more different stations) of messages can occur, and that colliding messages must be retransmitted. Common forms of this class are S-ALOHA (Slotted ALOHA) [8], and CSMA (Carrier Sense Multiple Access) [37].

Alternately, demand assignment techniques require that explicit control information concerning the users' need for channel capacity is exchanged. The control can be either centralized or distributed; in a centralized scheme a central controller exists that decides which user should next have access to the channel, whereas in a distributed scheme, each user monitors the requests from other users to determine who next has channel access. In both schemes, the control information is exchanged through the channel, which leads to additional overhead [13-15].

The final class of MAC protocols, mentioned above, are the adaptive assignment schemes. So far, these have not been studied as extensively as the other schemes. Here, the access method can change according to the traffic load of the users, with the objective being to achieve near optimal performance at all times. However, the overhead incurred can often outweigh the advantages.

In this thesis, we consider two MAC protocols: slotted ALOHA and spatial TDMA. In some sense these, two protocols represent two extremes among all the multiple access protocols. In the slotted ALOHA protocol, no attempt is made to coordinate the access of the nodes to the channel, while in the spatial TDMA protocol, every station is designated to transmit in some predetermined timeslot(s). In spatial TDMA, the "collision" problem is totally eliminated by adopting a link activation mechanism that is conflict-free and can thus guarantee a finite time for message transmission [35].

The earliest MAC protocol in PRN:s was the one-hop centralized pure ALOHA first described by Abramson in [7]. With the pure ALOHA protocol, a station transmits whenever it has a packet to send, with no coordination with other stations sharing the channel, thus leaving the possibility for collisions. Thanks to feedback mechanisms, stations may rapidly know if the packet transmission resulted in a collision or not. Once a transmitting station detects a collision, it retransmits the packet after a random amount of time. In general, the packet throughput provided by the pure ALOHA is not very high due to collisions and idle periods in the channel.

To improve efficiency, a modification of pure ALOHA, slotted ALOHA, was developed that divided the channel into time slots. For the MAC protocol, nodes transmit at random with some given probability, q. This access scheme and collision mechanism has been investigated by Roberts [8]. In the new algorithm, stations are allowed to transmit packets only at the start of a time slot. By this modification, the probability of ”overlapping” decreases and therefore resulting in an improvement of network performance and doubling the packet throughput of the original ALOHA protocol. With the collision one attractive feature exists that even when packets do collide, it may still be possible to receive the strongest packet if the power ratio of this packets to other packets, is above a certain threshold. In this situation we say that the receiver 'captures' this packet. This threshold is called the protection ratio. To further improve network performance, other random channel access protocols, e.g., Carrier Sense Multiple Access (CSMA), have been proposed [37].

We now concentrate on some MAC protocols for the multihop scenario. The most popular topic in the literature has been the slotted ALOHA multihop networks. The performance of the slotted ALOHA protocol in a multihop environment has been studied in [3] and [6] and, the optimum transmission range in planar networks of randomly distributed nodes determined. Resulting from the packet throughput analysis, it has been suggested that the selection of q be 0.113 [3]. A more exact analysis involving several routing algorithms with power adaptation is given by Hou and Li [5]. Moreover, in [5-6] it was found that the optimal number of neighbors, is in the range 6 to 8. In [10], Nelson and Kleinrock have refined the analysis presented in [6], but with capture effect and a different routing algorithm. Shiao and Yee [11] have investigated the determination of global optimal routing assignment and the transmission probabilities to maximize the end-to-end throughput. Their end-to-end throughput showed an increase of approximately 45 % in comparison with the results in [9], where the capacity of some multihop radio networks with regular structure using the slotted ALOHA random access protocol is studied.

Since random MAC protocols exhibit comparatively poor performance in high load situations; "conflict-free" multiple access have been proposed to ensure that a transmission, whenever made, is successful. That is, a packet transmission is not disturbed by another transmission. In [12], the channel access protocol spatial TDMA for multihop PRN:s is proposed. The term spatial refers to the spatial reuse property of the radio networks, i.e., multiple nodes may be allowed to transmit simultaneous as long as they do not "interfere" with one another. The key point in spatial reuse is that when a node is transmitting in some part, it is possible to reuse the same frequency and time in another part of the network with no (significant) interference. This effect is due either to the propagation loss or the fact that one part of the network is shielded from other areas, i.e. terrain shadowing (perhaps by natural obstacles such as mountains or by the nature of radio propagation). When the node locations are fixed and known, transmissions are scheduled such that only non-interfering links are used simultaneously. Also in [12], an approximated analysis for the *average packet delay* was performed.

In 1989, Cidon and Sidi [13] proposed two distributed algorithms for multihop PRN:s: the round-robin algorithm where the nodes priorities are cycled; and the wait-for-neighbors algorithm where assigned nodes are eliminated from the following slot assignment procedure before all neighboring nodes are assigned. In the last algorithm, whenever a node is assigned to transmit in a slot, it does not participate in the slot assignment procedure in the posterior slots, until it hears that all its neighnbours have been assigned at least once, and only then it resumes its participation in the slot assignment procedure.These two algorithms ensure conflict-free transmissions by the nodes of the network. In 1990, Ephremides and Troung [14] proposed centralized and distributed algorithms to find a maximal schedule where each node is assigned at each time slot diagonally; nodes with higher priorities are assigned in the remaining timeslots. Robertazzi and Shor also described traffic-sensitive algorithms for the generation of schedules [15], in particular, a distributed degree algorithm that is, a "traffic-sensitized" version of the algorithm developed in [14]. Literature surveys about the modeling and performance analysis of multihop PRN:s can be found in [20-21].

In earlier studies, very simple connectivity based transmission models were used. The network is described by its connectivity matrix. Two nodes are assumed to be connected if a two-way radio link of sufficient quality can be established. In the random networks investigated, this could include all stations within a certain radius. A transmitting station is assumed to interfere with the reception of a packet if it is connected with the receiving station. Thus, the connectivity matrix contains all the information about connectivity and interference [3,12,13]. However, this view yields very pessimistic results since even weakly received signals are assumed to interfere regardless of the signal strength of the desired signal. The phenomenon that a strong signal may be "captured" by the receiver that suppresses interference was included in later models [6,8]. In [16], this model is refined and the Signal-to-Interference Ratio at the receiver is used to determine whether packets are lost or not. In these studies a simple distance dependent propagation-loss model was used, corresponding to isotropic propagation over a smooth earth. This appears to be a pessimistic assumption as well, since studies have shown that signal strength variations (fading) may in fact improve the performance of the network [17]. In [18], a random network was studied in a random terrain taking distance loss as well as shadowing losses in a "typical" terrain into account and it was shown that the $r^{-\alpha}$ model [19], used in former studies, yields pessimistic results in predicting the network connectivity. Moreover, the use of ”realistic” propagation models for predicting the network connectivity which incorporate the effects of irregular terrain (e.g., diffraction of mountains) has been completely ignored in most of the analytical performance studies in radio networks of this kind.

1.4 Outline of the thesis

One drawback with the performance formulation in the literature studies is that the existing models consider only part of the PRN functions, thereby making analysis tractable [21]. Furthermore, most of the studies of MAC protocols in multihop PRN:s have been performed using oversimplified propagation models despite the current availability of powerful radio propagation models. To further enrich our basic understanding of PRN:s, we propose a more integrated approach [36], that incorporates a detailed propagation model [19,27-28] with simple nodal queueing. With this new modeling of multihop PRN:s we are able to include most of the relevant factors in computing the network connectivity, we are able to better model interference and identify what impact these factors have on network performance. In order to include the actual radio propagation aspect useful for a "realistic" model, parameters such as path loss and radio range are needed. To calculate these parameters, we can probably get the data base of a particular map terrain or use prediction techniques to accurately predict coverage in specific locations [27]. In our study we create a synthetic (random) terrain, which allow us to use the same methodology as if it were a real terrain to calculate the radio influence on network performance.

One of the most important performance measures that strongly influence the choice and performance of network algorithms [26], is the *average packet delay* required to deliver a packet from origin to destination. This work examines the delay associated with two multiple access schemes, studying "refined" slotted ALOHA protocols [3-11,16,18,36] and spatial TDMA protocols [12-15,30,34-36]. The modeling mentioned above is used and analysis is largely based on computer simulations, since the intricate interference patterns existing in this unique environment are extremely difficult to capture in an tractable analytical model. The work is restricted to a single frequency which is assigned for use by the node in ground radio networks.

The thesis is organized as follows. Chapter 2 introduces the models and assumptions used for performance analysis of the MAC protocols concerned, while Chapter 3 illustrates the type of results obtained for multihop slotted ALOHA protocols. A near optimal transmission probability assignment is presented which minimized the network delay.

Chapter 4 is devoted to the spatial TDMA protocols, where new ways of creating transmission schedules are proposed. In Chapter 5, the transmitter power and antenna height are used in sample networks to illustrate their impact on the network connectivity. Finally, Chapter 6 discusses the results and some conclusions.

Chapter 2

System Models

This chapter introduces the performance analysis used in this thesis and consists of three main parts: the models, the performance measure, and the ”measurement” methodology.

2.1 Models

The following models for studying network performance for multihop PRN:s, are presented: the network model, the terrain model, the path loss model, the connectivity model, the routing algorithms and the traffic model.

2.1.1 Network model

To study MAC protocols one must make preliminaries definitions regarding the environment in which they operate. Here, we will often refer to the following issues [43]:

- Radio channel is medium through which data is transferred from its source to its destination. This channel uses electromagnetic propagation in open space.

- Radio link is the one-way communication between a transmitter and a receiver through the radio channel, where the signal at the receiver has an acceptable quality that will be defined later. Throughout the thesis, the term radio link is often shortened to link.

- Connectivity, in a broad sense, is the ability of a node to hear the transmission of another nodes. A more detailed discussion about our connectivity model is found in Section 2.1.4.

- Collision is a situation in which, at the receiver, two or more transmissions overlap in time.

Typically, a PRN consists [illegible]ection of nodes that communicate with each other through the radio channel. T[illegible]des are geographically spread out over a given area. Traditionally [26], the topology of a PRN can be represented by a graph as in Fig. 2.1. The graph, G = (N, L), contains a set of nodes N and a set of radio links, L. Each radio link in L corresponds to an ordered pair of nodes, i.e. (i,j), and indicates that transmission from i

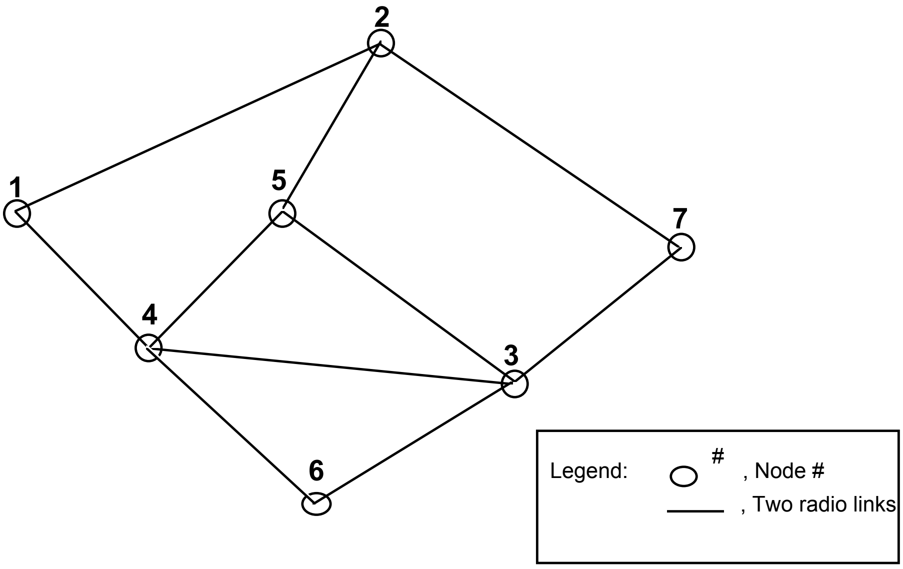

Figure 2.1 Connectivity graph of a PRN of seven nodes (N =7) and 20 links.

can be heard with an adequate signal energy at j. Shortly, under this condition we say that (i,j) $\in$ L. Moreover, in Figure 2.1 each edge denotes two radio links, one in each direction, i.e., (i,j) is one link and (j,i) is another link. So, we assume that if (i,j,) $\in$ L, then the (j,i) $\in$ L. Also, Figure 2.1 is often named the connectivity graph of a PRN. Since the connectivity depends on many factors (e.g., the transmitted power) we will introduce them before.

However, in real life systems one cannot ignore the scenario, i.e. the terrain, in which we consider our PRN:s will be placed. Furthermore, the terrain shadowing has a great influence in the radio communication among the nodes. Thus, to make use of most of the input parameters that affect radio propagation we introduce our terrain model.

2.1.2 Terrain model

The terrain height variations are generated by a slightly modified version of a stationary two-dimensional random process as proposed in [18]. Let H(x,y) denote the height at location (x,y). H(x,y) is generated by:

$$H(x,y) = \sum_{k=-\rho}^{\rho} \sum_{l=-\rho}^{\rho} \left| H^{*}(x-k, y-l) \right| \cdot p(k,l) \qquad (2.1)$$

where H*(x,y) is a two-dimensional white Gaussian process with zero mean and variance σ (*height parameter*), and p(x,y) can be seen as the impulse response of a filter, given by :

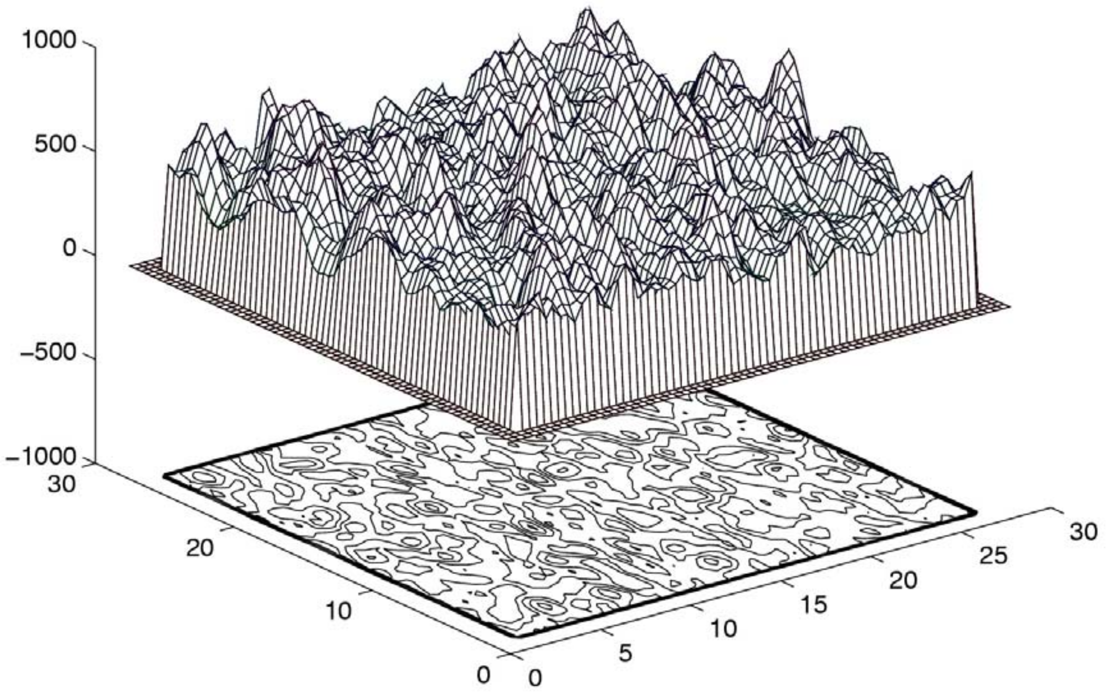

Figure 2.2 Computer plot and contour plot of a terrain realization. Both x and y axes are 28 km. Heights vary in this realization between 300 and 800 m. The terrain parameters are: σ = 40 m, ρ = 3 m.

$$p(x,y)=\begin{cases} 1+cos(\pi\cdot(\frac{x^2}{(\rho+1)^2}+\frac{y^2}{(\rho-1)^2})) & |x|\le(\rho+1),|y|\le(\rho-1) \\ 0 & \text{otherwise} \end{cases} \tag{2.2}$$

ρ can be referred to as the *smoothness parameter* in meters. In Figure 2.2, one terrain realization is shown. Here, the terrain parameters are σ = 40 meters and ρ=3 meters. Heights vary between 300 and 800 meters, and the area is 28x28 km^2. A realization of this kind is regarded, in this context as a "rough" terrain, that mimics a real scenario for a radio network. In Table 2.1 we have, as an example, given a few combinations of the terrain parameters.

Type of terrain	height parameter (σ in m)	smoothness param. (ρ in m)
mountainous	$\sigma \ge 25$	$2 > \rho > 20$
undulating	$1 > \sigma > 25$	$2 > \rho > 20$
smooth or 'flat'	$\sigma \approx 0$	$\rho \ge 20$

Table 2.1 Simple classification of different terrain types according to our model.

2.1.3 Path loss model

The mechanisms which govern radio propagation are complex and diverse, and they can generally be attributed to three basic propagation mechanisms: reflection, diffraction, and scattering. Reflection occurs when a propagating electromagnetic wave impinges on an obstacle with dimensions very large compared to the wavelength of the radio wave. Reflections from the surface of the earth produces reflected waves that may interfere constructively or destructively at the receiving site. Diffraction, on the other hand, occurs when the radio path between the transmitter and receiver is obstructed by an impenetrable object, and the obstacle encountered is not large compared with the operating radio wavelength. Based on Huygens´ principle, we can model propagation phenomena by introducing secondary waves that are formed behind the obstructing object even though a line-of-sight (LOS) between the transmitter and receiver does not exits. Thus, diffraction can be regarded as the ”bending” of radio waves around the edge of an obstruction [31]. The scattering mechanism, finally, is not considered in our models.

It is well known that radio signals are attenuated as they propagate from the transmitter station to the receiver station. The main variation of the signal strength versus distance is described by a *path loss* term, which states the relation between the emitted power and the received signal strength for a given separation of the antennas. The prediction of path loss is a very important step in performance analysis, operation and/or design of multihop PRN:s. Throughout the thesis, we use the path loss prediction model by Ladell [19] where the loss due to the terrain can be split into three components: a distance dependent path loss, a plane-earth propagation loss, and a (multiple knife-edge) diffraction loss due to the mountains in our terrain model. We neglect the influence, for instance, of the vegetation in the terrain. With this detailed radio propagation model, it is possible to estimate the total propagation loss in each link, L_{ij}. Here we introduced the propagation loss L_{ij}, which is the ratio of the emitted signal $P_{transmitted}$ in node i when the received signal in node j, is $P_{received}$. Expressed in decibels, this becomes:

$$(L_{ij})_{dB} = 10 \cdot \log_{10} L_{ij} = 10 \cdot (\log_{10} P_{transmitted}) - 10 \cdot (\log_{10} P_{received}) \tag{2.3a}$$

Moreover, the inverse of the propagation loss in link between the node i and j is the power gain G_{ij} [33] and it can be expressed as:

$$G_{ij} = (L_{ij})^{-1} \tag{2.3b}$$

A convenient way to indicate the power gain between each pair of nodes in the network is by means of the so-called gain matrix **G** [28]. The gain matrix might be described as **G** $=\left\{G_{ij}\right\}$, where G_{ij} is the power gain between node i and node j.

We briefly describe the path loss components of the radio prediction method mentioned above.

Free space loss (distance depend)

To calculate the propagation loss in dB due some distance d, we use the well-known formula (assuming a link between isotropic antennas) [31]:

$$L_{fs} = 20 \cdot log_{10}(\frac{4\pi d}{\lambda}) \tag{2.4}$$

where L_{fs} is the free space loss.

Modified flat earth propagation loss (plane-earth)

For simplicity, we assume that the earth is modeled as a plain partially conducting surface. In other words for the moment, we momentarily neglect the roughness of the terrain and model the earth as a smooth sphere. In [19], a method to calculate the flat earth propagation loss L_{flat} the actual field strength relative to the free space strength if the ground conductivity is neglected. A typical communications link can be described by the geometry in Figure 2.2. T and R represent the transmitting and receiving sites, respectively.

The heights above the earth's surface are h_t (at the transmitting site in meters) and h_r (at the receiving site in meters). L_{flat} in dB can be expressed

$$L_{flat} = 20 \cdot \log\ (2 \cdot \left|\sin(0.5 \cdot ((A_t + B) \cdot (A_r + \mathrm{B}))^{1/2})\right|) \tag{2.5}$$

where

$$A_{t,r} = \frac{4\pi\, h_{t,r}^2}{\lambda\, d} \tag{2.6}$$

$$B = \frac{\lambda C}{\pi d(\varepsilon - 1)} \tag{2.7}$$

$$C = \begin{cases} \varepsilon^2 & \text{for vertical polarization} \\ 1 & \text{for horizontal polarization} \end{cases} \tag{2.8}$$

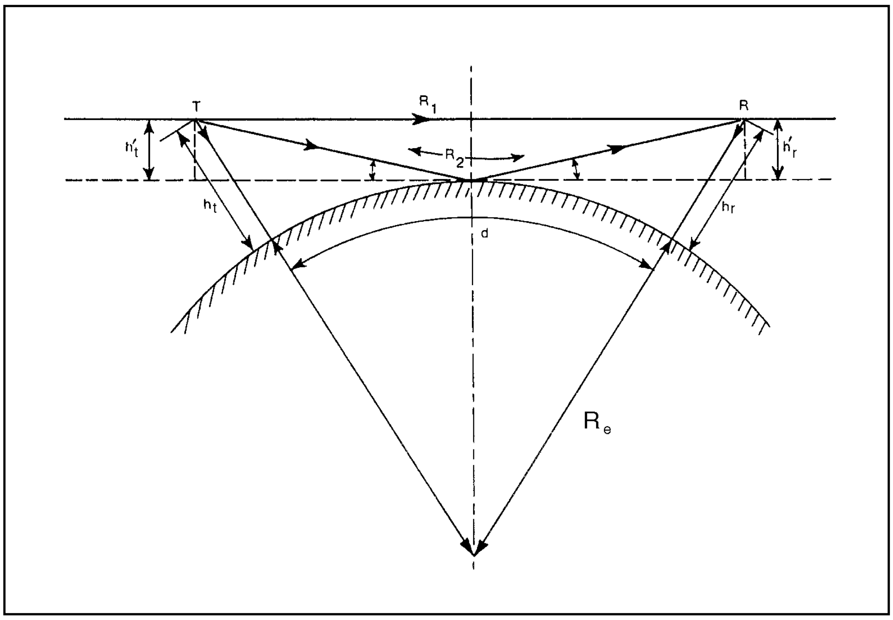

Figure 2.3 Two mutually-visible antennas located above a smooth, spherical earth of effective radius R_e. Figure from [31].

λ = wavelength, m   ε = relative permittivity ,
d = distance between the two stations in meters.

To use this former formula for the flat earth propagation loss, we need to take into account the curvature of the earth, by limiting distances to:

$$d \le 12 \cdot 10^3 \cdot \lambda^{1/3} \tag{2.9}$$

The earth curvature correction factor can be expressed as:

$$Y = \begin{cases} -2.8 \cdot x & x < 0.53 \\ 6.7 + 10 \cdot \log_{10} x - 10.2 \cdot x & 0.53 \le x < 2 \end{cases} \tag{2.10}$$

Here, we have introduced the normalized distance x as:

$$x = (2\pi / \lambda)^{1/3} (k \cdot R_e)^{-2/3} \cdot d \tag{2.11}$$

where $R_e =$ effective *earth* radius, m = 6370 000 m

$k =$ *earth* radius factor (4 / 3 for standard ratio atmosphere)

In summary, the modified flat earth propagation loss, L_{mflat}, can be written as:

$$L_{mflat} = L_{flat} + Y \tag{2.12}$$

Diffraction loss

Propagation over rough terrain is often adversely affected by obstructions such as hilltops. Path loss resulting from such obstacles is termed ”diffraction loss”. Methods to calculate the multiple knife-edge diffraction can be found in [31-32]. The diffraction model used is based on the multiple knife-edge diffraction presented by Epstein-Peterson and refined by Ladell [19]. In order to calculate for a single knife-edge diffraction, first calculate the auxiliary parameter ν (refer to Figure 2.3.a):

$$v = h\sqrt{\frac{2(d_1 + d_2)}{d_1 d_2 \lambda}} \tag{2.13}$$

Four parameters are needed to find the ν: d_1, the distance from the transmitting antenna to the obstacle, h, the relative height of the knife-edge h, d_2, the receiver distance away from the obstruction, and λ, the operating wavelength. When the value of ν is obtained, the diffraction loss due to a mountain can be found using the approximate formula below [19]:

$$\mathrm{L}(\mathrm{d}_1 ,\mathrm{d}_2,\mathrm{h}) = \begin{cases} -6.02 - 9.11\cdot v + 1.27\cdot v^2 \quad \mathrm{dB} & 0 \leq \mathrm{v} < 2.4 \\ -12.95 - 20\cdot \log_{10} v \quad \mathrm{dB} & \mathrm{v} \geq 2.4 \end{cases} \tag{2.14}$$

However, in many instances, there is more than one knife-edge source along a given propagation loss between two antennas, in which case the loss may be estimated by the Epstein-Peterson method. This technique computes the attenuation due to each obstacle in turn and compute their sum obtain the overall diffraction loss. For example, let the path between the transmitting antenna to the receiving antenna contain three obstacles as shown in Figure 2.3.b. A line is drawn from the transmitting antenna to the top of the second mountain, and the loss due to first mountain is then calculated using the single knife-edge diffraction (formulas 2.13 and 2.14). The effective height of first mountain is -h_1, the height below the line from T to the second mountain. In a similar manner the attenuation due to the second mountain is determined by connecting the peaks of mountain 1 and 3 and using the height above that line as the effective height, h_2, of the second mountain. Again we calculate the loss, in this case due to the second mountain, and we repeat the same procedure for the third mountain, i.e. the effective height h_3 is computed using the line joining mountain 2 to the receiving antenna. The total diffraction loss L_{dri}, is then obtained by summing the individual losses due to each obstacle:

$$L_{dri} = \mathrm{L}(\mathrm{d}_1, \mathrm{d}_2, -h_1) + \mathrm{L}(\mathrm{d}_2, \mathrm{d}_3, h_2) + \mathrm{L}(\mathrm{d}_3, \mathrm{d}_4, h_3) \tag{2.15}$$

[19].

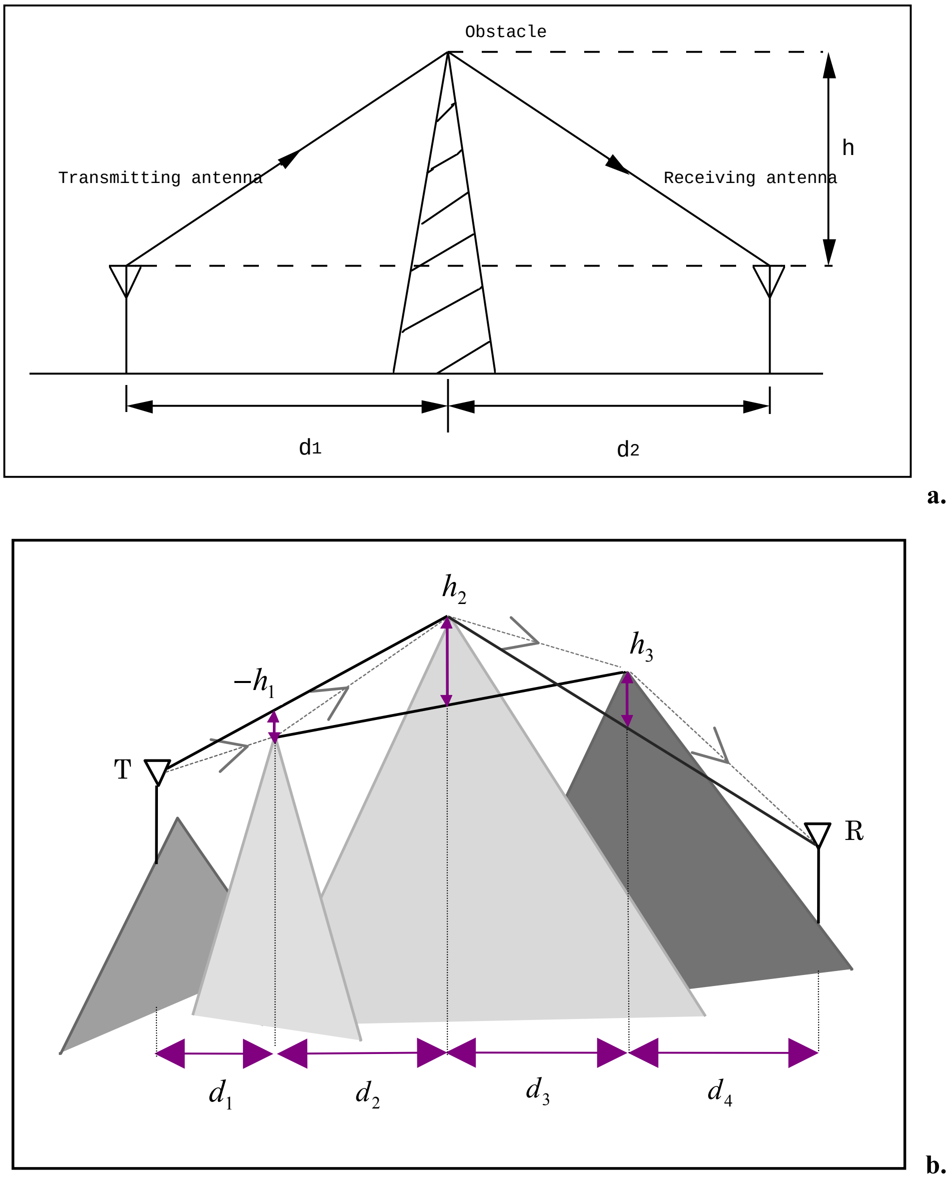

Figure 2.4 a. The (single) knife-edge diffraction model. b. The Epstein-Peterson (multiple knife-edge) diffraction construction.

Total path loss

The propagation loss is described by a model that combines the diffraction loss, L_{dri}, due to the mountains and the flat earth propagation, L_{mflat}, [19]:

$$L_c = \sqrt{L_{mflat}^2 + L_{dri}^2} \quad \text{dB} \qquad (2.16)$$

It should be emphasized that there is no theoretical justification for combining the losses in the way indicated by (2.16). However, this empirical model has proved to be in good agreement with measurements performed in various types of irregular terrain in Sweden [19].

The total path loss, L_t, can then be computed as:

$$L_t = L_c + L_{fs} \quad \text{dB} \qquad (2.17)$$

Finally, we now relate the power gain G_{ij}, between node I and j, with the total path loss L_t in the link (i,j) as follows (see Figure 2.5):

$$G_{ij} = \frac{P_r}{P_t} = \frac{G_t G_r}{L_t} \tag{2.18}$$

where

P_t = Transmitted power level (W or DBW)
P_r = Received power level (W or DBW)
G_t = Antenna gain (DB) at the transmitter site
G_r = Antenna gain (DB) at the receiver site.

We will assume that all the antennas are omnidirectiona in the azimuth plane, and we associate the antennas heights (Fig. 2.3) h_t, h_r to G_t and G_r, respectively.

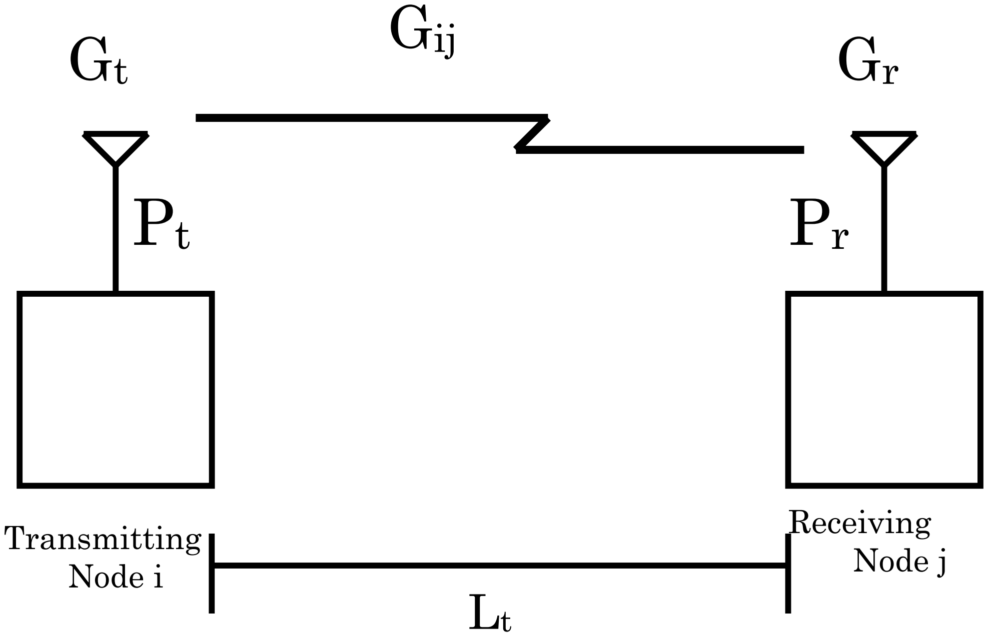

Figure 2.5 A radio link between node i and j.

2.1.4 Connectivity model

In the terrain a network of N randomly uniformly distributed nodes will be considered. Nodes i and j, with i, j $\in\{1,2,\ldots,N\}$ are either connected by a link or disconnected, depending on the propagation loss between the nodes. The propagation effect is modeled by link gains where G_{ij} (inverse of propagation losses for the link concerned) denotes the power (propagation) gain on the link between nodes i and node j [28], and is derived from the terrain model. Note that even through the network, in principle, is fully connected, many links can be characterized by a very low gain (high loss) and establishing a communication link may not be possible if an adequate signal energy at the receiver is required. In the follows, we assume a simple connectivity model where if the propagation loss in a given link (i,j) is larger than some *threshold path loss*, communication cannot be sustained, i.e., no connection exists along the link between node i and j. The *threshold path loss* ϕ_o is defined as the maximum path loss for which a communication link may be established in the absence of all interference. Computing the link budget [33], involve the calculations of the useful signal power, and noise power available at the receiver. One can regard as the link budget a ”balance sheet” of gains and losses. Moreover, the desired transmission is also received in the presence of network self-interference, which in turn, depends on the MAC protocol, the density of the network and the traffic load (see section 2.16). Therefore, the Signal-to-Interference-Ratio (SIR) is commonly used as a measure of the link quality. For a link (i,j) we introduce the SIR, Γ_{ij}, when node i transmits with power P_t, to node j:

(2.19)

where N is the noise power, and I is the interference power.

In order to have a reliable link a minimum SIR is required, referred to as the SIR threshold γ_0 or the SIR target. Moreover, to relate the SIR threshold γ_0 and the ϕ_o mentioned above, we consider in Eqn. 2.19 the case when I=0:

(2.20a)

or in dB

$$(\gamma_o)_{dB} \leq (P_{EIRP})_{dB} + (G_r)_{dB} - (\phi_o)_{dB} - (kT_o)_{dB} - (F_{rec})_{dB} - (B)_{dB} \qquad (2.20b)$$

and where,

ϕ_o = threshold path loss
N= k T_o B F_{rec}
$P_{EIRP} = P_t \cdot G_t$ = The **E**fficient **I**sotropic **R**adiated **P**ower
k= Boltzmans constant $= 1.38 \cdot 10^{-23}$ J/K
T_o = reference temperature = 290 K.
F_{rec} = Noise Figure of the receiver.
B= Bandwidth of the receiver in Hz.

Thus, in order to model the effect of the interference at a given receiving site, we consider a packet to be correctly received if its received signal exceeds the sum of the power of the other colliding packets by at least γ_o dB (capture property). When we consider the capture effect, a slotted access scheme is assumed and a packet from node i is successfully received at node j if the Signal-to-Interference-Ratio from Eqn. 2.19:

(2.21)

is greater than the threshold γ_o, otherwise the packet is lost. Here we have introduced the binary variable

$$X_k = \begin{cases} 1 & \text{node k transmits} \\ 0 & \text{node k does not transmit} \end{cases} \qquad (2.22)$$

and P_i and P_K, the transmitter power of station i and k respectively. Also, we remind that each node uses the same transmitter power. The former notation is used to distinguish between the desired transmission and the interferes at the receiving node j.

The threshold path loss on a given link between two nodes can be found from (2.20b):

$$(\phi_o)_{dB} \le P_t + G_t + G_r - (\gamma_o)_{dB} - (F_{rec})_{dB} - (B)_{dB} + 204 \qquad (2.23)$$

For instance, by putting the following values in equation (2.23),

P_t = - 5 dBW, G_t, G_r = 3 dB, $(\gamma_o)_{dB}$ = 10 dB, $(F_{rec})_{dB}$ =15 dB, $(B)_{dB}$ = 50 dB

we would have $(\phi_o)_{dB}$ = 130 dB. It should be noted that we assume a bandwidth of 100 KHz, capable of supporting date rates around 100 Kbits/sec. This could be, for instance, a requirement for low rate data communications.

Figure 2.6 illustrates the same terrain with less contours as in Figure 2.2. Ten nodes (N=10) are placed on it, with the network connectivity depicted as well. We refer to this network as network A, with Figure 2.6 being its connectivity diagram. Sample network B is depicted in Figure 2.7. As mentioned earlier, we would like to have an idea of the quality of our links in the network or the average number of ”good” connections, therefore, an important parameter in multihop PRN:s could be a measure of the network connectivity. For simplicity, we have chosen the average number of neighbors $\overline{N}$ for this purpose where neighbors to a transmitting station consist of all nodes within the transmission range according to our assumption of connection based on the path loss threshold. The parameter $\overline{N}$ is calculated as follows:

$$\overline{N} = \sum_{i=1}^{N} N^{i} /\mathrm{N} \tag{2.24}$$

where N^{i} is the number of neighbors to node i. From network A (Figure 2.6), it can be seen that $\overline{N}$ is equal to 3.2 nodes. In the same way, for network B, $\overline{N}$ = 4.2 nodes. In general, we can consider two kind of connected networks: partial connected network and fully connected network. Moreover, in a multihop PRN each node is *connected* to some subset of the other nodes. Thus, we say that a network is *connected* if there is a path between every node to reach every other node. By a path we mean a collection of node-to-node link connecting a given source to a given destination. Hence, to characterize our interest here in the effect of connectivity in PRN we might define in this context:

Partially connected network: It is a PRN where every node cannot reach every other node in one hop and thus we do require a routing algorithm. Unless we stated the contrary, in this thesis, we refer to the partial connected network as a connected network.

Fully connected network: It is a PRN where every node can reach every other node with reliable link quality in one hop and thus no explicit routing is required. In this case, N^{i} = N-1, for every node i in the network.

2.1.5 Routing Algorithms

In a multihop PRN, the function of the routing algorithm is to guide the packets through the radio network to their proper destination. Connections are made in such a way that between any given pair of nodes, there is at least one path available. In this structure, a packet needs to be relayed from node to node to reach its final recipient. If a given node has more than one outgoing link, it must make routing decisions, i.e., for every incoming packet, it must be decide on which outgoing link the packet will be relayed. For reasons of efficiency, a routing

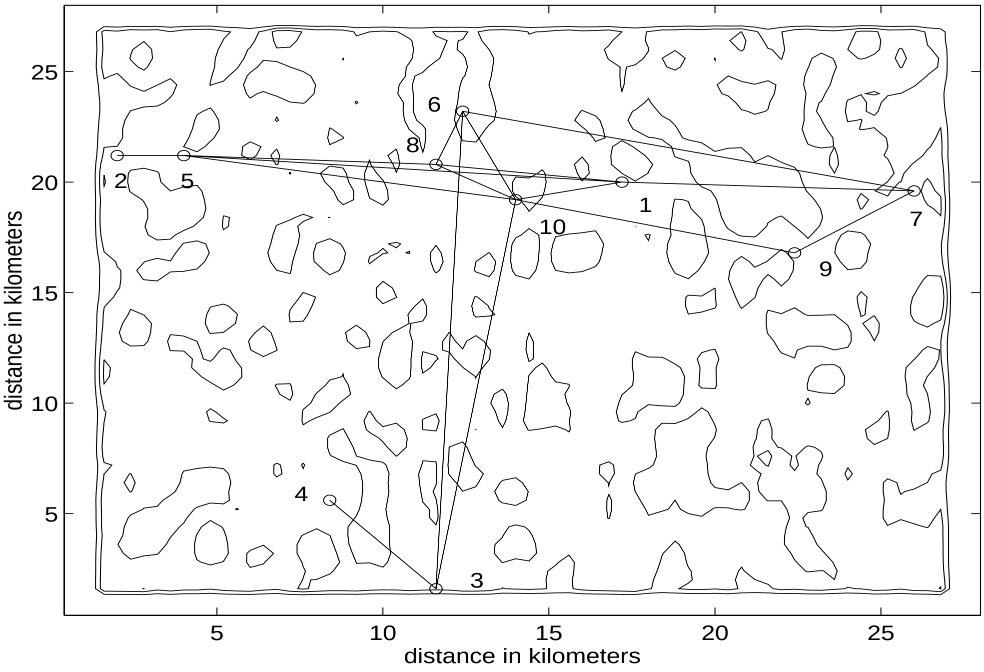

Figure 2.6 Contour plot of the terrain and Network A. Terrain parameters are: σ = 40 m, ρ = 3 m. The circles indicate the position of the stations, which are numbered 1,2..10. The lines represent the connections among the nodes.

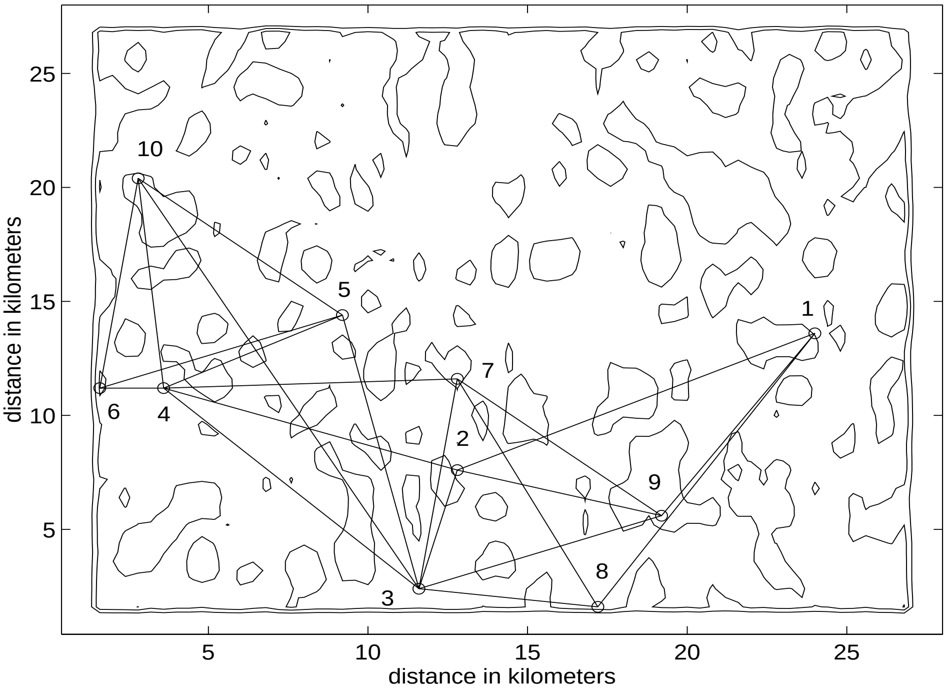

Figure 2.7 Contour plot of the terrain and Network B. Terrain parameters are: σ = 40 m, ρ = 3 m. The circles indicate the position of the stations, which are numbered 1,2..10. The lines represent the connections among the nodes.

node typically attempts to relay packets along paths of ”minimum” delay (i.e., the shortest paths) leading to their destinations. A few terrain adaptive routing schemes such as: the Minimum Hop Algorithm, the Minimum Maximum Path Loss algorithm, and the Minimum Interference algorithm were defined and investigated in [18]. As a result of the former study, it was observed that the expected numbers of hops increase with the increasing roughness of the terrain. The Minimum Hop and the Minimum Interference algorithms exhibited a similar network delay, both being better than the Minimum Maximum Path Loss algorithm. For this thesis, we use the *Minimum Hop Algorithm (MHA)* which searches between nodes i and j for the path with the minimum number of hops. Take for instance network B in Figure 2.7. To get a message from node 1 to node 10, the path that is taken will follow links (1,2), (2,3) and (3,10). If however the link (3,10) would not be there, there would be at least three paths, namely, path 1: (1,2), (2,3), (3,4), (4,10); path 2: (1,2), (2,3), (3,5), (5,10); and path 3: (1,2), (2,3), (3,7), (7,4), (4,10). With path 1, path 2 and path 3, a packet takes 4 hops, 4 hops and 5 hops to reach the intended receiver, respectively. So first, the MHA would choose path 1 and path 2 due to they offer fewer number of hops than path 3. Besides, the number of hops in the two reminder paths is the same. In this case one of the two is chosen randomly. Actually, the MHA count the number of hops in every possible path. The algorithm then select the path with a minimum number of hops. All this information of a path, a packet will take in order to go from node i to j is described and summarized in the routing table, which is based on the reliable links of the network. The routing table for network B derived from the MHA is shown below in Table 2.2. Again, e.g., to get a packet from node 1 to node 10, we consult Table 2.2 where the position (i=1, j=10) is equal to 2 which means to go first from node 1 to node 2 or use first the link (1,2) and so as was outline above; r_{ij} indicates the one-hop sequence predetermined by the MHA in order to go from node i to node j.

The MHA uses static table-based routing where a node consults a table to select the outgoing link on which the packet is to be forwarded. This algorithm counts the number of hops in every possible paths and selects the path with a minimum number of hops. Actually, the MHA can be seen as a variation of the Maximum Forward Progress within Radius (MFR) algorithm [3,5]. In the MFR algorithm, a station transmits its packet to the station that is as close to the final destination as possible, limited only by the transmission range. MHA can be seen as a terrain adaptive MFR a strategy in the sense that the transverse distances in each hop are maximized. However, the MHA does not always choose its next node in the direction of the destination node. MHA is not a distributed algorithm since it uses knowledge of the entire network, whereas MFR is a completely distributed algorithm based on the local knowledge of each node but it needs to know the direction of the intended receiver.

π_{ij}	1	2	3	4	5	6	7	8	9	10
1	---	2	2	2	2	2	8	8	9	2
2	1	---	3	4	3	4	3	1	9	3
3	2	2	---	4	5	4	7	8	9	10
4	2	2	3	---	5	6	7	3	2	10
5	3	3	3	4	---	6	3	3	3	10
6	4	4	4	4	5	---	4	4	4	10
7	8	3	3	4	3	4	---	8	9	3
8	1	1	3	3	3	3	7	---	1	3
9	1	2	3	2	3	2	7	1	---	3
10	3	3	3	4	5	6	3	3	3	---

Table 2.2 Routing table of the network B.

Another convenient description of the connectivity properties is the **average hop count** ($\bar{h}$) which is defined as the average length of a "shortest" path taken over all pairs of nodes. This parameter is calculated as follows:

(2.25)

where $1 \leq$ i; $j \leq$ N , $i \neq j$ and π_{ij} stands for minimum number of hops separating nodes i and j i.e. the hop count achieved by the MHA. Alternatively, the routing matrix might be described as $\pi = \{\pi_{ij}\}$, where π_{ij} is the minimum number of hops from node i to node j.

2.1.6 Traffic model

When discussing network performance, we should carefully specify the traffic model being used. Important parameters in our traffic model are the packet length, the arrival process, the queueing process, and the traffic matrix.

As mentioned previously, packets, are assumed to be of constant length. Besides, packet arrivals are modeled to occur according to a Bernoulli process with mean λ over the network. Let us name λ as the total traffic load of the network. Furthermore, packet arrivals at a node are of two classes (1) external and (2) internal. External arrivals to node i are assumed are generated by an independent Bernoulli process with mean

$\lambda_i = \lambda$/N (packets per slot) i $\in$[1,N]
(2.26)

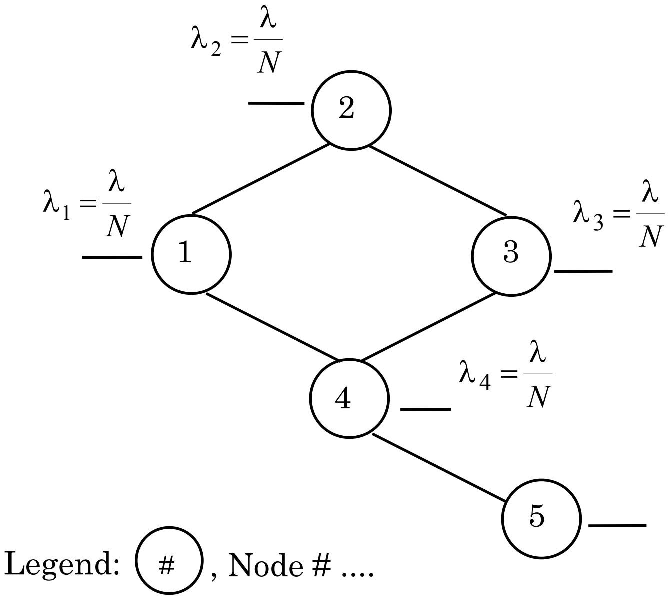

Figure 2.8 The traffic model for a network of five nodes (N=5) with uniform traffic.

and originate from some attached device(s) to node i, i.e., a computer or external source to the network. Figure 2.8 represents the traffic model used for a network of five nodes. Moreover, internal packets arrive from other nodes and can further be classified as: transit packets that must be retransmitted to others nodes after they are received, and terminal packets that are destined to the node and therefore need not be relayed. Each station is assumed to have a buffer of infinite size. Packet arrivals at a node will be illustrated in Figures 3.1 and 3.2. The queueing process for each one of the MAC protocols concerned will be briefly described in Chapters 3 and 4.

We also relate the total traffic with the individual external arrivals a at each node as follows:

$$\lambda = \sum_{i=1}^{N} \lambda_i \tag{2.27}$$

The traffic matrix is defined as $\mu = \{\mu_{ij}\}$, where μ_{ij} is the expected number of packets per slot generated at node i with final destination node j. We assume a uniform traffic matrix, i.e.:

$$\mu_{ij} = \begin{cases} \frac{\lambda_i}{N-1} & \mathrm{i} \neq \mathrm{j} \\ 0 & \mathrm{i} = \mathrm{j} \end{cases} \tag{2.28}$$

Since the MAC protocols are designed to provide reliable links between nodes, the link traffics are of our interest. One way to estimate the amount of traffic on each link is presented in [15, 26]. The idea behind this is to take advantage of the uniform distribution assumption and obtain the number of paths that use a particular link (i,j). With this information, we can build a ”load matrix” which is a valuable tool to study traffic ”adaptive” multiple access protocols, i.e., a traffic-sensitive spatial TDMA algorithm allocates slots depending on the estimated amount of traffic passing through each link. Next, we explain this approach to estimate the load matrix.

We can start by consider a fully connected network where the expected traffic in each link (i,j) per slot is the same, namely:

$$\lambda_{ij} = \mu_{ij} = \frac{\lambda}{N(N-1)} \tag{2.29}$$

However, due to some links in the network are not usable (i.e., they are characterized by a too high loss), it is necessary to route their expected traffic through other reliable links. This produces uneven loaded links compared to the fully connected network. In this situation is convenient to re-formulated the right side of equation 2.29 to include the routed traffic. Moreover, since we have assumed that there are several and uniform packet streams μ_{ij} packets/sec, each following a unique path that consists of sequence of radio links through the network. Then the total arrival rate at link (i,j) is [26]:

$$\lambda_{ij} = \sum_{\substack{all\ packet\ streams \\ cros\sin g\ the\ link(i,j)}} \mu_{ij} = \mu_{ij} \sum path \text{ crossing the link (i, j)} \tag{2.30}$$

Thus, we might consider the number of paths using a particular available link. Denote the number of paths that use the link (i,j) as $P^{(ij)}$, in a connected network. Thus, our load matrix is defined as $P = \{ P^{(ij)} \}$, where $P^{(ij)}$ is also an undirected measure of the amount of traffic load that can be expected to transverse the link (i,j). We can see from (2.30):

$$\lambda_{ij} = \frac{\lambda}{N(N-1)\bar{h}} P^{(ij)} \tag{2.31}$$

It should be noted that some $\lambda_{ij} = 0$ when the link (i,j) is not usable or unreliable.

From Eqn. 2.30 we have:

(2.32)

Node	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	0	0	0	0	4	0	7	2	0	4
2	0	0	0	0	9	0	0	0	0	0
3	0	0	0	9	0	6	0	0	0	10
4	0	0	9	0	0	0	0	0	0	0
5	4	9	0	0	0	0	0	4	0	8
6	0	0	6	0	0	0	5	5	0	1
7	7	0	0	0	0	5	0	0	3	0
8	2	0	0	0	4	5	0	0	0	2
9	0	0	0	0	0	0	3	0	0	6
10	4	0	10	0	8	1	0	2	6	0

Table 2.3 Load matrix for network B under uniform traffic assumption.

$$P^{(ij)} = \frac{\lambda_{ij}\, N(N-1)\,\bar{h}}{\lambda} \tag{2.32}$$

Moreover, we introduce $P^{(i)}$, the estimated amount of traffic passing through each node i as:

$$P^{(i)} = \sum_{j=1}^{N^{i}} P^{(ij)}$$

Moreover, to compute the load matrix we proceed as follows. As an example we consider network B which is depicted in Figure 2.7. To find a path between node 1 to node 3 an imaginary line is drawn between the two nodes. Next, we refer to the routing table, Table 2.2, where it is instructed to use the route or path 1-2-3. The amount of traffic on links (1,2) and (2,3) is then incremented by 1 unit, respectively. The same procedure is repeated for every route in the network. When routes between every distinct pair of nodes are taken into account, the matrix of the load on each link (in Table 2.3) can be generated.

2.2 Performance measure

The merging of computers and communications during the past two decades has led to an explosive growth in communication networks. **Performance measures** used to evaluate communication networks vary depending on the type of network being analyzed and the applications being used. For multihop PRN:s, the commonly used performance measures are throughput, and delay. Below, the throughput is defined:

Throughput is: The expected number of packets that reach their final destination per slot in the entire multihop network. It a measure of the degree of utilization of network resource.

However, the main performance measure of interest is the average expected **packet delay**, D. **Packet delay** is defined as: the time between the arrival of a packet at the buffer of the originating station and the end of the slot in which is successfully received at the final destination station. In the described network of N nodes, in general, a randomly selected packet to be transmitted from node i to node j has the delay D_{ij}, expressed in timeslots. If two nodes are neighbors, one successful transmission will require one timeslot. However, due to the fact that D_{ij} is a random variable one must resort to make statistical interference of D_{ij} by means of this expected value

$$E[D_{ij}]=E\left[\frac{\sum_{k=1}^{n_p} D_{ij}^{(k)}}{n_p}\right] \tag{2.34}$$

where $D_{ij}^{(1)}$,$D_{ij}^{(2)}$,..., $D_{ij}^{(n_p)}$ be a sample of the random variable D_{ij} from a single simulation run (Section 2.3) and n_p is the number of packets successfully received in that run between node i and j.

The average expected delay to transmit a packet from node i to j, can be formulated as,

$$D=\frac{1}{\binom{N}{2}}\sum_{j=1}^{N}\sum_{i=j+1}^{N}E\left[D_{ij}\right] \tag{2.35}$$

where E[D_{ij}] is expressed in expected delay between node i and j.

Furthermore, if we let E[$D_{ij}|\lambda, H$] be the expected delay to transmit a packet from node i to j given a certain traffic load λ and some given terrain H, the average expected delay in this case can be expressed as,

$$D(\lambda, H)=\frac{1}{\binom{N}{2}}\sum_{j=1}^{N}\sum_{i=j+1}^{N}E\left[D_{ij}|\lambda, H\right] \tag{2.36}$$

Optimum network performance is achieved in our context when the D(λ ,H) is minimized by one parameter of the MAC protocol.

Unstable System: is one where the expected number of messages in the system grows without bounds. So, in, in this state the PRN is not very useful due to D will be very high. Our criterion for instability is the queue length at each station. If any of the queues at any time exceeds than 20 packets, we consider the system to be unstable. It should be noted that stability is not the main focus of this thesis.

2.3 Performance Evaluation

An exact analysis for the average expected delay using queueing analysis in multihop PRN:s has not been carried out for Eqn. 2.36, it is very difficult [12] due to the queueing dependency among the nodes and the large state vectors involved. For these reasons, we have chosen computer simulations as our performance evaluation method.

In simulations of this kind, various components of the actual PRN (network topology, antennas, radio links, queues, multiple access protocols, network control structures) are represented in a computer program. The events that would occur during the actual operation of the network (arrivals, transmissions, routing and departures of packets, error conditions such as packet loss due to noise and radio interference) are generated during the execution of the program. In general, the simulation program generates events and then simulate the network's response based on these events. The simulation program also gathers data during the simulation and computes performance measures. The performance evaluation is described in appendix A, where tables of simulation parameters are shown.

Before we present the models used, let us introduce a typical scenario for our study:

We start by consider an area without telecommunication infrastructure, where in part of it is required to provide data communications, e.g. in a rural environment. We assume that the terrain area under study contains mountains and valleys, but the vegetation is not considered. We use N-nodes PRN:s, which will be deployed in the terrain of interest in order to support data communication. These nodes are equipped with omnidirectional antennas, and they can transmit using relative low power level. A node must be in either the transmitting mode or the receiving mode, and not both. To achieve reliable communication beyond the radio range of the individual nodes multihop transmission technique is used. In addition to that, the nodes can handle data rates of R_b Kbits/s, and they use a binary modulation scheme combined with a simple error coding which allow them to have a bit error rate P_ε. Indeed a node transmitting a packets is advised of the correct reception by an acknowledgment packet.

The results in this thesis has been obtained under the following assumptions:

- R_b = 100 Kbits/s (symbol duration is long compared to spread delay, since in most outdoor areas the rms multipath spread measured at distance up to a few kilometers is < 10 μs [42]).
- $P_\varepsilon \leq 10^{-6}$.
- Packet length : 5 bytes header + 35 bytes information.
- The time axis is divided into timeslots, each the length corresponding to the transmission time of a packet. All packets are assumed to be of the same length. The propagation time is ignored.
- The operating frequency of the network is 300 MHz.
- Terrain profile and obstacles in the path between two nodes according to the terrain model in section 2.1.2.
- All nodes are assumed to be equipped with an omnidirectional antenna transmitting at the same power P_t. Transmitter power, P_t : -5 dBW ($P_t \approx 316$ mW).
- Antenna gains (G_t, G_r) : 3 dB. The antenna height at a node: 20 m above the ground.
- We assume a simple model, where if the Signal-to-Interference-Ratio (SIR) is above 10 dB and the given P_ε, the acknowledgment traffic can be then neglected.