IMPROVING NETWORK RELIABILITY BY EXPLOITING PATH DIVERSITY IN AD HOC NETWORKS WITH BURSTY LOSSES

by

ÖZLEYIS OCAKOGLU

Submitted to the Graduate School of Engineering and Natural Sciences
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ABSTRACT

In wireless mobile ad hoc networks, end-to-end connections are often subject to failures which do not make the connection non-operational indefinitely but interrupt the communication for intermittent short periods of time. These intermittent failures usually arise from the mobility of hosts, dynamics of the wireless medium or energy-saving mechanisms, and cause bursty packet losses. Reliable communication in this kind of an environment is becoming more important with the emerging use of ad hoc networks for carrying diverse multimedia applications such as voice, video and data.

In this thesis, we present a new path reliability model that captures intermittent availability of the paths, and we devise a routing strategy based on our path reliability model in order to improve the network reliability. Our routing strategy takes the advantage of path diversity in the network and uses a diversity coding scheme in order not to compromise efficiency.

In diversity coding scheme, if the original information is encoded by using a (N,K) code, then it is enough for the destination to receive any K bits correctly out of N bits to successfully decode the original information. In our scheme, the original information is divided into N subpackets and subpackets are distributed among the available disjoint paths in the network. The distribution of subpackets among the diverse paths is a crucial decision. The subpackets should be distributed 'intelligently' so that the probability of successful reconstruction of the original information is maximized. Given the failure statistics of the paths, and the code rate (N, K), our strategy determines the allocation of subpackets to each path in such a manner that the probability of reconstruction of the original information at the destination is maximized. Simulation results justify the accuracy and efficiency of our approach. Additionally, simulation results show that our multipath routing strategy improves the network reliability substantially compared to the single path routing.

In wireless networks, a widely used strategy is to place the nodes into a low energy consuming sleep mode in order to prolong the battery life. In this study, we also consider the cases where the intermittent availability of the nodes is due to the sleep/awake cycles of wireless nodes. A sleep/awake scheduling strategy is proposed which minimizes the packet latency while satisfying the energy saving ratio specified by the energy saving mechanism.

ÖZET

Telsiz mobil tasarsiz aglarda, uçtan-uca baglantilarda, baglantiyi islemez hale getirmeyen fakat iletisimi kisa süreler için durduran kesikli bozulmalar olur. Bu kesikli bozulmalar genellikle, ag elemanlarinin (host) devingenliginden, telsiz ortamin dinamik yapisindan ve enerji tasarruf stratejilerinden kaynaklanir ve çogusma biçiminde (bursty) paket yitimlerine neden olur. Bu tip bir ortamda güvenilir iletisimin önemi, tasarsiz aglarda ses, video, veri gibi çesitli çogul ortam uygulamalarinin ortaya çikmasi ile artmaktadir.

Bu tezde, agdaki yollarin kesikli kullanilabilirligini yansitan yeni bir yol güvenilirlik (path reliability) modeli ortaya konulmus ve bu model üzerine, ag güvenilirligini iyilestirmek için bir yönlendirme stratejisi gelistirilmistir. Gelistirdigimiz yönlendirme stratejisi agdaki yol çesitliliginden yararlanir ve verimliligi artirmak üzere çesitleme kodlamasi (diversity coding) kullanilir.

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LIST OF ABBREVIATIONS

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BB	Beta-Binomial
AODV-BR	Ad Hoc On Demand Distance Vector Routing-Backup Routing
BSR	Backup Source Routing
ALTDSR	Alternative Path Dynamic Source Routing
DSR	Dynamic Source Routing
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RREQ	Route Request
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1. INTRODUCTION

1.1. Motivation

Recent advances in wireless networking and mobile computing have increased the demand for infrastructureless networking. Wireless ad hoc networking is an example, where mobile hosts rely on each other to keep the network connected without relying on any infrastructure. Many routing protocols in order to establish the end-to-end connectivity in ad hoc networks have been proposed in the literature [1], [2], [4]-[6].

However, due to the mobility of hosts and the characteristics of wireless medium, end-to-end connections are inherently unreliable in ad hoc networks. The established paths between the endpoints frequently become unavailable for short periods of time, because of intermittent failures occurring on the path. For example, consider a relay node which connects two other intermediate nodes. Note that, every intermediate node acts in fact as a relay node in the network. If the relay node is highly mobile, as it moves out of the intersection region of transmission ranges, the connecting link will be broken and as it comes back, link will become available [22], [23], [24]. Additionally, due to the errors stemming from various reasons such as fading, interference etc., wireless channels fails for short periods. On the other hand, wireless nodes may have sleep/awake cycles in order to save their battery powers. A node in its sleep cycle fails to forward the incoming packet causing a type of node failure [32], [33], [37]. Similar scenarios may cause unavailability of paths. Intermittent unavailability of paths results in packet loss or delay, and thus may result in the degradation of Quality of Service (QoS) in the network.

The emerging use of multimedia applications in ad hoc networks has increased the need to support QoS requirements [7], [8], [9], [10]. The earlier ad hoc routing protocols such as DSR [1] and AODV [2] are insufficient in this sense, since the qualities of the established paths are not taken into account [11], [12].

Multipath routing ([3], [4], [5], [6]) is a promising technique that improves the packet delivery ratio. However, the allocation of the traffic among the available paths has a crucial effect on the performance. In this thesis, we propose an optimal strategy to distribute the traffic among paths in order to minimize packet loss rate. Our scheme is based on diversity coding. The underlying idea of diversity coding is that the packets are encoded in such a way that when at least K packets out of N packets are received, the original data can be successfully decoded. Although we focused on wireless mobile ad hoc networks, our scheme can be incorporated into any routing scheme in networks with intermittent connectivity.

The use of more accurate packet loss models is of paramount importance in developing schemes to increase the packet delivery rate. In recent studies in which the packet losses are modeled, either the average path failure probability is used [53] or pure erasure channel is assumed [54], [55]. However, experiments on real data showed that there is temporal dependence in packet loss [57], [58]. Motivated by the lack of research, we established a packet loss model considering the inherent temporal dependence in packet loss.

1.2. Thesis Statement and Organization

In this thesis, we propose a reliable and efficient routing strategy for networks with intermittent connectivity. In our strategy, we exploit path diversity in order to improve reliability, and use diversity coding in order not to compromise efficiency. In path diversity, the source transmits information over several available paths to the destination simultaneously. Since the probability of all paths failing at the same time is low, the probability of delivering information to the destination is increased. However, if the same packets are transmitted over all paths, then the redundancy is increased significantly, and thus network efficiency is reduced. Thus, we suggest using diversity coding scheme, where we can control the amount of redundancy in the transmissions. In diversity coding scheme, if the original information is encoded using (N,K) code, then it is enough for the destination to receive K bits correctly out of N bits to successfully decode the original information. In this thesis, we assume that the data is first encoded by (N,K) code, and then divided into N subpackets. Each subpacket is then sent over different multiple disjoint paths. If the destination receives at least K out of N such sub-packets, then the transmission is considered successful. Thus, the network reliability is defined as the probability of receiving K or more packets at the destination.

In order to have significant improvement in the network reliability, we have to satisfy the following two objectives. First, the allocation of subpackets into multiple paths should be done intelligently with respect to the relative reliabilities of the paths. Second, the reliability of the paths should be modeled as accurately as possible, so that it can capture its real-life characteristics.

Consequently, in this thesis we have the following contributions: Our first contribution is a new path reliability model that captures intermittent availability of the nodes. Particularly, we use a Markovian node model in which current state corresponds to its availability for transmission. The complexity of the analysis with this node model increases exponentially, when higher order statistics are taken into consideration. Thus, we propose Beta-Binomial (BB) approximation for the path reliability which is a simpler to work with and sufficiently accurate. This approximation can be expressed as a function of a single correlation parameter.

Our second contribution is that we provide a numerical solution to the optimal allocation of subpackets over different paths. Given the failure statistics of the paths, and the code rate (N,K), the allocation of subpackets to each path is determined. Our simulation results justify the accuracy and efficiency of our approach. Additionally, our simulation results have shown that when intermittent availabilities (Markovian model) of the nodes are taken into consideration during the allocation decision, the network reliability can be improved significantly compared to the case when it is assumed that nodes remain available or unavailable incessantly.

Beside these contributions and advantages, multipath routing and diversity coding come with some drawbacks. When multiple paths are used, not necessarily all the paths are the shortest paths between the source and destination node. Therefore, some extra delay will occur because of using these more reliable but longer paths. In addition to that, diversity coding comes at a cost of added overhead. This will result in more bandwidth consumption, also the intermediate nodes consume more energy to route these overhead packets.

Our third contribution is based on the fact that in many cases the intermittent availability of the nodes is due to the sleep/awake cycles of the nodes. In wireless networks, the nodes are put into low energy consuming sleep mode in order to prolong the battery life. By using the results derived in this thesis, we propose a new approach in designing sleep/awake schedules for wireless nodes. In this approach, we considered information latency as the Quality of Service (QoS) metric, and designed probabilistic sleep/awake schedules that maximize the QoS, while satisfying a target energy consumption ratio.

The organization of the thesis is as follows. In Chapter 1, motivation and background of the problem that we address and related works that investigate similar problems are introduced. In Chapter 2, types of path failures that result in packet loss are overviewed and our model for time correlated path failures is described in detail. In the same chapter, a formal definition of network reliability is given and it is expressed analytically. Two approximation techniques in order to simplify the analysis of network reliability are also introduced in this chapter. In Chapter 3, the main focus of the thesis, the problem of maximizing network reliability is defined and a numerical solution is derived. In Chapter 4, we overview the concept of sleep/awake scheduling and present our sleep/awake schedule strategy which is effective in the context of maximizing network reliability while satisfying the rules of energy saving mechanism. Numerical results supporting our strategy are also given in this chapter. Chapter 5 presents simulation results for various scenarios to show the performance of our traffic allocation strategy. Chapter 6 concludes the thesis.

1.3. Background

1.3.1. Multipath Routing in Wireless Ad Hoc Networks

Limited transmission ranges of wireless nodes necessitate the traversal of data through several intermediate nodes. Thus, each node operates not only as a host but also as a router; forwarding packets coming from other nodes. Ad hoc networks may have a dynamic topology due to the mobility of nodes. Nodes can change their location rapidly and the set of nodes connected to the network frequently changes. Additionally, mobile devices are usually battery-driven, so the energy is limited. These characteristics of ad hoc networks make the routing a challenging task. There is a considerable amount of work that takes the advantage of redundancy in the paths between a source and destination for different objectives such as load balancing, fault tolerance, reliability, and energy efficiency. Several multipath routing protocols have been proposed [3], [4], [5], [6] in order to satisfy one or more of these multipath routing objectives.

There are mainly two approaches on the utilization of the discovered multiple paths. First approach uses only the optimal path to transmit the data packets and utilizes the rest of the paths as backup. The objective of this approach is usually to increase fault tolerance and/or reduce the frequency of route discoveries. AODV-BR [13] is an example of this kind. In AODV-BR, the discovery of alternate paths is assigned to individual nodes. Nodes discover alternate routes by overhearing the route reply messages of their neighbors. There is no multiple complete path information at the source; instead alternate paths stored at the nodes are used to recover the broken part of the primary path. A similar approach is Backup Source Routing (BSR) [14] which is an extension of DSR. BSR piggybacks backup route information into the headers of the packets together with the primary route information. Another multipath extension to DSR is alternative path DSR (ALTDSR) [15]. ALTDSR establishes a primary path and alternative paths during the route discovery phase in order to tolerate any single node fault on the primary path.

The second approach utilizes all discovered multiple paths simultaneously in order to transmit the data packets. One of the common objectives for this type of utilization is balancing the network load. Ref. [16] and Ref. [17] have explored that balancing the load among multiple paths has a positive effect on end-to-end delay. Despite the common belief, Ref. [18] showed that multipath routing does not improve the load balance compared to single path routing unless multiple paths are far apart to each other. Another common objective for using parallel multiple paths is the improvement of the reliability of data delivery. A trivial way of increasing the reliability of data delivery is sending multiple copies of the same packet along different paths. However, it is possible to achieve the same reliability with a higher efficiency by using diversity coding. The work of Ayanoglu et. al. [63] has motivated the studies which use diversity coding in conjunction with multipath routing. These studies will be discussed in Section 1.4.

1.3.2. Multipath Routing Protocols

1.3.2.1. Essentials of Routing Protocols

Routing protocols in ad hoc networks are used to find and maintain routes between source and destination nodes as in the traditional wired networks. There are two main types of routing protocols, table-based and on-demand. In table-based routing protocols, every node maintains its routing table that holds routing information for all of the nodes in the network whether it is necessary or not. Periodic exchange of routing information among the nodes is required to update the routing tables in table-based routing protocols. Therefore, table-based routing protocols are not suitable for wireless ad hoc networks where the nodes are highly mobile and energy constrained. On-demand routing protocols are more suitable for wireless ad hoc networks. A route is found between a source node and destination node only when it is necessary.

Route discovery, route maintenance and traffic allocation are the three main components of on-demand multipath routing protocols. Route discovery and route maintenance are common operations that must be performed for both single path and multipath routing, whereas traffic allocation is specific to multipath routing. *Traffic Allocation* is the process of distributing the packets to be sent, among the selected routes between the source and destination node.

Route Discovery is the process of finding multiple routes between a source and a destination node. Different mechanisms may be applied under different protocols in order to find the routes. Similarly, *Route Maintenance* mechanisms may vary among different multipath routing protocols; however, all these mechanisms have the general objective to use the up-to-date and effective routes, and discard the routes that become obsolete.

Routes that are found by the multipath routing protocols may be node disjoint, link disjoint or non-disjoint. Node disjoint paths have no common nodes or links with other routes except the source and destination node. Link disjoint paths may have common nodes with other paths but there are no common links in between. Non-disjoint routes have no restriction on having common nodes or links. Figure 1.1 depicts an example for the node disjoint path type.

Figure 1.1 Node disjoint route example

Examples for link disjoint and non-disjoint route types are shown in Figure 1.2 and Figure 1.3 respectively.

Figure 1.2 Link disjoint route example

Figure 1.3 Non-disjoint route example

Two of the most common single path routing protocols for ad hoc networks are DSR [1], and AODV [2]. DSR is an on-demand routing protocol, where the source node determines the complete path to the destination and includes it in the packet's header. Meanwhile, AODV is based on distance vector routing which uses hop-by-hop routing and maintains routing information at the intermediate nodes. Currently proposed multipath routing protocols are mostly an extension of either DSR or AODV.

1.3.2.2. Split Multipath Routing (SMR)

Lee and Gerla proposed SMR (Split Multipath Routing) in [3]. SMR is an on-demand multipath routing protocol designed for ad hoc networks, which has the objective to build maximally disjoint paths. In this scheme, when a source node needs a route to a destination, and it does not have a route to that destination, it initiates a route discovery. A RREQ (Route Request) packet propagation scheme is also proposed in [3] to discover multiple paths between the source and destination nodes. The RREQ packet transmitted by the source node contains the source node ID and a sequence number, which uniquely identifies the corresponding RREQ packet. When an intermediate node receives a RREQ packet that is not duplicated, it appends its ID and re-broadcasts the RREQ packet. In traditional on-demand routing protocols like DSR [1] and AODV [2], if intermediate nodes have routing information in their route cache for the corresponding destination node, they reply to the RREQ packet with a RREP (Route Reply) packet. In SMR, if the nodes reply from their cache, only a few RREQ packets will propagate throughout the network. With only a few RREQ packets traversing the entire network, it is not easy to establish maximally disjoint multipaths between the source and destination nodes. For this reason, in SMR intermediate nodes are not allowed to reply to the RREQ packets from the route cache. The destination node selects two routes that are maximally disjoint and sends RREP packet back to the source over the selected paths and thus setting up multiple paths between the source and destination.

Additionally, two different methods for route maintenance are proposed in SMR. When any of the selected two paths are broken, the first scheme initiates a new route discovery. Meanwhile, the second scheme initiates a new route discovery only when both of the selected routes are broken. Load balancing and shorter end-to-end delay are the observed advantages of SMR when compared to its predecessor DSR.

1.3.2.3. Multipath On-Demand Routing (MDR)

MDR (Multipath On-Demand Routing) is an on-demand multipath routing protocol proposed in [4]. Similar to SMR, MDR uses a RREQ flooding scheme for route discovery. The destination node sends a RREP packet back to the source node over the selected paths. The main difference between SMR and MDR is that there is no route maintenance phase in MDR in order to lower the communication overhead.

1.3.2.4. Ad Hoc Distance Vector Multipath (AODVM)

Ye et. al. have proposed AODVM (Ad Hoc Distance Vector Multipath) in [5], which is a modified version of AODV. AODVM aims to discover multiple node disjoint routes from a source to a destination node. Intermediate nodes record the information contained in duplicate RREQ packets in their RREQ table. Similar to SMR, intermediate nodes are not allowed to send RREP packets using the routing information available in their routing table. When the destination node receives a RREQ packet from one of its neighbor nodes, it updates the sequence number and sends back a RREP packet to the source node over the same path that RREQ packet in has traversed. RREP packet also contains the ID of the neighbor that the corresponding RREQ packet has been received from. Every time the destination node receives a RREQ packet from other neighbors, it generates another RREP packet and sends it to the source node as explained above. An intermediate node deletes the entry corresponding to neighbor node from its RREQ table, when it has received a RREP packet from that neighbor node. It also adds a routing entry for the discovered route in RREP packet in its routing table. Deleting the record from the RREQ table corresponding to a neighbor node is necessary to ensure that discovered paths are node disjoint.

1.3.2.5. Ad Hoc On-Demand Multipath Distance Vector (AOMDV)

Marina and Das proposed AOMDV (Ad hoc On-demand Multipath Distance Vector) in [6], which is another multipath extension to AODV protocol. AOMDV route discovery aims to find loop-free and link disjoint multiple paths. They use an “advertised hop-count” scheme to guarantee the loop free feature. There is no traffic allocation scheme designed for AOMDV. Route discovery for a destination node is necessary, whenever the known route to the specified destination node is broken when AODV is used. Each route discovery is associated with high overhead and latency. Therefore, route discovery is performed only when all links to the destination are broken in AOMDV. AOMDV uses the underlying routing information as much as possible to avoid extra overhead and latency. Nodes use RREQ packets to discover the up-to-date routing information because each RREQ packet contains routing information for the source node in reverse order. On the other hand, accepting all RREQ packets to retrieve routing information causes routing loops. Therefore, AOMDV uses advertised hop-count technique to find loop-free routes. In Ref. [6], advertised hop-count is defined as the maximum hop-count of the multiple paths to a destination node *d* available at an intermediate node *i*. This hop-count is used when sending RREQ packets corresponding to a destination node.

1.4. Optimal Multipath Routing

1.4.1. Diversity Coding

Diversity Coding is an error control based approach. It is introduced for self-healing and fault-tolerance in digital communication networks in [63]. The scheme achieves nearly instantaneous recovery from link failures. Link failures are treated as an erasure channel problem. Recovery from link failures is done at the receiver side. There is no need for a feedback channel if there is only a single destination.

In the proposed scheme, the information bits are divided into *N* data channels in which the data is sent in parallel. *M* extra channels are added in order to recover from any *M* channel failures out of *N+M* channels. *M* extra channels are used for transmitting the parity bits which are constructed from information bits by linear transformations. This is called *M-for-N* diversity coding.

1.4.2. Distribution of Packets over Paths in a Lossy Network

Recent research in ad hoc multipath routing can be classified into two directions according to the routing components they are focused on. There is a considerable amount of work which concentrates on the route discovery and maintenance component of multipath routing. We have examined the most popular ones in Section 1.3.2. Meanwhile, previous work on traffic allocation component of multipath routing is scarce, even though it has significant effect on the performance of the routing protocols.

The distribution of packets over several paths is a key issue in multipath routing. The multipath routing has been used to increase the reliability of transmissions. However, increased reliability comes at a cost of added redundancy. Added redundancy depends on the number and the quality of the available paths. A particularly important result is that when used in conjunction with diversity coding, the utilization of multiple paths simultaneously has proven to have positive effect on the reliability of data delivery with low overhead [54], [55].

1.4.3. Related Work

Dulman et. al. proposed an approach to control the trade off between overhead and reliability in [19]. In this approach, the data packet is split into subpackets. The number of subpackets that a packet should split into is equal to the number of *disjoint paths* discovered by the route discovery mechanism. A single sub-packet is transmitted along each path. In order to increase the reliability, erasure codes are used for adding redundancy to the original packet. Thus, a set of sub-packets is determined, which requires only E_k of the k subpackets to be delivered in order to re-construct the original packet at the destination. The authors rely on a pathrater-type mechanism in order to classify the available routes according to their failure probabilities. Given the number of disjoint paths and the failure probabilities of each path, the redundancy that should be added in order to satisfy a constraint on the reliability of delivery is expressed analytically. However, the failure probabilities are assumed to be constant over the lifetime of the transmission. Note that ad hoc networks are typically quite dynamic due to node mobility, channel conditions, etc., and thus this assumption is usually not valid. Also, in this work the authors constrained themselves in finding node disjoint paths. Thus, the number of subpackets that a packet is split into is usually small since there only a few number of disjoint paths in the network [5]. Another invalid assumption of the proposed scheme is that all paths have similar failure probabilities. The authors need this assumption, since they, in a naïve way, send equal number of sub-packets over all available paths. Thus, in order to accommodate different path failures more redundancy should be added unnecessarily, if the subpackets are sent evenly among the available paths.

In a different application, Ref. [60] stressed the importance of information awareness in sensor networks and proposed a mechanism to forward the critical information at a desired reliability. Multiple copies of the critical packets are sent in order to increase the probability of successful delivery. Two approaches for sending multiple copies are explored. In the first one, multiple copies of each packet are sent along a single optimal path. However, this approach has two disadvantages; first the single path delivery is not robust to failures, and second it experiences higher delays since packets are sequentially forwarded. In the second approach, source sends redundant copies of a packet through multiple paths in order to obtain the desired reliability. In this work, the authors made a simplifying assumption that the error rates of the channels do not differ across a path which is not generally correct in practice.

In Ref. [53], the authors study the use of multiple parallel paths and diversity coding. It relies on a cross layer information collection to optimally distribute the packets to minimize energy consumption while satisfying the reliability constraint. The authors exposed the optimization problem and suggest solving it by convex programming. The network reliability model depends on the simplistic assumption that success probabilities of paths do not change in time.

To the best of our knowledge, Ref. [54] is the most similar study compared to the work described in this thesis. In Ref. [54], the authors examined the optimal allocation of traffic among multiple paths in order to increase the network reliability. The objective is to fragment the packets and send the fragments over multiple paths in an optimal fashion, so that the probability of successful re-construction at the destination is maximized. In order to increase efficiency, the authors suggested using diversity coding. The main difference of Ref [54] with our work is on the assumptions. The authors of [54] modeled each path as a pure erasure channel in which either all or none of the packets sent along the path is received at the destination. The probability of success is defined as the probability of successful reconstruction of the packet at the destination. In [54], given the failure probabilities of the paths, the overhead factor, the allocation of subpackets to the paths, and the corresponding probability of success is analytically expressed. The probability of success is only analyzed for a special case where the paths have the same failure probabilities and the subpackets are uniformly distributed among available paths. As a result of this analysis, it is concluded that as the number of used paths increases, the probability of success increases.

In [55], the authors derived an approximation for the probability of success in order to find the optimal allocation of subpackets. First, an analytical expression for the approximation of the probability of success is derived for the case where the paths have the same failure probabilities (uniform probability vector) and the subpackets are uniformly distributed among available paths (uniform allocation vector). Then the analytical expression is extended gradually to the cases; where the probability vector is not uniform, and then to the case, where the allocation vector is not uniform.

2. MODEL FOR TIME CORRELATED PATH FAILURES

In wireless mobile ad hoc networks, the paths between a source-destination pair frequently become unavailable due to node and/or link failures occurring somewhere on the path. These failures may be permanent, transient or intermittent. Intermittent failures are type of failures which occur for short periods of time, repetitively. Fragile characteristics of wireless mobile ad hoc networks cause kinds of node or link failures arising from different reasons such as mobility, constrained energy, fading in the communication channel, and errors in the noisy wireless medium. Moreover, certain denial-of-service attacks can also lead to node or link failures. Permanent failures that make the path non-operational indefinitely are often due to the physical damage of the mobile node, battery depletion or a long-term malicious attack. Mobility, energy saving mechanisms, and bursts of errors on wireless links usually cause transient or intermittent failures, which do not make the path non-operational but prevent communication between source and destination for intermittent short periods. In this thesis, we are interested in transient or intermittent node/link failures, which are quite common in mobile wireless ad hoc networks.

2.1. Types of Path Failures

The path failures that we are interested in this thesis can be classified into four groups according to the reason of the failure; node mobility, energy saving mechanisms, wireless link conditions and denial of service attacks.

2.1.1. Intermittent Failures due to Node Mobility

Node mobility is one of the major challenges of ad hoc networks and great amount of research has been done to model the node mobility [20], [21]. The effect of mobility on node failures is examined with a simple example. Figure 2.1 shows a part of a path that connects the source to destination. Although mobile *Node*1 and mobile *Node*3 cannot communicate directly due to their transmission ranges, communication is maintained through mobile *Node*2. However, in order to act as a relay for *Node*1 and *Node*3, *Node*2 should be in the transmission range of *Node*1 and *Node*3, i.e., *Node*2 should be in intersection region of Cell A and Cell B in Figure 2.1. Since *Node*2 is mobile, it can enter, stay and leave the intersection region for certain period of times, repetitively.

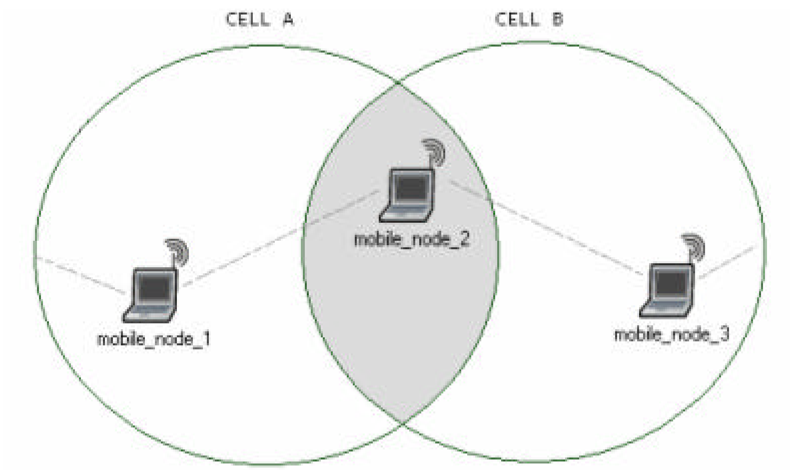

Figure 2.1 Node failure scenario due to mobility

Being motivated from a similar mobility scenario, the connection availability was modeled with a Continuous Time Markov Chain in [22], [23], and [24]. The time duration a node is absent and the time duration it is present in the intersection area are both modeled with an exponential distribution. Note that being absent represents a failure event and being present represents a repair event. Moreover, the authors in [22] presented an analytical expression for failure rate and repair rate in terms of the distance that a mobile node passes in the intersection region and mobile node's speed. Assuming that the distance that a mobile node passes in the intersection region is approximately same for all nodes in the network, the rate of mobility of a node gives intuition about the failure/repair rate of that node.

2.1.2. Intermittent Failures due to Energy Saving Mechanisms

Limited energy is a critical design constraint in ad hoc networks especially for the ones that are constituted of battery powered wireless nodes. Various efforts have been done in order to extend the life of energy-constrained nodes. In [25], [26], the authors provide energy-efficient MAC layer solutions, whereas in [27], [28], [29], and [30] the authors propose energy-aware routing protocols, and [31] offers a battery management technique.

A particularly effective energy saving mechanism is to switch nodes between low- and high-power consuming states, i.e., sleep/awake model (e.g., see [32], [33], [34], [35], [36], [37]). In Ref. [35], the authors describe a sleep/awake model for a sensor node's radio with four states; transmitting, receiving, sleep and idle. In transmitting and receiving states, node is considered active; in idle state, node can listen to channel; and in sleep state, node is completely turned-off and can neither transmit, receive nor listen to the channel.

A path is disconnected, when a node on the path is in sleep state, since a node in that state does not perform its forwarding task. Therefore, for our purposes we can model a sensor node with only two states, namely sleep and awake. A sensor node in the awake state schedules the time instant in the future at which it will move to the sleep state. Durations of sleep and awake periods may be either constant which corresponds to periodic schedule or exponentially distributed [35].

In reality, there is usually temporal correlation between the states of a node, i.e. the current state of the node depends on its previous state. Due to this dynamic behavior of sensor nodes, the state transition can be modeled by Discrete Time Markov Chain.

For example, Ref. [38] models only the node behavior with Discrete Time Markov Chain, whereas Ref. [32] models both the sensor node dynamics and the operational states of its next-hop neighbors with Discrete Time Markov Chain.

2.1.3. Intermittent Failures due to Wireless Channel Conditions

In ad hoc networks, links between communicating nodes are wireless channels. Wireless channels are frequently exposed to bursts of errors due to noise, fading / shadowing effects, interference, etc. The channels are usually not memoryless, which means errors on the channel are correlated. So the assumption that packet losses are independent is not appropriate. Gilbert-Elliot channel is widely used to model the wireless channels with correlated failures as in [39], [40], [41], and [42].

Gilbert-Elliot channel model is a first order Markov model. More complex models may work better to capture higher order statistics, however complexity increases exponentially. [43] and [44] stated that it is appropriate to model the transmission on a flat Rayleigh-fading channel with two-state Markov chain.

2.1.4. Intermittent Failures Due to Denial of Service Attacks

Ref. [45] defines Denial-of-Service (DoS) as any event that degrades network capacity to perform its expected job. Generally, DoS arises from adversary attacks. Due to their inherent characteristics, ad hoc networks are more vulnerable to DoS of attacks and the absence of a central authority makes detection of the attacks more difficult. There are various types of attacks targeting different layers such as jamming, battery exhaustion, misdirection, neglect and greed, black hole attack. Various defense mechanisms are proposed in [46], [47], [48], [49], [50] in order to detect, prevent and mitigate these attacks.

DoS attacks and especially the ones that target the routing layer cause node or link failures. For example, in Neglect and Greed attack, a compromised or malicious node arbitrarily neglects to forward the incoming packets, while still participating to other jobs in the network. Similarly, in Misdirection attack, misbehaving node routes the packets along wrong paths. When a black hole occurs in the network, great amount of packet loss arises.

In general, an attacker aims to damage the network as much as possible and attacks persistently. On the other hand, intelligent attackers as mentioned in [51], [52], may change its attack pattern or misbehave intermittently in order to avoid from an intrusion detection system or a similar detection mechanism.

2.2. Network Model

Any of the failures examined in Section 2.1 are usually experienced in an ad hoc network several times repeatedly at any node or link. This makes the nodes and the links, and thus the paths unreliable, since the affected node or link cannot perform its job of forwarding the incoming packet, which results in a packet loss or end-to-end delay.

Modeling the failures, or specifically modeling the packet loss appropriately is important for the design of more accurate network protocols, since the aim of network protocols is to increase the Quality of Service of the nodes, e.g., the packet success rate. In a widely used simple failure model (e.g., [53], [54], [55]), it is assumed that the probability of packet loss on a particular path at time slot $t+1$ is independent of the probability of packet loss at time slot t. On the other hand, Ref. [56] and [57] stated that the experiments on real data showed that there is temporal dependence in packet loss. Ref. [58] investigated the mobility related packet loss, the congestion related packet loss and the total packet loss in mobile ad hoc networks via simulation. The simulation results showed that for all types of packet loss, the packet loss distribution over time is bursty. In [57], the accuracy of different Markovian models with increasing order k, where k=0 represents independent model, are evaluated. The authors concluded that as order k increases, i.e., as the time correlation increases, the accuracy of the model increases.

With a similar motivation, in this thesis we consider temporally correlated failures that can be modeled with Markovian models. However, since the complexity increases exponentially as order k increases, in this thesis only ***First Order Markov Model*** is used to model the node and link failures, and thus implicitly packet losses.

In our work, we model the mobile ad hoc network as a graph with unreliable vertices in order to represent the failure-prone nodes and reliable edges in order to represent error-free links. The reliable edge assumption may seem inappropriate for real wireless links. However, any reliable edge on the graph can be easily transformed to an unreliable vertex and two reliable edges as explained in [59]. Additionally, source and destination nodes are assumed to be reliable. Furthermore, we assume that the vertices fail independently.

2.2.1. Node Model

We model the unreliable behavior of wireless mobile ad hoc nodes with Discrete Time First Order Markov Chain. As depicted in Figure 2.2, there are two states; namely ***ON*** state and ***OFF*** state. ***ON*** state corresponds to the state in which the incoming packet is successfully transmitted to the next hop and ***OFF*** state corresponds to the state in which the incoming packet is dropped. In this context, ***ON*** state represents the state of a mobile node in which it is in the intersection region of a sender and receiver pair or the awake period of a node which has a sleep/awake schedule. Similarly, ***OFF*** state represents the state of a mobile node in which it is out of the intersection region of sender and receiver or the sleep period of a node which has a sleep/awake schedule.

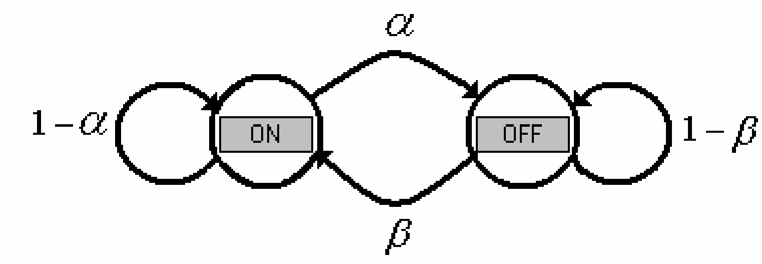

Figure 2.2 First order Markov chain model

Parameters of the model are defined as follows;

a **:** Probability of transition to ***OFF*** state from ***ON*** state or equivalently probability that next packet is dropped provided that previous packet transmitted

$1-a$ **:** Probability of staying ***ON*** state or equivalently probability that next packet is transmitted provided that previous packet transmitted

b **:** Probability of transition to ***ON*** state from ***OFF*** state or equivalently probability that next transmitted is lost provided that previous packet dropped

$1-b$ **:** Probability of staying ***OFF*** state or equivalently probability that next packet is dropped provided that previous packet dropped

p_0**:** State probability for ***ON*** state

p_1**:** State probability for ***OFF*** state

From above definitions, the steady state probabilities p_0, p_1 are computed as;

$$p_0 = \frac{b}{a+b} \quad (2.1)$$

$$p_1 = \frac{a}{a+b} \quad (2.2)$$

where $p_0 + p_1 = 1$, and $0 < a < 1$, $0 < b < 1$. It can be easily shown that the duration of ***ON*** state, $\overline{T}_{ON}$, and duration of ***OFF*** state, $\overline{T}_{OFF}$, are geometrically distributed with means $\frac{1}{a}$ and $\frac{1}{b}$, respectively.

It is obvious that different nodes with the same steady state probabilities p_0 and p_1 may have different state transition probabilities (a , b). The (a , b **)** values correspond to failure and success rate of a node in a real scenario. For example, b represents the rate of leaving the intersection region of the sender and receiver pair for a mobile node**,** frequency of sleep state for an energy-saving node, the probability of attack for a misbehaving node or the failure rate of a wireless channel.

2.3. Definition of Network Reliability

According to the application, different Quality of Service parameters may be chosen to analyze the network performance. Our QoS parameter is the network reliability, which is an important metric of ad hoc networks, especially for multimedia applications.

Sending multiple replicas of the same packet along different disjoint paths to increase reliability is a well-known solution and used in [60], [61], [62]. A more effective scheme can be applied by the help of diversity coding rather than sending the whole packet repetitively.

In [63], it is shown that if M parity packets which are generated from K data packets by linear transformations are sent to the destination with the original data packets, the reception of *any* K packets are enough to reconstruct the original data.

We assume that the data packet, say X bits is divided into K equal-size fragments and Y bits of parity which is generated from X bit original data is also divided into M fragments such that all of them have the same size with the fragments of the original packet. In total, $K + M = N$ fragments are sent to the destination. If any combination of K fragments out of N fragments is received at the destination, the original data packet can be reconstructed successfully. Since each fragment is in fact a network-layer packet, we will use the term 'packet' in place of 'fragment' in the rest of the thesis.

We assume that there are I paths available for a specific source and destination which are constructed by any route discovery mechanism available in the literature [4], [5], [6]. Thus, N packets should be distributed among these available paths. Let N_i be the number of packets transmitted on path i, and K_i be the number of packets received from path i. In Chapter 3, we propose an optimal way of distributing N packets among available paths.

Hence, we express the network reliability as the probability of receiving at least K packets at the destination, when N packets are sent from the source;

$$\Pr\left(\sum_{i=1}^{I} K_i \geq K \quad where \quad \sum_{i=1}^{I} N_i = N \right) \tag{2.3}$$

2.4. Analytical Expression of Network Reliability

Path set is the set of all available paths from a source and destination and a path is a concatenation of nodes. Therefore, we will express node reliability first and extend it to path reliability, in order to express the network reliability analytically.

2.4.1. Analytical Expression of Node Reliability

We define the node reliability, $P_{success}$ as the probability of forwarding at least K of N incoming packets. In Section 2.2.1, node is modeled as a Markov chain with two states. If the node is in ***ON*** state, it forwards the incoming packet with probability 1 and if it is in ***OFF*** state, it forwards the incoming packet with probability 0. We assume that state transitions occur at the beginning of time slots and only one packet is received in each slot.

Let us denote the first slot with t_0, in which the first packet arrives. In time slot t_0, a node may be in ***ON*** state with probability p_0 or in ***OFF*** state with probability p_1. During the next N time slots, a node makes

x times ***ON****-to-****ON*** transitions with probability $(1-a)^x$

y times ***ON****-to-****OFF*** transitions with probability a^y

z times ***OFF****-to-****OFF*** transitions with probability $(1-b)^z$

t times ***OFF****-to-****ON*** transitions with probability b^t

In order to illustrate better, we represent the possible transitions of a node during N time slots with a binary tree in Figure 2.3.

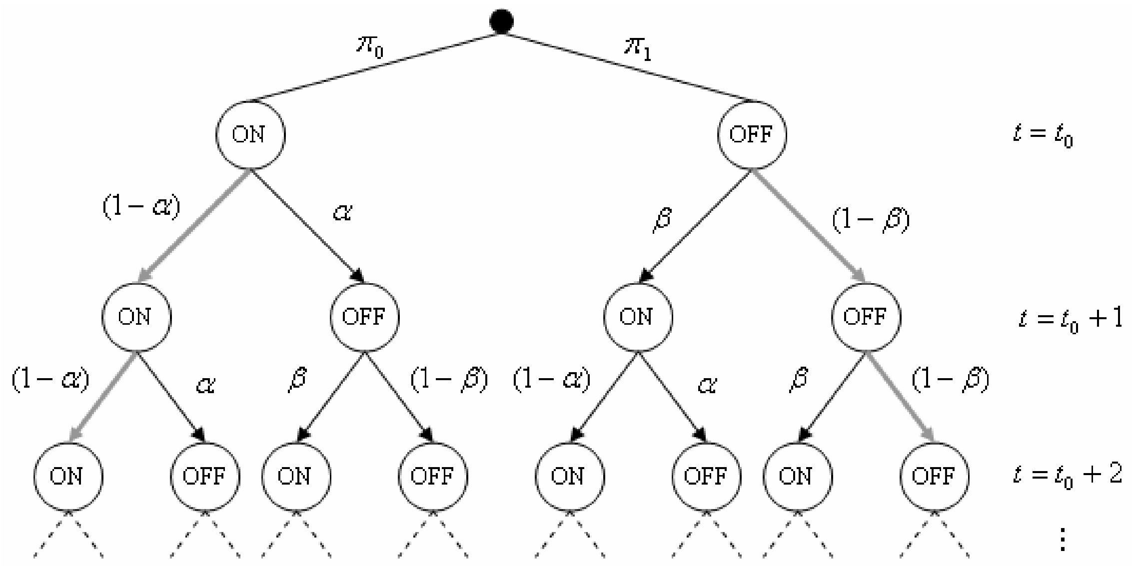

Figure 2.3 Binary tree representation of possible transitions of a node

The binary tree representation given in Figure 2.3 can be used to mathematically calculate the probability of forwarding exactly *K* of *N* incoming packets for a node. Each level on the given binary tree corresponds to a different time slot and the depth of binary tree is *N*. Each traversal from the initial state to the one of the leaf nodes gives a possible sequence of transitions during *N* time slots. The probability of this transition sequence can be computed by multiplying the probability values given on the branches of the tree. Some of these transition sequences lead to the requirement of forwarding exactly *K* of *N* incoming packets. Hence, the probability of forwarding exactly *K* of *N* packets is sum of the probability values calculated for the transition sequences that satisfy the requirement. The constraint that determines whether a given transition sequence satisfies the requirement or not can be defined as: the number of transitions ending in ***ON*** state in a transition sequence must be equal to *K-1* if the initial state is ***ON*** and *K* if the initial state if ***OFF***. Additionally there are two constraints that must hold for any transition sequence. It is obvious that if the initial state is ***ON***, the node will preserve its ***ON*** state or will make at least one ***ON*** to ***OFF*** transition. Similarly, if the initial state is ***OFF***, the node will preserve its ***OFF*** state or will make at least one ***OFF*** to ***ON*** transition. The case that the node is always in ***ON*** state or ***OFF*** state will be considered separately. As an expected result of the traditional two state Markov chain, the difference between the number of ***ON*** to ***OFF*** transitions and ***OFF*** to ***ON*** transitions may be at most 1. Considering the constraints given above, probability of forwarding exactly K of N packets can be expressed mathematically as follows;

$$\Pr(K \quad of \quad N) = \sum_{x=0}^{K-1}\sum_{t=0}^{T-K-1} p_0 \binom{K-1}{x}\binom{N-K-1}{t}(1-a)^x (a)^y (b)^z (1-b)^t \Bigg|_{\substack{y>0,\\ z=K-1-x,\\ y=N-K-1-t,\\ 0\le y-z\le 1}}$$
$$+ \sum_{x=0}^{K-1}\sum_{t=0}^{T-K-1} p_1 \binom{K-1}{x}\binom{N-K-1}{t}(1-a)^x (a)^y (b)^z (1-b)^t \Bigg|_{\substack{z>0,\\ z=K-1-x,\\ y=N-K-1-t,\\ 0\le y-z\le 1}} , \tag{2.4}$$

where $0 < K < N$.

If $K=0$, $P(0 \quad of \quad N) = p_1(1-b)^{N-1}$, and

if $K=N$, $P(1 \quad of \quad N) = p_0(1-a)^{N-1}$.

Accordingly, the node reliability, $P_{success}$ is;

$$Pr\ (number\ of\ forwarded\ packets \geq N) = \sum_{i=K}^{N} \Pr(i \quad of \quad N) \tag{2.5}$$

2.4.2. Extension to Path Reliability

A path is a concatenation of nodes, where the availability of each node is modeled as a two state Markov chain. Similar to node reliability, we define the path reliability as the probability of receiving at least K packets at the destination node of the path when N packets are sent from the source node.

A packet sent from the source node reaches the destination node by traversing all the intermediate nodes on the path. Therefore, all the intermediate nodes should forward the packet successfully, or equivalently all of the nodes should be in ***ON*** state in order to successfully receive and transmit a packet. On the other hand, if any of the intermediate nodes on the path is in ***OFF*** state when a packet arrives, that packet will be lost and the packet will not reach its destination. Let us illustrate this case with an example, where we consider a path consisting of two intermediate nodes. The correct transmission of a packet over this path can be modeled by 2^2 = 4 states where in

State (00); both nodes are in ***OFF*** state
State (01); first node is ***ON*** state, second node is ***OFF*** state
State (10); first node is ***OFF*** state, second node is ***ON*** state
State (11); both nodes are in ***ON*** state.

Let (a_1, b_1) and(a_2, b_2) denote the transition probabilities of *Node*1 and *Node*2, respectively. The transition probability matrix, *S* can be written in terms of (a_1, b_1) and (a_2, b_2);

$$S = \begin{bmatrix} (1-b_1)(1-b_2) & (1-b_1)b_2 & b_1(1-b_2) & b_1 b_2 \\ (1-b_1)a_2 & (1-b_1)(1-a_2) & a_1 b_2 & (1-a_1)a_2 \\ a_1(1-b_2) & b_1 a_2 & (1-a_1)(1-b_2) & (1-a_1)b_2 \\ a_1 a_2 & a_1(1-a_2) & (1-a_1)a_2 & (1-a_1)(1-a_2) \end{bmatrix}$$

Clearly, the three states, namely State (00), State (01), and State (10) correspond to the case of where the packet does not reach the destination, while State (11) corresponds to the case where the packet reaches the destination. Therefore, Markov chain with four states can be equivalently represented by a Markov chain with two states, where (00), State (01), and State (10) correspond to ***ON*** state and State (11) corresponds to ***OFF*** state. The transition matrix, S_{joint} of the reduced Markov is;

$$S_{joint} = \begin{bmatrix} 1-b_{joint} & b_{joint} \\ a_{joint} & 1-a_{joint} \end{bmatrix} \tag{2.6}$$

$(1-a_{joint})$ is the transition probability of switching from ***ON*** state back to the ***ON*** state for the reduced Markov can be found directly from the transition matrix *S;*

$$1 - a_{joint} = (1 - a_1)(1 - a_2), \tag{2.7}$$

$$a_{joint} = 1 - (1 - a_1)(1 - a_2). \tag{2.8}$$

However, b_{joint} cannot be found directly from the transition matrix *S*, but it can be extracted as follows;

$$b_{joint} = a_{joint}\left(\frac{p_0^{joint}}{1 - p_0^{joint}}\right). \tag{2.9}$$

We assume that the nodes on the path act independently, so the steady state probability of path being in ***ON*** state, i.e., p_0^{joint} can be found as;

$$p_0^{joint} = p_0^{(1)} p_0^{(2)}. \tag{2.10}$$

This model can be easily extended to the case, where the path consists of M nodes since we are interested only in the cases when either all the nodes on the path forward or at least one of them do not forward. Therefore, the analytical expression found in Section 2.4.1 for node reliability can be used for the path with the following state transition probabilities;

$$1 - a_{joint} = \prod_{i=1}^{M}(1 - a_i), \tag{2.11}$$

$$a_{joint} = 1 - \prod_{i=1}^{M}(1 - a_i), \tag{2.12}$$

$$b_{joint} = a_{joint}\left(\frac{p_0^{joint}}{1 - p_0^{joint}}\right), \tag{2.13}$$

where $p_0^{joint} = \prod_{i=1}^{M} p_0^{(i)}$.

2.5. Approximation of Network Reliability

In Section 2.4.1, we derived an analytical expression for $P_{success.}$ However, it is not in a compact analytical form to be used in an optimization problem maximizing $P_{success}$. In this chapter, we find a close and compact approximation for $P_{success.}$

First consider the trivial case, when the event of forwarding a packet is independent of the event of forwarding the previous packet, and the probability of forwarding a packet is p_0. Then, the probability of forwarding exactly i of N packets can be found by binomial distribution such that

$$P(i \quad of \quad N) = \binom{N}{i} p_0^{\,i} (1 - p_0)^{N-i} . \tag{2.14}$$

On the other hand, if the successes of two successive transmissions are correlated, binomial distribution does not work. Thus, we should determine a probability distribution in which the correlation between successive transmissions is a parameter of the distribution and the distribution gives correct results in cases when the two events are actually independent.

2.5.1. Modeling Correlated Failures by Beta-Binomial(BB) Distribution

In [64], Beta-Binomial (BB) distribution is used to model the correlated failures in multiversion software. Multiversion software programming is a way to enhance the reliability of software by means of parallel redundancy. The main idea is that different software versions are developed independently so that they will probably fail on different inputs. As discussed in [65], program failure behavior of different versions are correlated even though they are developed independently, since all versions are subject to the same input. Experiment results given in [66], and [67] also support the idea that independently developed software versions' failure behavior is correlated. As an expected result, correlated failures must be considered when proposing a model of a multiversion software system. They defined two parameters, p , q , in the context of multiversion programming. Let p be the mean failure probability of a program version on a random input. They use q as a measure of correlation among program versions and refer to it as the correlation level. The so-called correlation level q expresses the degree to which the versions are similar in their failure behavior.

The authors in [64] model correlated failures in multiversion software using BB distribution. They state three main reasons for using BB distribution to model correlated failures. First, the authors show that the failures of multiversion software gathered from test data fits to BB distribution. Second, BB distribution has an analytical closed form depending on only two parameters which are the mean failure probability of a program version and the so-called correlation level. Third, when the correlation is zero, BB distribution is reduced to the Binomial distribution.

In [64], correlated failures in program versions are modeled by a random intensity parameter P which represents the probability that a randomly chosen program will fail. It has a probability mass function $f_P(p)$, which is a beta density function. The probability mass function is interpreted as a fraction p of all program versions fails with probability $f_P(p)$. Beta density function is used in many different contexts previously. For example, beta density function is used in [64] to model correlated failures in multiversion software, in [68] to model correlated events such as the number of infectious disease in a household, and in [69] to model correlated failures in survivable storage systems. We will use the same probability mass function and in our context, and we will assume that the probability that a fraction p of packets out of all incoming packets are forwarded with probability $f_P(p)$. Beta Density function is given by,

$$f_p(p) = \frac{p^{a-1}(1-p)^{b-1}}{B(a,b)}, \qquad 0 < p < 1, \qquad a,b > 0, \tag{2.15}$$

where $B(a,b)$ is the Beta function with parameters a and b. Beta function, $B(a,b)$ is defined as in Eq. (2.16).

$$B(a,b) = \int_0^1 u^{a-1}(1-u)^{b-1}du. \tag{2.16}$$

Beta-Binomial distribution is obtained by randomizing the binomial parameter (which is the probability of failure) in Binomial distribution. Let $b_N(i)$ denote the probability that i program versions fail out of N program versions, then this probability can be found by the following equation;

$$b_N(i) = \int_0^1 \binom{N}{i} p^i (1-p)^{(N-i)} f_p(p)dp. \tag{2.17}$$

Substituting Eq. (2.16) into Eq. (2.17), $b_N(i)$ is obtained as;

$$b_N(i) = \binom{N}{i} \frac{B(a+i, N+b-i)}{B(a,b)}. \tag{2.18}$$

In [70], mean, m and variance, s^2 of BB distribution are defined as;

$$m = N\frac{a}{a+b}, \tag{2.19}$$

$$s^2 = N\frac{ab}{(a+b)^2}\frac{(a+b+N)}{(a+b+1)}. \tag{2.20}$$

Eq. (2.19) and Eq. (2.20) show the relation of the mean and variance of any BB distribution to the parameters of the distribution. Now let us show how the parameters p and q relate to the mean and variance.

In the context of multiversion programming, the mean of the number of programs failing (m) and the variance of the number of programs failing (s^2) are defined as;

$$m = Np \qquad (2.21)$$

$$s^2 = Np(1-p)\frac{1+Nq}{1+q} \qquad (2.22)$$

Since m and s^2 should also correspond to the mean and the variance of the BB distribution, comparing the equations (2.19) and (2.20) with the equations (2.21) and (2.22), p and q are found to be related to the parameters of the BB distribution with the following equations;

$$p = \frac{a}{a+b} \qquad (2.23)$$

$$q = \frac{1}{a+b} \qquad (2.24)$$

Thus, the BB distribution can be also expressed with only two parameters; p and q.

2.5.2. Approximation of Network Reliability by BB Distribution

In a similar fashion, we believe that BB distribution is a good approximation to represent the exact $P_{success}$ values as seen in Figure 2.5. Now, let us show how these parameters relate to our model. Let us denote the success event, i.e. the event of forwarding the packet *i*, with a random variable X_i such that

$$X_i = \begin{cases} 1 & , \quad packet_i \quad forwarded \\ 0 & , \quad packet_i \quad dropped \end{cases}$$

Conditional probabilities are;

$$P(X_{i+1} = 1 \mid X_i = 1) = (1-a)$$

$$P(X_{i+1} = 0 \mid X_i = 1) = a$$

$$P(X_{i+1} = 1 \mid X_i = 0) = b$$

$$P(X_{i+1} = 0 \mid X_i = 0) = (1-b)$$

Expected value of success event is;

$$E[X_i] = P(X_i = 1) = p_0 \qquad (2.25)$$

Covariance of two success events is;

$$Cov(X_{i+1}, X_i) = E[X_{i+1}, X_i] - E[X_i]E[X_{i+1}] \qquad (2.26)$$

$$= (1 - a)p_0 - p_0^2$$

$$= (1 - a - b)p_0(1 - p_0)$$

Variance;

$$s_i^2 = E[X_i^2] - E[X_i]^2 = p_0(1 - p_0) \qquad (2.27)$$

Consequently, correlation of two success events is;

$$r = \frac{Cov(X_{i+1}, X_i)}{s_{i+1} s_i} = (1 - a - b) \qquad (2.28)$$

If $r > 0$ so that $(a + b) < 1$, the event of forwarding a packet is positive correlated with the event of forwarding the previous packet. If $r < 0$ so that $(a + b) > 1$, the event of forwarding a packet is negative correlated with the event of forwarding of previous packet. If $r = 0$ so that $(a + b) = 1$, the event of forwarding a packet is uncorrelated with the event of forwarding the previous packet.

Similar to Ref. [64], we model the mean and the variance of the number of packets forwarded as follows;

$$m = Np_0 \qquad (2.29)$$

$$s^2 = Np_0(1 - p_0)\frac{(1 + Nq)}{(1 + q)}, \qquad (2.30)$$

where N is the number of packets sent from source and p_0 is the mean success probability of forwarding a particular packet. The parameter q is the so-called correlation level and in our context, it expresses the degree to which the forwarding events are similar in their success behavior. q is related to the pairwise correlation among successive failure events but as it can be seen from Eq. (2.28) it is not the same. We aim to find an analytical expression for q in terms of the conditional probabilities (a, b). In [64], the correlation level is estimated by measuring the actual variance from the test data. In a similar fashion, we estimate q from the actual variance. Let s^2 denote the actual variance. Note that in our context, the parameter s^2 represents the variance of the number of packets forwarded. It can be computed with the following equation;

$$s^2 = \sum_{i=0}^{N} i^2 \Pr(i \quad of \quad N) - m^2 \qquad (2.31)$$

The correlation level q is extracted by the help of the Eq. (2.30). Re-arranging Eq. (2.30) to obtain the expression for the correlation level q,

$$s^2 = Np_0(1-p_0)\frac{(1+Nq)}{(1+q)},$$

$$s^2 + s^2 q = Np_0(1-p_0)(1+Nq)$$

$$s^2 + s^2 q = Np_0(1-p_0) + N^2 p_0(1-p_0)q$$

$$q(N^2 p_0(1-p_0) - s^2) = s^2 - Np_0(1-p_0)$$

$$q = \frac{s^2 - Np_0(1-p_0)}{N^2 p_0(1-p_0) - s^2} \qquad (2.32)$$

In order to find a good approximation for q, s^2 is computed from the exact values of *Pr (i of N)* from the formula given in Section 2.4.1 and a large set of data covering different values of N and p_0 is used. We determine that the correlation level fits to the following formula;

$$q \cong \frac{2}{N}\frac{(1-a-b)}{(a+b)} \qquad (2.33)$$

In order to give a figure of merit for this approximation, let us first discuss the way we have used to find an expression for the correlation level q. In Eq. (2.28), we found the exact correlation of two successive events as $(1-a-b)$. Thus, we anticipated that the correlation level q is somewhat related to the exact correlation, probably in a linear fashion. Therefore, we first plotted the change of the correlation level $\frac{1}{q}$ subject to $\frac{1}{(1-a-b)}$. The q value here is calculated using Eq. (2.32). After doing the calculations for different N and (a, b) values, for all the cases we have surprisingly seen that $\frac{1}{q}$ is almost linearly related to $\frac{1}{(1-a-b)}$ given p_0. Some examples are given in Figure 2.4. Then, the next step is to derive the line equation.

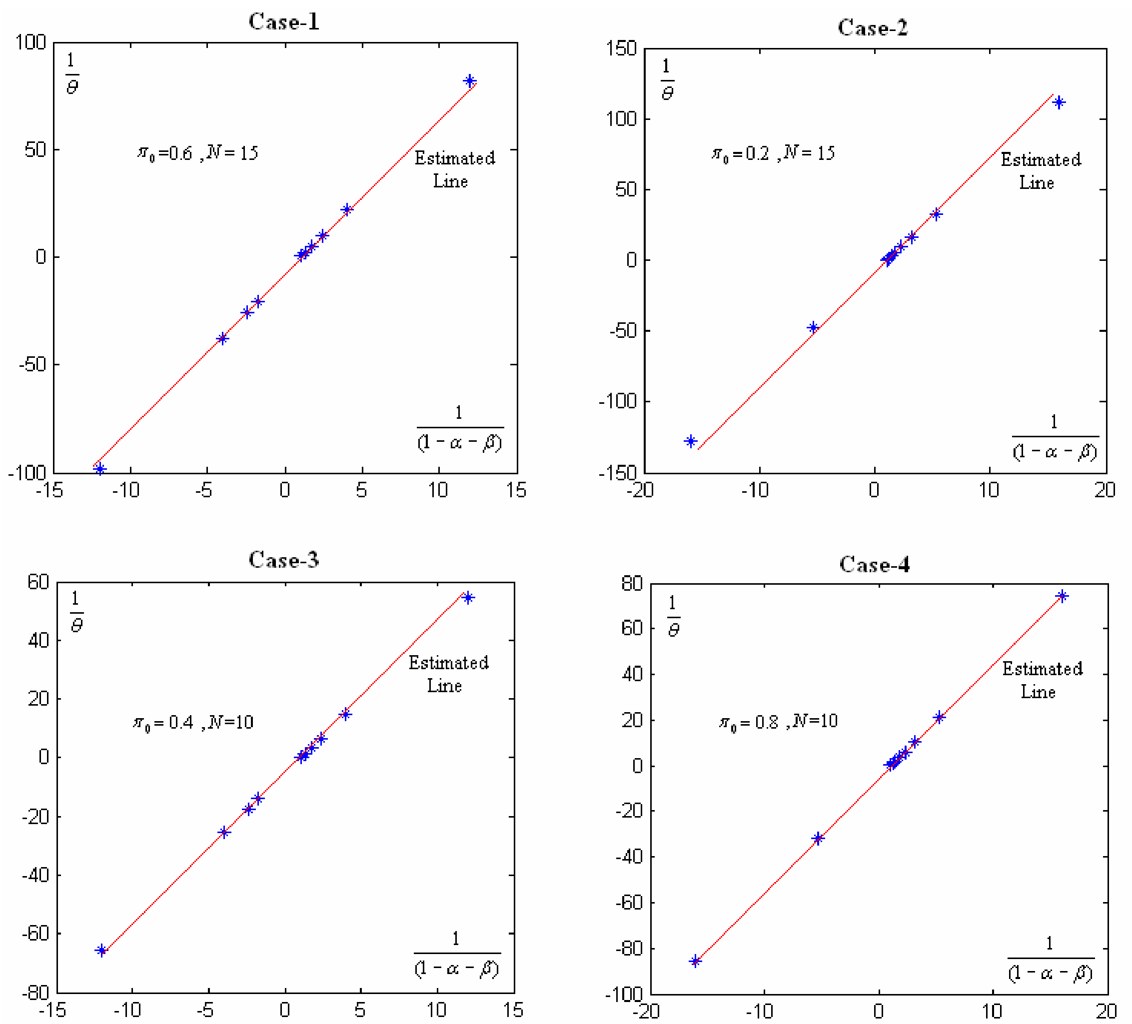

Figure 2.4 Correlation level approximation examples

Generic form of the line equation can be expressed as below:

$\frac{1}{q} = A\left(\frac{1}{1-a-b}\right) + B$, where $A, B \in R, A \neq 0$

Using the calculated points on Figure 2.4 to derive the equation for the estimated line, we find the equations given below:

For Case-1

$$\frac{1}{q} = 7.4988\left(\frac{1}{1-a-b}\right) - 7.9464, \text{ where } N = 15$$

For Case-2

$$\frac{1}{q} = 7.496\left(\frac{1}{1-a-b}\right) - 7.936, \text{ where } N = 15$$

For Case-3

$$\frac{1}{q} = 4.998\left(\frac{1}{1-a-b}\right) - 5.41, \text{ where } N = 10$$

For Case-4

$$\frac{1}{q} = 4.993\left(\frac{1}{1-a-b}\right) - 5.394, \text{ where } N = 10$$

More examples can be given, and we have one much more calculations to support the approximation, but due to the space limitations we give the above four examples. We see that the line equation can be approximated by the formula given below:

$$\frac{1}{q} = \frac{N}{2}\left(\frac{1}{1-a-b}\right) - \frac{N}{2} \qquad (2.34)$$

Re-arranging terms in Eq. (2.34) ,

$$\frac{1}{q} = \frac{N}{2}\left(\frac{1}{1-a-b} - 1\right) = \frac{N}{2}\left(\frac{1-1+a+b}{1-a-b}\right) = \frac{N}{2}\left(\frac{a+b}{1-a-b}\right) \qquad (2.35)$$

By taking the inverse of Eq. (2.35), we find the approximated expression of the correlation level q as given in Eq. (2.33).

$$q \cong \frac{2}{N}\frac{(1-a-b)}{(a+b)} \qquad (2.33)$$

Therefore, the probability that i packets forwarded out of N packets which we define as $P_{success}$ can be well approximated by Beta-Binomial distribution with parameters p_0 and q. Interchangeably, BB distribution can be represented by parameters (a,b). Recall the equations (2.19) and (2.20) which relates the mean and variance of the BB distribution to the parameters of the distribution. From the equations (2.29) and(2.30), the following equations can be extracted;

$$p_0 = \frac{a}{a+b} \qquad (2.36)$$

$$q = \frac{1}{a+b} \qquad (2.37)$$

Note that p_0 and q are related to the Markov parameters (a, b) with the following equations;

$$p_0 = \frac{b}{(a+b)} \qquad (2.38)$$

$$q \cong \frac{2}{N}\frac{(1-a-b)}{(a+b)} \qquad (2.33)$$

As a consequence, probability distribution of forwarding i of N incoming packets is approximated with the BB distribution as follows;

$$b_N(i) = \binom{N}{i}\frac{B(a+i, N+b-i)}{B(a,b)}, \qquad (2.39)(2.33)$$

where $a = \frac{N}{2}\frac{b}{(1-a-b)}$ and $b = \frac{N}{2}\frac{a}{(1-a-b)}$.

Figure 2.5 shows the exact distribution of the probability of forwarding i of N incoming packets versus Beta-Binomial distribution when a =0.3, b =0.2, and N =15. The approximation error is less than 1%.

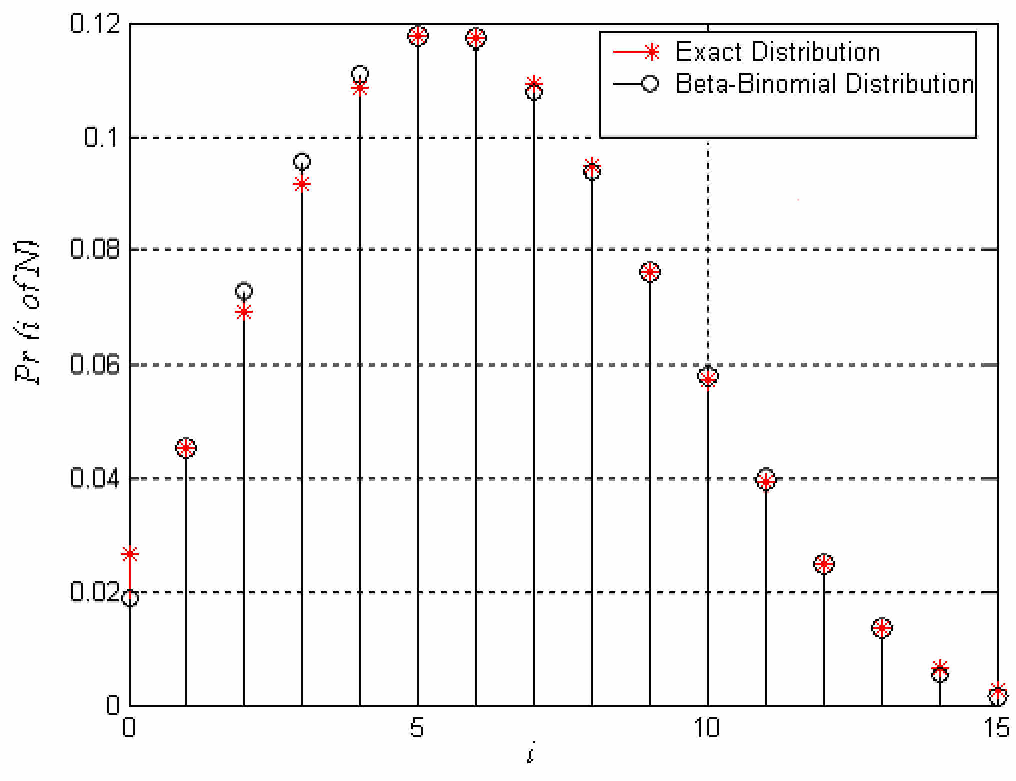

Figure 2.5 Exact Distribution vs Beta-Binomial Distribution

2.5.3. Continuous Approximation of BB Distribution

Since Beta-Binomial (BB) distribution is a discrete distribution, when it is used in an optimization problem, the integrality constraints make the problem harder. We propose that Gaussian distribution is a good continuous approximation for BB distribution. In this approximation, the mean and variance of the BB distribution as defined in Eq. (2.19) and Eq. (2.20) is used as the mean and variance of the Gaussian distribution.

Figure 2.6 compares BB distribution with its Gaussian approximation and depicts Mean Squared Error (MSE) when Gaussian distribution is used instead of BB distribution. As shown in the figure, when for a and b values close to each other, the MSE is approximately zero. Although it increases with increasing difference between

a and b values, MSE remains in the order of 10^{-3}. Thus, continuous Gaussian approximation can be used effectively when the computational complexity prohibits the use of discrete Beta Binomial distribution.

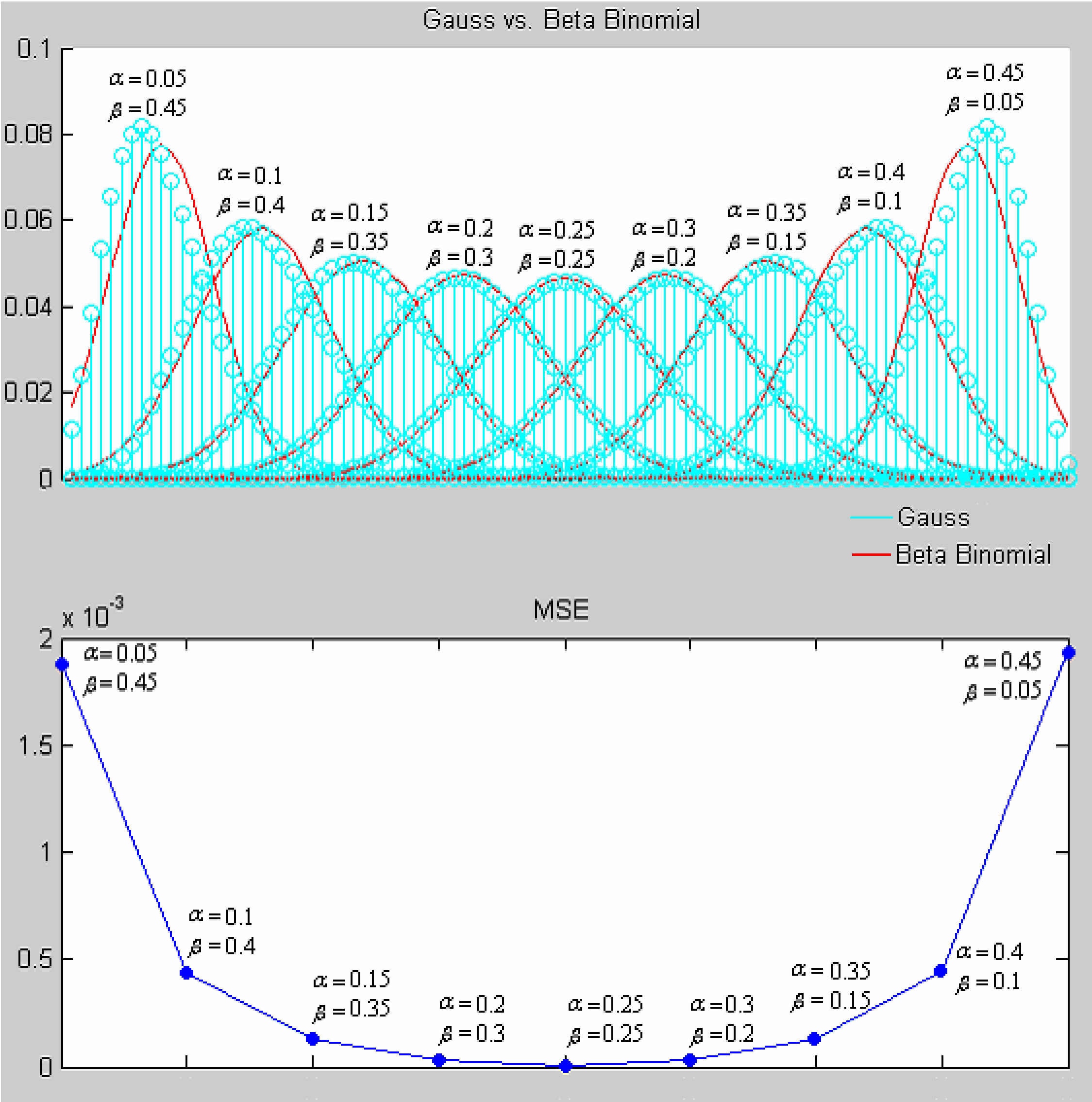

Figure 2.6 Beta Binomial Distribution vs Gauss Distribution

2.6. Summary of the Chapter

In this chapter, firstly we investigate the possible causes of packet losses in mobile wireless ad hoc networks by classifying them according to the reason of the packet loss. We showed that all types of packet loss exhibits temporal correlation. In order to capture this characteristic, we propose a ***First Order Markov Model***. Markovian modeling increases the complexity of network reliability analysis substantially. No closed form analytical expression of network reliability can be obtained. One important contribution of this chapter is the approximation of network reliability by BB distribution.

3. OPTIMAL TRAFFIC ALLOCATION DESIGN

3.1. Problem Definition

The source transmits N packets and the destination needs at least K of the transmitted packets in order to reconstruct the original information. Assume that there are I paths available from a specific source to a destination and N packets will be distributed among these available paths. N_i is the number of packets transmitted on path i and K_i is the number of packets received from path i. Hence, we express network reliability as the probability of receiving at least K packets at the destination, when N packets are sent from the source;

$$\Pr\left(\sum_{i=1}^{I} K_i \geq K \quad where \quad \sum_{i=1}^{I} N_i = N \right) \tag{3.1}$$

In this chapter, our goal is to find the optimal distribution of the N packets among the available paths which maximizes network reliability.

In [55], the authors have considered a similar objective. However, there is an important difference between the path model used in [55] and our path model. The authors in [55], assume that paths are pure erasure channels. A pure erasure channel means that if a particular path fails, it transmits none of the packets allocated to that path and if it does not fail, then it transmits all of the allocated packets. Pure erasure channel assumption implies that the state of the path does not change during the transmission of the allocated packets. However, this assumption does not hold for paths with frequent topological changes, especially if the number of packets allocated to that path is large. In contrast, we model the paths as two state Markov chains where the nodes on the path may fail or become available for transmission. In this more realistic approach, we assume that the state of a path remains the same for the short time interval that elapses for transmission of a single packet, and the state of the path may change between the transmissions of any two successive packets. As a consequence of this approach, a path may relay any number of packets out of the allocated packets. More clearly, according to [55], if the source allocates N_i packets to path i and the destination receives K_i packets out of N_i packets, then there are two possibilities;

i. $K_i = N_i$ with probability p_i

ii. $K_i = 0$ with probability $1 - p_i$,

where p_i is the failure probability of path i.

On the other hand, according to our scheme K_i can be any number between 0 and N_i, including 0 and N_i. Therefore, our model is not restricted to only two possibilities, there are $N_i + 1$ possibilities and each possibility has a different success probability, $\Pr(K_i \quad of \quad N_i)$. Modeling paths as Markov processes instead of pure erasure channels makes a difficult problem much harder.

Additionally, we do not require success probabilities of different paths to be the same. This is more realistic since each path in the network has different characteristics. Recall that, in Section 2.4.2 we model a path with Markov parameters (a_{joint}, b_{joint}). In Section 3.2, we comment on how these Markov parameters can be obtained in a network. Let $\Pr^i(K_i \quad of \quad N_i)$ denote the probability of receiving K_i packets out of N_i packets from path i with Markov parameters (a_i, b_i).

We assume that the route discovery mechanism in the network finds only node-disjoint paths. Therefore, the success probabilities of the paths are independent. Let $R(K_1, K_2, ..., K_I)$ denote the probability that the number of packets received from paths $i = 1,2,..,I$ are exactly $K_1, K_2, ..., K_I$ respectively. $R(K_1, K_2, ..., K_I)$ can be found as follows;

$$R(K_1, K_2, ..., K_I) = \prod_{i=1}^{I} \Pr{}^i (K_i \quad of \quad N_i). \tag{3.2}$$

Then the network reliability can be rewritten in terms of paths' success probabilities as follows;

$$\Pr\left(\sum_{i=1}^{I} K_i \geq K \quad where \quad \sum_{i=1}^{I} N_i = N \right) = \sum_{\forall K_1, K_2, ..., K_I \ni K \leq \sum_{i=1}^{I} K_i \leq N} R(K_1, K_2, ..., K_I) \tag{3.3}$$

where $$0 \leq K_i \leq N_i \tag{3.4}$$

The constraint $\forall K_1, K_2, ..., K_I, \ni K \leq \sum_{i=1}^{I} K_i \leq N$ on summation means that every $K_1, K_2, ..., K_I$ combination satisfying the requirement $K \leq \sum_{i=1}^{I} K_i \leq N$ should be included in the summation.

The problem of finding the optimal distribution of packets among available paths in order to maximize network reliability can be written as an optimization problem as;

Maximize: $$\Pr\left(\sum_{i=1}^{I} K_i \geq K \right) \tag{3.5}$$

Subject to: $$0 \leq K_i \leq N_i \tag{3.6}$$

$$\sum_{i=1}^{I} N_i = N .$$

3.2. Obtaining Markov Parameters

The parameters (a, b) are defined as Markov parameters of our model. Actually, the parameters (a, b) correspond to respectively, failure and success rates of a node/link or path. For a mobile node, (a, b) corresponds to the failure rate and the repair rate (See Section 2.1.1). For an energy saving node, (a, b) corresponds to the rate of entering sleep state and the rate of entering awake state. Recall that the equations (2.12) and (2.13) in Section 2.4.2 shows how the Markov parameters of path i can be computed in terms of the Markov parameters of the nodes on the path i. We assume that failure and success rates of the nodes/links or alternatively failure and success rates of the paths are supplied to our optimal traffic allocation module. Failure and success rates may be predetermined (i.e. sleep/awake schedule of the nodes) or they may be obtained by a kind of network measurement mechanism and updated periodically. The job of network measurement may be dedicated to a single module or there may be a distributed measurement mechanism that runs on each node.

Network measurement mechanism should collect statistical information throughout the network and update the failure and success rates periodically. There are many routing protocols which are based on network measurements. For example, Signal Stability-Based Adaptive Routing (SSA) [82] uses the measurements on signal strength and stability of individual hosts as route selection criteria. Signal strength and stability information is obtained by the help of the extended device driver interface and the beacons which are “I am alive” messages that are exchanged between wireless devices at regular intervals. Similarly, in Associativity-Based Routing (ABR) [83] the optimal route is selected based on the link stability. Each node has an association which shows node’s connectivity with its neighbors. Node’s association with its neighbors change as it moves and its transition period can be measured by associativity ticks.

In Ref. [21], the probability that a wireless link exists between two mobile nodes at time $t_0 + t$ given that the link exists at time t_0 is analytically expressed in terms of the mobility profiles and transmission ranges of the nodes. On the other hand, probing mechanisms as in Ref. [84] can be used to measure the activity of the ad hoc nodes. Marti et. al. in [85] proposed two network monitoring mechanisms; watchdog and pathrater in order to mitigate the effect of misbehaving nodes in the network. It is assumed that ad hoc nodes have wireless interfaces that supports promiscuous mode. Watchdog mechanism runs on each node and listens the next node's transmissions in order to detect misbehaving nodes. Pathrater is a mechanism which rates the nodes according to the observed activities of the nodes. When nodes become known to the pathrater mechanism, it assigns "neutral" ratings to the nodes. At periodic intervals pathrater mechanism increases the ratings of the nodes in all actively used paths. Nodes' ratings are decreased when a link failure is detected or node becomes unreachable.

As a consequence, there are promising mechanisms offered in the literature in order to measure the metrics of nodes and paths in the network. However, the actual implementation of the mechanism which provides these metrics is beyond the scope of this thesis.

3.3. Optimization of Traffic Allocation

In this section we propose a solution to the optimization problem defined in Section 3.1. Recall that K_i is the number of packets received from path i. Let $\overline{K}$ be a vector with I elements and each element, K_i represents the number of packets received from path i, where $i = 1,...,I$. In order to illustrate Eq. (3.3) better, let us classify the possible $\overline{K}$ vectors into N sets according to the total number of packets received at the destination. Accordingly, the set S_m is defined as the set of $\overline{K}$ vectors satisfying (3.7).

$$\sum_{i=1}^{I} K_i = m \tag{3.7}$$

Therefore, the Eq. (3.4) can be rewritten in terms of S_m as follows;

$$\Pr\left(\sum_{i=1}^{I} K_i \geq K \quad where \quad \sum_{i=1}^{I} N_i = N \right) = \sum_{m=K}^{N} \sum_{\forall \overline{K} \in S_m} R(\overline{K})$$

where

$$R(\overline{K}) = \prod_{i=1}^{I} \Pr^i \left(K_i \quad of \quad N_i \right) \tag{3.8}$$

The inner summation $\sum_{\forall \overline{K} \in S_m} R(\overline{K})$ represents the probability that the total number of packets received at the destination is m. This probability is equal to the sum of the product of the individual probabilities of values $K_1, K_2, ..., K_I$ that sum to m.

Consider two independent random variables x_1 and x_2 with the corresponding probability distributions f_1 and f_2. The probability of their sum being m can be found by convolving the probability distributions f_1 and f_2 as follows;

$$\Pr(m) = \sum_{k=-\infty}^{\infty} f_1(m-k) f_2(k) \tag{3.9}$$

Therefore, the probability distribution of the total number of packets received at the destination is the convolution of the probability distributions of individual paths. Let $f_i(k)$ denote the probability distribution of the number of packets received from path i and f_{total} denote the probability distribution of the total number of packets received at the destination, then the following relation holds;

$f_{total} = f_1(k) * f_2(k) * ... * f_I(k)$, where '*' represents the convolution operation.

In Section 2.5.2, we have approximated the probability distribution of the number of packets received from path i by Beta-Binomial (BB) distribution. Unfortunately, the convolution of BB distributions does not converge to a known distribution. Moreover, when BB distribution is used, the optimization problem defined in Eq. (3.3) becomes a "harder" problem because of the nonlinearity of the objective function and the integrality of K_i and N_i. However, there are some solution techniques that can be use to solve special cases of the problem [86].

In this thesis, we aim to obtain an accurate and approximate solution in a fast manner, so we relax the integrality requirements on the variables K_i and N_i and approximate the probability distribution of the number of packets received from path i by Gaussian distribution instead of BB distribution. Continuous relaxation technique is widely used in the literature [55], [86], [87] and in Section 2.5.3, we show that the Gaussian approximation is appropriate to be used instead of BB distribution. Thus, the probability distribution of the total number of packets received at the destination, f_{total} is the convolution of I Gaussian distributions. Given I independent Gaussian probability density functions, $G_i = g\left(k; m_i, s_i^{\,2}\right)$ it can be shown that the convolution of these probability density functions is also a Gaussian probability density function $G = g\left(k; m, s^{\,2}\right)$ with mean $m = \sum_{i=1}^{I} m_i$ and variance $s^{\,2} = \sum_{i=1}^{I} s_i^{\,2}$.

Thus, the probability density function of the number of packets received at the destination when N packets are sent is approximated by $g\left(k; m, s^{\,2}\right)$. The probability that at least K packets are received at the destination, when N packets are sent can be found by integrating the probability density function from K to N. As a consequence, the Eq. (3.8) can be approximated as follows;

$$\Pr\left(\sum_{i=1}^{I} K_i \geq K \quad where \quad \sum_{i=1}^{I} N_i = N\right) = \int_{k=K}^{N} g(k; m, s\,)dk \tag{3.10}$$

$$= \frac{1}{2}\left(erf\left(\frac{N-m}{\sqrt{2}s}\right) - erf\left(\frac{K-m}{\sqrt{2}s}\right)\right),$$

where error function is defined as;

$$erf(x) = \frac{2}{\sqrt{p}} \int_0^x e^{-t^2}\, dt \qquad (3.11)$$

Now, let us express the parameters (m, s^2) in terms of the paths' success and failure rates, (a_i, b_i), the number of packets received from each path, K_i and the number of packets sent over each path, N_i.

$$m_i = N_i p_0^{\,i} \qquad (3.12)$$

$$s_i^{\,2} = N_i p_0^{\,i}\left(1 - p_0^{\,i}\right)\left(\frac{1 + N_i q_i}{1 + q_i}\right), \qquad (3.13)$$

where

$$p_0^{\,i} = \frac{a_i}{a_i + b_i} \qquad (3.14)$$

$$q = \frac{2}{N_i}\frac{(1 - a_i - b_i)}{(a_i + b_i)} \qquad (3.15)$$

Let us denote the product $q_i N_i$ by X_i and rewrite $s_i^{\,2}$;

$$q_i N_i = \frac{2(1 - a_i - b_i)}{(a_i + b_i)} \equiv X_i \qquad (3.16)$$

$$s_i^{\,2} = N_i \Pi_i (1 - \Pi_i)\left(\frac{1 + X_i}{1 + \frac{X_i}{N_i}}\right) \qquad (3.17)$$

The problem can be written and solved for any X_i. Due to the space limitation, let us consider the special case where $N_i >> X_i$ and approximate $s_i^{\,2}$ as follows;

$$s_i^{\,2} = N_i \Pi_i (1 - \Pi_i)(1 + X_i) \equiv N_i C_i \qquad (3.18)$$

Note that in Eq. (3.19), C_i is a constant with respect to N_i. Thus, m and s^2 simplify to

$$m = \sum_{i=1}^{I} N_i \frac{a_i}{a_i + b_i} \quad (3.20)$$

$$s^2 = \sum_{i=1}^{I} N_i C_i \quad (3.21)$$

Consequently, we obtain from the optimization problem defined in Eq. (3.3), the following continuous, nonlinear optimization problem.

Maximize: $$\frac{1}{2}\left(erf\left(\frac{N-m}{\sqrt{2}s}\right) - erf\left(\frac{K-m}{\sqrt{2}s}\right)\right) \quad (3.22)$$

Subject to: $$\sum_{i=1}^{I} N_i = N,\ 0 \le K_i \le N_i \quad (3.23)$$

This problem can be solved numerically by appropriate techniques of nonlinear optimization. Numerical solution of this optimization problem gives real values for $N_1, N_2, ..., N_I$. Since only integer solutions are meaningful for our application, a rounding technique should be used. We propose such a rounding strategy; if $N_i < 1$, round it to 0, if $N_i \ge 1$, round it to the closest integer. If all the rounded N_i values are equal and the constraint is not satisfied, increase one of them by 1.

3.4. Numerical Results

We have proposed a method for approximating the path reliability in Chapter 2. In Section 3.1, we stated an optimization problem that maximizes the probability of receiving at least K of N packets at the receiving node and in Section 3.3 we showed that this optimization problem can be solved by numerical methods. Here we give some numerical results to support the proposed model. In order to obtain analytical results, we define the problem as a nonlinear optimization problem in Matlab 6.0 [88]. Matlab solves nonlinear equations by least squares method. We use “fsolve” command of

Matlab which uses the Quasi-Newton algorithm. Simulations are done by Opnet Modeler 10.0 [89]. Detailed information about simulation environment and network model is given in Chapter 5 where some more simulation results are discussed. Simulation network topology is given in Figure 3.1.

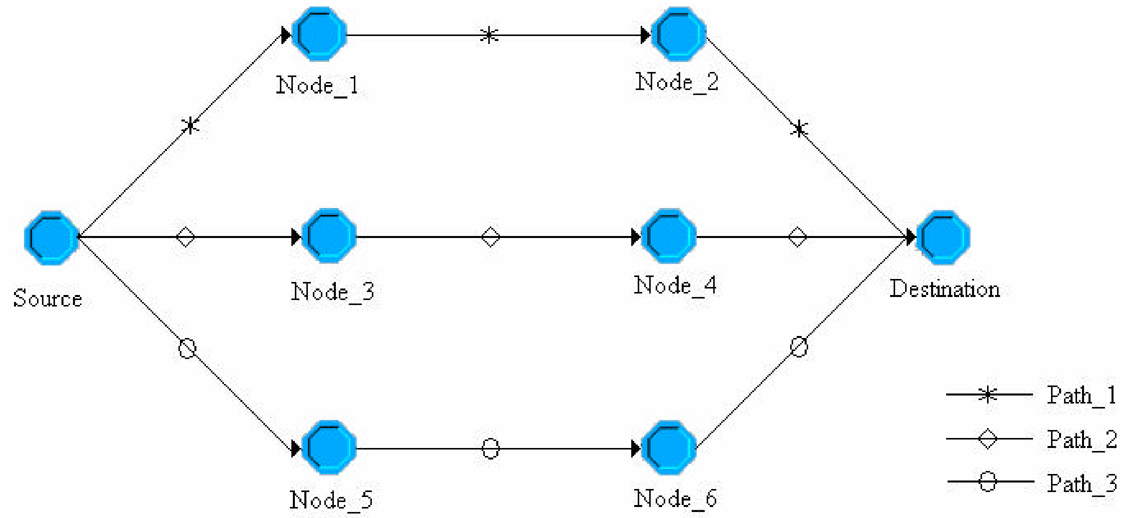

Figure 3.1 Simulation network topology

The two scenarios discussed below expose the behavior of the model whether it can successfully approximate reliability of a path or not and whether it can successfully approximate the probability of receiving at least *K* of *N* packets at the receiving node. Node parameters and path parameters for the first scenario are given in Table 3.1 and Table 3.2 correspondingly.

	Alpha	Beta	P0	P1
Node_1	0.05	0.45	0.9	0.1
Node_2	0.05	0.45	0.9	0.1
Node_3	0.1	0.1	0.8	0.2
Node_4	0.1	0.1	0.8	0.2
Node_5	0.15	0.35	0.7	0.3
Node_6	0.15	0.35	0.7	0.3

Table 3.1 Node parameters for the first scenario

	$Alpha^{Path}$	$Beta^{Path}$	$P0^{Path}$	$P1^{Path}$
Path_1	0.0975	0.4157	0.81	0.19
Path_2	0.1900	0.3378	0.64	0.36
Path_3	0.2775	0.2666	0.49	0.51

Table 3.2 Path parameters for the first scenario

Success probabilities of receiving at least K = 65 packets of 100 packets are given in Figure 3.2. We see that the analytical probability values and the simulation results are similar.

Moreover, simulation results support our mathematical model. After solving the optimization problem numerically, "$N1$ = 100, $N2$ = 0, $N3$ = 0" is found as the optimum distribution of 100 packets among three paths. It was not feasible to perform the simulation for each of the possible packet distribution for the sake of computational time. We choose 10 different alternatives to compare the results with the optimum selection. Simulation results show that there is no better path alternative to obtain a better success probability.

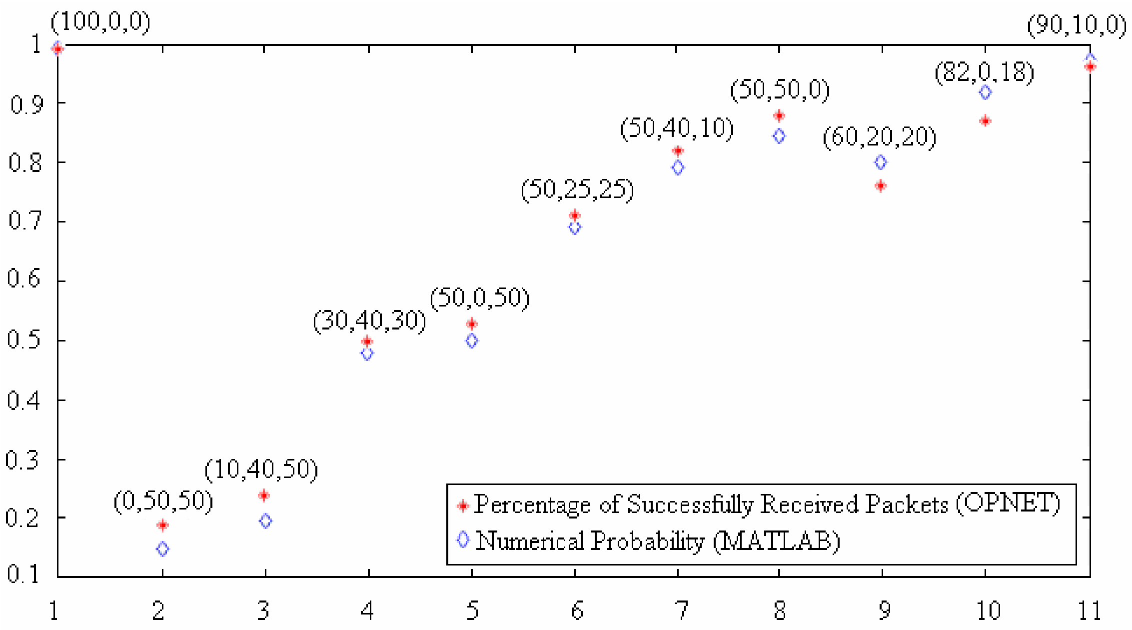

Figure 3.2 Probability of receiving *K* = 65 out of 100 packets

Node parameters for the second scenario are given in Table 3.3, and path parameters for the second scenario are given in Table 3.4.

	Alpha	Beta	P0	P1
Node_1	0.015	0.185	0.9250	0.0750
Node_2	0.03	0.37	0.9250	0.0750
Node_3	0.015	0.185	0.9250	0.0750
Node_4	0.03	0.37	0.9250	0.0750
Node_5	0.0488	0.1178	0.7071	0.2929
Node_6	0.0488	0.1178	0.7071	0.2929

Table 3.3 Node parameters for the second scenario

	$Alpha^{Path}$	$Beta^{Path}$	$P0^{Path}$	$P1^{Path}$
Path_1	0.0446	0.2640	0.8555	0.1445
Path_2	0.0446	0.2640	0.8555	0.1445
Path_3	0.0953	0.0953	0.5	0.5

Table 3.4 Path parameters for the second scenario

Success probabilities of receiving at least *K* = 60 packets of 100 packets are given in Figure 3.3. "*N1* = 46, *N2* = 46, *N3* = 8" is found as the optimum distribution of 100 packets among three paths. Simulation results show that there is no better path alternative to obtain a better success probability. On the other hand, "*N1* = 50, *N2* = 50, *N3* = 0" is an example of a different alternative that also has a high probability of receiving at least *K* = 60 packets of 100 packets. This shows that there may be distributions different than the optimum distribution that has acceptably high probability. However, the optimum distribution found by the model is theoretically the best one to use.

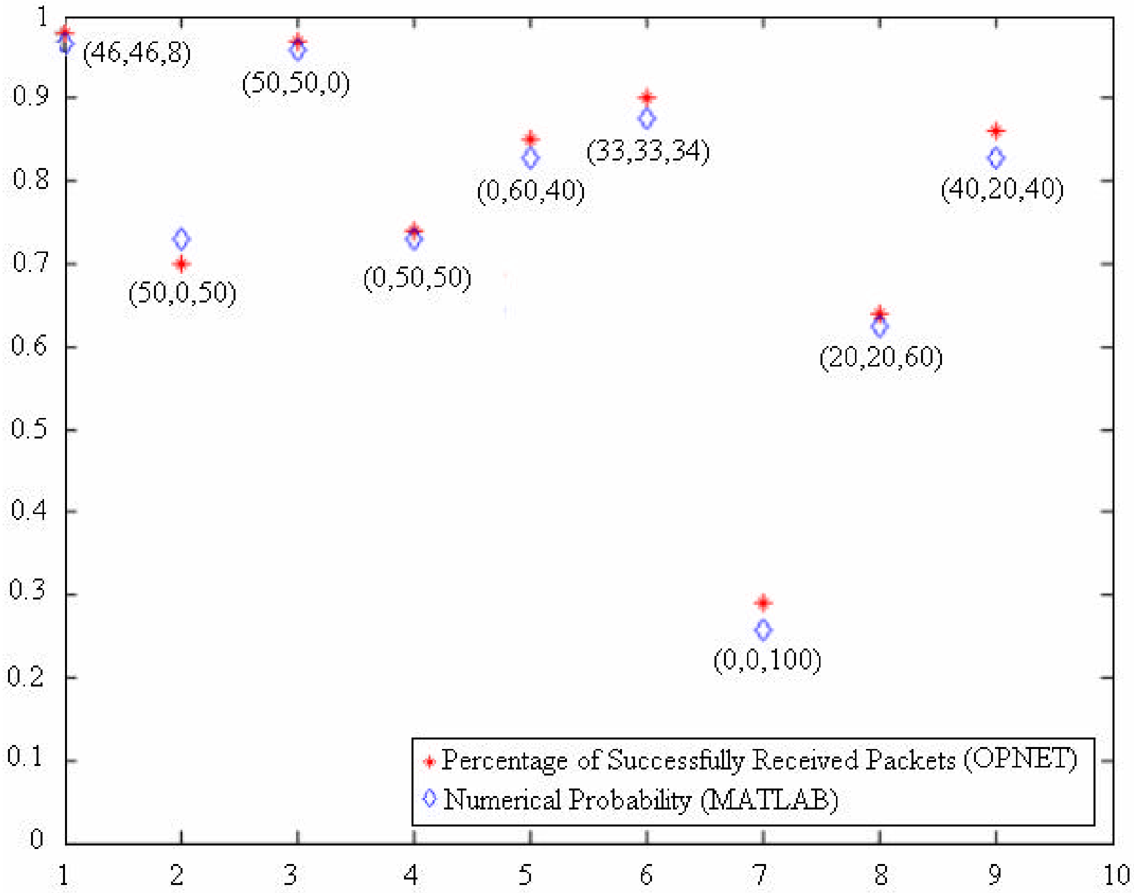

Figure 3.3 Probability of receiving *K* = 60 of 100 packets

3.5. Summary of the Chapter

In this chapter, we proposed a strategy that distributes the packets among multiple disjoint paths in order to maximize the network reliability. Given the failure statistics of the paths, our strategy utilizes the available paths or a subset of these paths in an effective manner. Simulation results justify the accuracy and effectiveness of our scheme.

4. SLEEP/AWAKE SCHEDULE DESIGN FOR WIRELESS NODES

4.1. Introduction

Wireless networks are usually composed of battery-powered nodes and it is of primary importance to extend their battery lifetime. In wireless nodes, the main sources of energy consumption are CPUs, and radio transceivers. It is known that most of the time nodes remain idle, i.e., do not process or transmit/receive information. However, in these idle instances nodes continue to consume and thus, waste significant amount of energy. It is a widely accepted approach to put the nodes into *sleep* mode, where the CPU and transceiver are turned off or put into low energy consuming mode.

Although considerable energy can be saved by placing individual nodes into sleep mode, this approach creates connectivity problems in networks consisting of such nodes. When a node is in sleep mode, the node will be unavailable for relaying packets and this may result in increased latency and packet loss. Previous work has addressed some of the issues arising in such networks. For example, [36] offers a new topology management scheme called STEM, which allows designers to trade off between different QoS metrics including energy, latency, and density. Ref. [77] explores the relationship between the added deployment redundancy and the amount of reduction in percentage of awake times for both coordinated and uncoordinated sleep schedules. Chiasserini et. al. in [32] investigates the energy consumption and latency by modeling dynamics of a sensor network with Markov model. Ref. [38] uses a Markov model with six states in order to predict the energy consumption of a sensor node and consequently construct the energy map of the sensor network.

In this study, we analyze the relation between the packet delay and the sleep/awake schedules. We define sleep/awake schedule as the set of time intervals over which the node remains *ON* and *OFF*. Consequently, we determine the conditions on the sleep/awake schedule that minimizes the energy consumption while minimizing the packet drop probability. Note that this relationship can be interpreted as the trade-off between the QoS requirement and energy consumption in battery operated nodes.

4.1.1. Sleep Awake Strategies

When each node in a network has a sleep/awake schedule, we define the collection of all schedules the *network sleep/awake strategy*. The network sleep/awake schedules vary with the kind of wakeup mechanism used to keep adjacent nodes connected. References [72] and [73] categorize existing wakeup mechanisms and discuss the limitations of each category. According to [72] and [73], existing wakeup mechanisms fall into three main groups; synchronous, asynchronous and on-demand. In synchronous wakeup mechanisms, all communicating nodes in the network have the same periodic sleep/awake schedule. Clocks of all nodes should be synchronized so that they wake up at the same time to communicate with each other. For example, power saving mode of IEEE 802.11 uses synchronous wakeup mechanism. However, IEEE 802.11 is designed for single hop or fully connected networks and when it is applied to multihop networks, three problems; clock synchronization, neighbor discovery, and network partitioning arise [74].

On the other hand, asynchronous wakeup strategy does not require clock synchronization. In asynchronous approach, each node has its own sleep/awake schedule and goes to sleep independently. However, the problem with asynchronous approach is the fact that the intervals the neighboring nodes are awake may never overlap and thus these nodes may never be able to communicate. In [74], asynchronous power-saving protocols are proposed for IEEE 802.11-based, multi-hop ad hoc networks. The idea behind their protocols is to arrange the sleep/awake schedules of nodes such that any two neighboring nodes are guaranteed to detect each other in finite time. In [72], asynchronous wakeup mechanism is proposed with the constraint that the schedules of any two neighboring nodes overlap by *m* slots.

Finally, in on-demand wakeup mechanisms, nodes sleep until they receive an out-of-band wakeup signal. This is achieved by using a low power wakeup radio in addition to the data radio. Since wakeup radios consume extremely low energy compared to data radios, they can always stay awake. For example, Ref. [75] proposes "wake-on-wireless" technique which uses a separate wakeup channel which has frequency band different from the data channel. A similar approach proposed in [76], uses a low power radio working on Radio Frequency Identifier (RFID) technology. These kinds of mechanisms have a limitation that low power wakeup radios usually have smaller transmission ranges compared to data radios. Consequently, a node may be in transmission range of the other node's data radio while being out of the transmission range of the same node's wakeup radio.

The coordination of the sleep/awake schedules of sensor nodes by one of the strategies explained above are needed to improve network service quality such as packet delivery delay stemming from sleep periods. However, such coordination results in higher implementation complexity, computational and messaging overhead. On the other hand, the extreme approach is to allow nodes to have independent sleep/awake schedules at a cost of increased latency. Dousse et. al. in [33] showed that the latency of a message have an acceptable bound even when the sleep/awake schedules are uncoordinated and the number of awake nodes at any particular time is very low. Thus, motivated by this result, in this thesis, we assume that there is no coordination among nodes and asynchronous sleep/awake strategy is employed.

When we consider sleep/awake schedule design, another important consideration is to design periodic or aperiodic schedules. Periodic sleep/awake schedule is preferred in sensor networks as shown in [26], and [36]. Periodic sleep/awake schedule means that the durations of sleep/awake states are constant. On the other hand the durations of sleep/awake states may be aperiodic and more specifically with geometrically distributed sleep and awake intervals as assumed in [32], [33], and [77]. Both schedule types are illustrated in Figure 4.1. In this thesis, we concentrate on the design of aperiodic and geometrically distributed sleep/awake schedules.

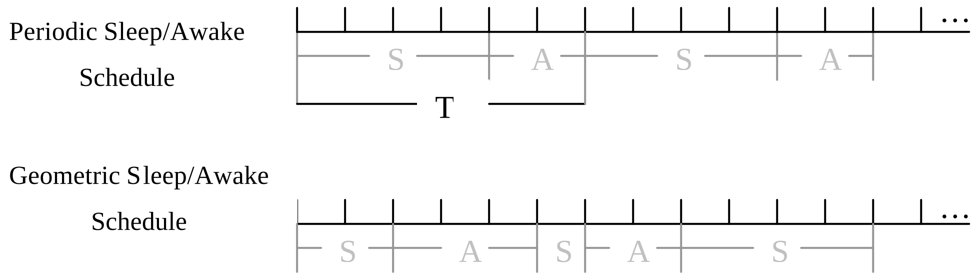

Figure 4.1 Periodic vs Geometric Sleep/Awake Schedule

4.1.2. Different Modes of Operation

A typical sensor node has four main energy consuming modules; processor, memory, sensing unit and radio. Each of these modules may be turned off during their idle periods in order to save energy. As a result, a power-aware sensor node model can be designed with different sleep states, where each state corresponds to a combination of different sleeping modules. For example, in one case, memory, processor and radio may be on while the sensing unit is off. Ref. [34] proposes five different feasible sleep states with increasingly deeper sleeps, i.e., more modules turned off when idle. Each state corresponds to a different level of power consumption such that more the number of sleeping modules, higher the energy saving. A sensor node's primary job is to sense its environment, process its readings and forward them to the sink. In addition, it acts as a relay by forwarding the traffic from other sensor nodes. In [78], power consumption during each task of a sensor node; sensing, processing, and communication are analyzed in detail. The authors in [78] claim that in terms of power consumption, wireless communication is the dominating factor among them. Ref. [79] states the same claim with the following example: it costs 3 Joules of energy to transmit 1Kb of data to a distance of 100 meters while a processor with 100 MIPS/W processing capability executes 3 million instructions for the same amount of energy.

In this thesis, we consider a network in which passive sensors that consume negligible power compared to other components of sensor node and are used together with ultra low power microprocessors. Therefore, for the sake of simplicity we neglect all of the sleep states other than the one in which all of the modules are off.

4.2. System Model

In our node model, there are two states: ***OFF*** state in which all the modules are off and ***ON*** state in which all the modules are ***OFF.*** Longer the overall time spent in sleep state, higher the energy saving is. Compared to a node which is always awake, the energy saving of a sensor node with two states; namely ***ON*** and ***OFF*** and a periodic sleep/awake schedule is;

$$E_s = \frac{T_{off}}{T} \qquad (4.1)$$

where T_{off} is the duration of the sleep state and T_{on} is the duration of the awake state and $T = T_{on} + T_{off}$.

Time is divided into equal length intervals called slots, where slot duration is equal to the transmission time of one packet so that exactly one packet is transmitted in each slot.

Assume a node has a battery lifetime of L_b slots, when it is always in ON state. If the node performs a sleep/awake strategy with energy saving E_s, then the lifetime of the node, L extends to $L = \frac{L_b}{E_s}$ slots. Let T be the duration of one sleep/awake period, i.e., $T = T_{on} + T_{off}$. Note that $\frac{T_{on}}{T} = \frac{t_{on}}{t}$ where t_{on} and t are integers and the fraction $\frac{t_{on}}{t}$ cannot be further simplified. We can write the following relation;

$$L = kT \text{, where } 2 \le k \le \frac{L}{t} \tag{4.2}$$

and let k be an integer selected such that T is always an integer. Each meaningful value of k corresponds to a different sleep/awake pattern with the same amount of energy saving ratio.

For example, a node with 50% energy saving ratio and $L = 16$ slots lifetime may have ($\frac{T_{on}}{T} = \frac{t_{on}}{t} = \frac{1}{2}$) three meaningful k values which are 2, 4, 8 and accordingly three different sleep/awake patterns which are shown in Figure 4.2.

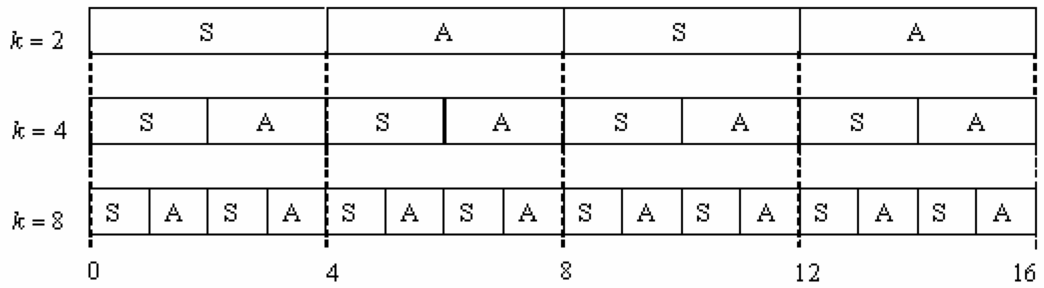

Figure 4.2 Different sleep/awake patters with the same energy saving ratio

Packet delay is an important QoS metric in most of the sensor network applications. In this chapter, we use packet delay as the QoS metric and redefine $P_{success}$ as follows: Let $P_{success}$ be the probability of forwarding at least K packets in N consecutive time slots.

Consider the example given above with the following QoS constraint;

$$P_{success} = \Pr(at \quad least \quad 2 \quad packets \quad in \quad 4 \quad slots) = 1$$

In other words, in every 4-consecutive-slots during the node's lifetime (which is $L = 16$ slots), at least 2 packets should be forwarded. The first sleep/awake pattern ($k = 2$) in Figure 4.2 does not satisfy the given QoS requirement, whereas both the second ($k = 4$) and the third ($k = 8$) sleep/awake schedule satisfy the given QoS requirement. Note that the third schedule requires more state transitions. Each state transition may have a cost in terms of both delay and energy, so the second schedule may be better to be employed.

4.3. Optimization of Sleep/Awake Schedule

We assume that the wireless network is composed of nodes, which switch between sleep (***ON***) and awake (***OFF***) states. We model the wireless node as a two state Markov chain in a similar fashion as done in Section 2.2.1. Now let us show how these parameters relate to the sleep/awake schedule design.

As a result of Markov property, the duration of the sleep state is geometrically distributed with mean $\frac{1}{b}$ and the duration of the awake state is geometrically distributed with mean $\frac{1}{a}$. Energy saving of the node, E_s can be defined similar to Eq. (4.1) as;

$$E_s = \frac{E[T_{off}]}{E[T_{off}] + E[T_{on}]} = \frac{\frac{1}{b}}{\frac{1}{b} + \frac{1}{a}} = \frac{a}{a+b} = (1 - p_0) = p_1 \tag{4.3}$$

Recall that in Section 2.4.1, we defined the reliability of a node, ($P_{success}$) as the probability of forwarding at least K of N incoming packets. Exact analytical expression of $P_{success}$ is derived in Section 2.4.1 and $P_{success}$ is well approximated by Beta-Binomial (BB) distribution in Section 2.5.2. Although we redefine $P_{success}$ in terms of packet delay, results obtained in Section 2.5.2 can be used with the assumption that exactly one packet is transmitted in each slot.

Pr(at least K packets in N consecutive slots)= $\sum_{i=K}^{N} \binom{N}{i} \frac{B(a+i, N+b-i)}{B(a,b)}$, where

$$a = \frac{N}{2}\frac{b}{(1-a-b)} \text{ and } b = \frac{N}{2}\frac{a}{(1-a-b)}.$$

The optimization problem is stated as below;

Maximize: $$\sum_{i=K}^{N} \binom{N}{i} \frac{B\left(\frac{Nb}{2(1-a-b)} + i, N + \frac{Na}{2(1-a-b)} - i\right)}{B(a,b)} \quad (4.4)$$

$$E_s = \frac{a}{a+b} \quad (4.5)$$

Subject to: $0 < a < 1$, $0 < b < 1$

BB distribution makes the optimization problem harder to solve. In order to have a quick insight, we approximate BB distribution by Gaussian distribution. Similar to Section 2.5.2, mean and variance of the BB distribution are used as the mean and variance of the Gaussian distribution. Since Gaussian distribution is continuous, the summation in Eq. (4.4) shall be approximated by an integral. The objective function in Eq. (4.4) can be re-written as follows;

Maximize: $$\int_{k=K-\frac{1}{2}}^{\infty} \frac{1}{\sqrt{2p}\, s} e^{-\frac{(k-m)^2}{2s^2}} dk = 0.5 + 0.5 erf\left(\frac{m - K + \frac{1}{2}}{\sqrt{2}s}\right) \quad (4.6)$$

We subtracted $\frac{1}{2}$ from the lower bound of the integral since when approximating a discrete distribution by a continuous distribution, considering continuity correction gives better approximation [55].

We want to find the optimal ($E[T_{on}], E[T_{off}]$) pair that

$$\text{Maximize:} \qquad P_{success} = 0.5 + 0.5 erf\left(\frac{m - K + \frac{1}{2}}{\sqrt{2}s} \right) \tag{4.7}$$

$$E_s = \frac{a}{a+b}, \tag{4.8}$$

$$\text{Subject to:} \qquad 0 < a < 1,$$

$$0 < b < 1$$

As defined in Eq. (4.3), $E_s = p_1$ and given E_s, we can compute $p_0 = 1 - p_1$ and the following relation;

$$\frac{1-E_s}{E_s} = \frac{b}{a} \tag{4.9}$$

$$b = \frac{1-E_s}{E_s} a \tag{4.10}$$

Let us denote $\frac{1-E_s}{E_s}$ by m and rewrite m, q, s and in terms of a and m;

$$m = N \frac{m}{(m+1)} \tag{4.11}$$

$$q = \frac{2}{N} \frac{(1-(m+1)a)}{(m+1)a} \tag{4.12}$$

$$s^2 = N^2 \frac{m}{(m+1)^2} \frac{2-(m+1)a}{2+(N-2)(m+1)a} \tag{4.13}$$

$$s = N \frac{\sqrt{m}}{(m+1)} \left(\frac{2-(m+1)a}{2+(N-2)(m+1)a} \right)^{1/2} \tag{4.14}$$

Remember that, according to the fundamental theorem of calculus combined with the chain rule, if *f(x)* is continuous on [*a*, *b*], *u*(*x*) is differentiable on [*a*, *b*], and *F(x)* is defined as;

$$F(x) = \int_{a}^{u(x)} f(t)dt \text{, then}$$

$$\frac{dF(x)}{dx} = f(u(x))\frac{du(x)}{dx}$$

Let us calculate the derivative of $P_{success}$ according to a , in order to find the optimum pair (a , ma).

$$\frac{dP_{success}(a)}{a} = \frac{d}{da}\left(\frac{m-K+\frac{1}{2}}{\sqrt{2}s}\right)e^{-\frac{(m-K)^2}{2s^2}} \qquad (\ 4.15.1\ )$$

$$\frac{d}{da}\left(\frac{m-K+\frac{1}{2}}{\sqrt{2}s}\right) = \frac{d}{ds}\left(\frac{m-K+\frac{1}{2}}{\sqrt{2}s}\right)\frac{ds}{da} \qquad (\ 4.15.1\ )2\ )$$

$$\frac{d}{da}\left(\frac{m-K+\frac{1}{2}}{\sqrt{2}s}\right) = \left(\frac{-\left(m-K+\frac{1}{2}\right)}{\sqrt{2}s^{\ 2}}\right)\left(\frac{N\sqrt{m}}{2(m+1)}\left(\frac{2-(m+1)a}{2+(N-2)(m+1)a}\right)^{-\frac{1}{2}}\left(-\frac{2(m+1)(N-1)}{\left(2+(N-2)(m+1)a\right)^2}\right)\right) \qquad (\ 4.15.1\ ).3\ )$$

$$\frac{d}{da}\left(\frac{m-K+\frac{1}{2}}{\sqrt{2}s}\right) = \left(\frac{\left(m-K+\frac{1}{2}\right)}{2\sqrt{2}}\frac{(m+1)}{N\sqrt{m}}2(m+1)(N-1)\right)\left(\left(\frac{1}{2-(m+1)a}\right)^{\frac{3}{2}}\left(\frac{1}{\left(2+(N-2)(m+1)a\right)}\right)^{\frac{1}{2}}\right) \qquad (\ 4.15.1\ ).4\ )$$

$$\frac{dP_{success}(a)}{a} = \left(\frac{\left(m-K+\frac{1}{2}\right)}{2\sqrt{2}}\frac{(m+1)}{N\sqrt{m}}2(m+1)(N-1)\right)\left(\left(\frac{1}{2-(m+1)a}\right)^{\frac{3}{2}}\left(\frac{1}{\left(2+(N-2)(m+1)a\right)}\right)^{\frac{1}{2}}\right)e^{-\frac{(m-K)^2}{2s^2}} \qquad (\ 4.15.1\ )5\ )$$

Expression above shows that $P_{success}$ does not have any local or global maxima, but three inferences can be extracted from the expression for $N > 1$;

- If $K = m + \frac{1}{2}$, $\frac{dP_{success}(a)}{a} = 0$, thus $P_{success}$ is independent of a .
- If $K > m + \frac{1}{2}$, $\frac{dP_{success}(a)}{a} < 0$, thus $P_{success}$ is a decreasing function of a .
- If $K < m + \frac{1}{2}$, $\frac{dP_{success}(a)}{a} > 0$, thus $P_{success}$ is an increasing function of a

Let us interpret these mathematical inferences in our model. Parameter m corresponds to the expected number of packets received when N packets are sent through a node with ***ON*** state probability p_0. Parameter a corresponds to the inverse of the mean duration of ***ON*** state, $E[T_{on}]$.

- If we want to maximize the probability that a node forwards more than the expected number of packets, the mean durations of ***ON*** state and ***OFF*** state of that node should be designed as large as possible.
- If we want to maximize the probability that a node forwards less than the expected number of packets, the mean durations of ***ON*** state and ***OFF*** state of that node should be designed as small possible.
- If we want to maximize the probability that a node forwards exactly expected number of packets, any selection on the mean durations of ***ON*** state and ***OFF*** state works.

These points are demonstrated in numerical studies given in the following section.

4.4. Numerical Results

Figure 4.3 shows the variation of $P_{success}$ with respect to the inverse of $E[T_{on}]$ for a node saving 50% energy, i.e., sleeps 50% of the time. The number of packets sent, N, is 15, and the expected number of packets received, m is 7.5.

As shown in Figure 4.3, for $K \geq 7.5 + 0.5 = 8$, $P_{success}$ increases with decreasing a, thus increasing $E[T_{on}]$, for $K \leq 7.5 + 0.5 = 8$, $P_{success}$ increases with increasing a, thus decreasing $E[T_{on}]$, and for $K = 7.5 + 0.5 = 8$, $P_{success}$ is constant.

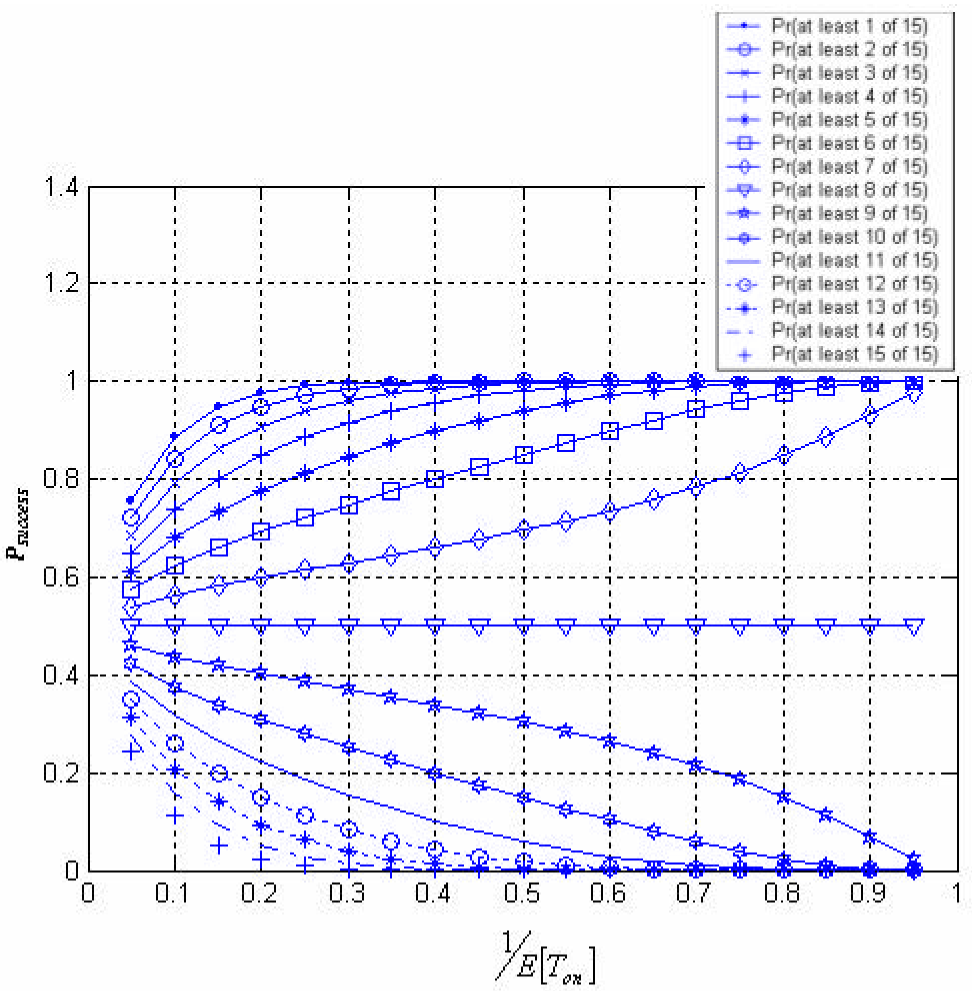

Figure 4.3 $P_{success}$ versus inverse of mean duration in On state for 50% energy saving

Similarly, the variation of $P_{success}$ according to the inverse of $E[T_{on}]$ for a node saving 20% energy is shown in Figure 4.4. The number of packets sent, N, is 15, and the expected number of packets received, m ,is 12. $P_{success}$ increases with increasing $E[T_{on}]$ and $E[T_{off}]$ for $K \geq 12.5$ and decreasing $E[T_{on}]$ and $E[T_{off}]$ for $K \leq 12.5$. Both figures support the analytical results.

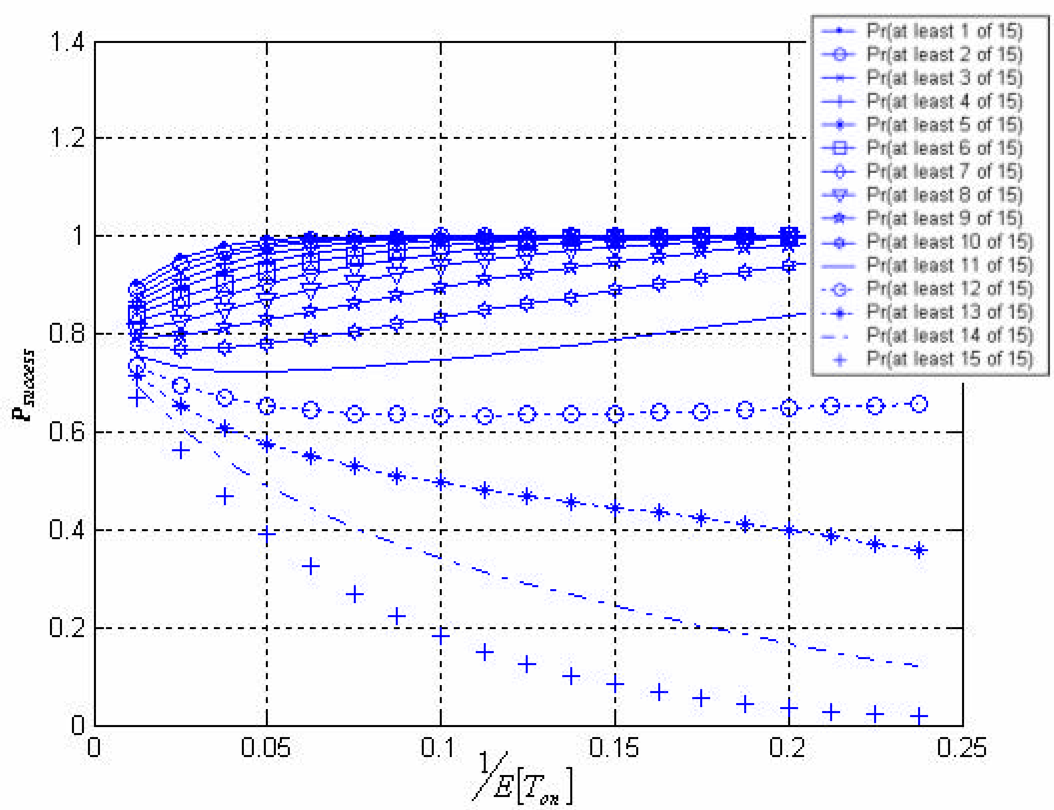

Figure 4.4 $P_{success}$ versus inverse of mean duration in On state for 20% energy saving

In order to maximize the probability that a node forwards less than the expected number of packets, $E[T_{on}]$ and $E[T_{off}]$ should be selected as small possible. However, there should be a lower bound on $E[T_{on}]$ and $E[T_{off}]$ since small $E[T_{on}]$ and $E[T_{off}]$ means frequent state changes and each state transition has a cost in terms of both delay and energy. In Figure 4.4, Pr(at least 5 of 15) increases with increasing a and reaches to 1 at $a = 0.1$, and stays constant for higher values of a. So, $a = 0.1$ is a lower bound to select $E[T_{on}]$. However in order to trade off more accurately, cost of the transition from sleep state to awake state should be included in the optimization problem.

Similarly, in order to maximize the probability that a node forwards more than the expected number of packets, $E[T_{on}]$ and $E[T_{off}]$ should be selected as large possible. Similarly, there is an upper bound on $E[T_{on}]$ and $E[T_{off}]$ such that $\frac{L}{E[T_{on}]+E[T_{off}]} \geq 2$.

Results obtained for a geometrically distributed sleep/awake schedule also apply to a periodic sleep/awake schedule.

Clearly, given a specific $P_{success}$ to be achieved, there may be different (a, b) pairs which satisfy the constraint on $P_{success}$. In Figure 4.5, $P_{success}$ values for several (a, b) pairs are calculated. Although the set of (a, b) pairs is wider than the depicted in the figure, a subset of the pairs is enough to give an insight. In Figure 4.5, (a, b) pairs satisfying the constraint $P_{success} > 0.9999$ are distinguished with 'X'. Among four possible pairs, the pair $(a, b) = (0.3, 0.5)$ gives the maximum p_1 value, which means the maximum energy saving, E_s.

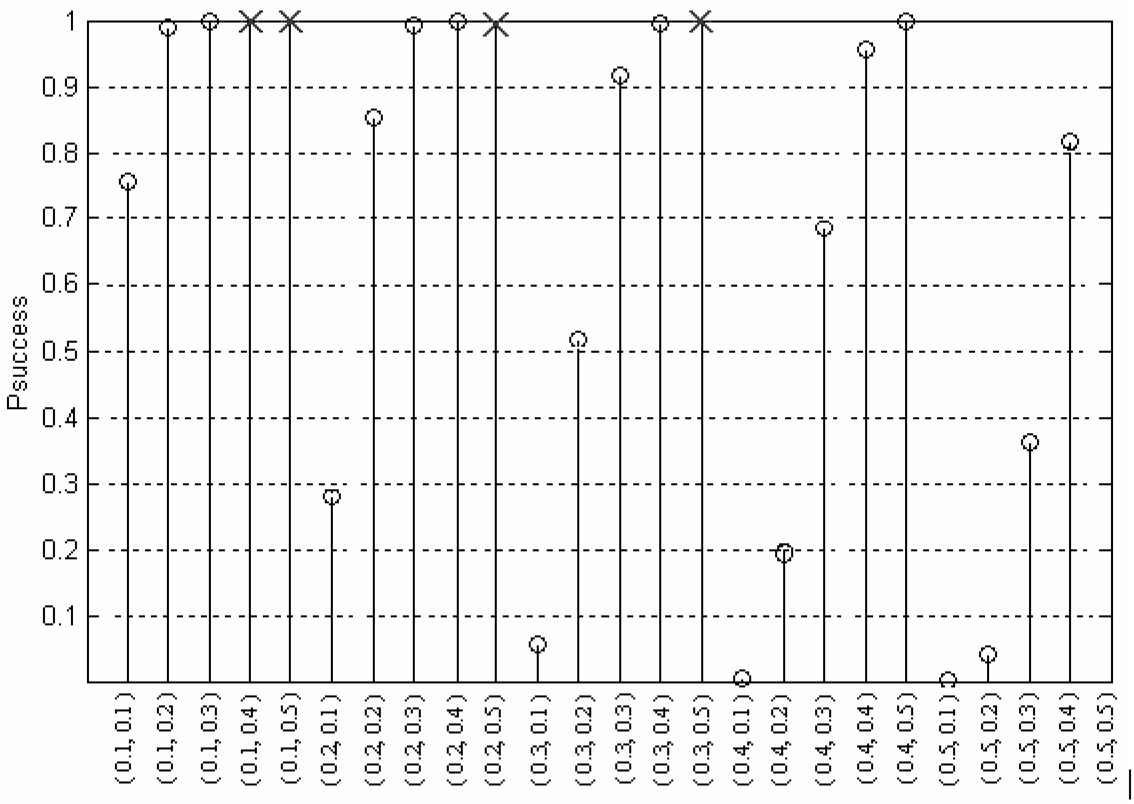

Figure 4.5 $P_{success}$ for several (a, b) pairs

4.5. Summary of the Chapter

In this section, we propose a sleep/awake scheduling strategy for wireless nodes which maximizes the QoS while satisfying the specified energy saving ratio, E_s of the node. On the other hand, some applications may have strict QoS requirement so lower energy saving ratios can be tolerated in order to achieve this requirement. Our model is also appropriate to be extended to find the optimal sleep/awake schedule for wireless nodes which maximizes the energy saving of the nodes while satisfying the specified QoS. Therefore, we define a second optimization problem. Remember that a and b are the inverses of $E[T_{on}]$ and $E[T_{off}]$ respectively. Given a constraint on $P_{success,}$ we want to find the optimal ($E[T_{on}], E[T_{off}]$) pair that maximize E_s.

Optimization problem can be written as follows;

Maximize:

$$E_s = \frac{a}{a+b} \tag{4.16}$$

Subject to:

$$0.5 + 0.5 erf\left(\frac{m - K + \frac{1}{2}}{\sqrt{2}s}\right), \tag{4.17}$$

$$0 < a < 1,$$

$$0 < b < 1$$

5. SIMULATION RESULTS

5.1. Accuracy of Analytical Model

Simulation of the proposed routing model has been performed in OPNET Modeler 10.0 [89] and results for selected scenarios have been discussed below. Important parameters of the simulation are as follows:

N : Number of packets transmitted from the source node.

K: Minimum number of packets expected to be received by the destination node.

I: Number of established disjoint paths in the network.

M: Number of nodes on a disjoint path.

N = 100 packets have been used for the simulations and different scenarios use different *K* values (*K*<100). Each scenario has been run for 100 times and the probability value is extracted from results of these 100 runs.

Simulated network model has three alternative disjoint paths. 100 packets are distributed among these three paths. Our routing model aims to find the optimum packet distribution among possible paths to maximize the probability of receiving at least *K* of *N* packets. Therefore, we compared probability of success ($P_{success}$) result achieved by the packet distribution found by our model with the other packet distribution alternatives via simulations for different scenarios. Ideally, the probability of success result for optimal packet distribution must be compared with all other possible distributions in order to verify optimality of the model distribution. The number of all possible packet distributions for I paths and N packets is N^I. Therefore, practically it is not possible to run the simulation for all possibilities even for a small network (3 paths) and for small number of packets (N=100). Assuming that one set of simulation takes approximately 10 minutes, I = 3 and N = 100 takes about $10 \times 100^3 = 10^7$ minutes (~6945 days) which is not feasible to realize. As a result, randomly selected alternatives have been compared to the optimum distribution.

Each intermediate node in the simulation network is modeled as an On / Off Markov process. The state transition probabilities (alpha and beta) of the nodes are configurable. These probabilities are given in Table 5.1, Table 5.3, Table 5.6 for the corresponding scenarios considered in this section. In the initialization phase, each node randomly goes to On state or Off state. A node stays in the same state for some duration and switches to the other state, repetitively during the simulation time. The duration of the state is exponentially distributed with a mean which is the inverse of the corresponding state's transition probability to the other state (1/alpha or 1/beta). If the intermediate node is in On state, it forwards the incoming packet, otherwise it drops. Source node discovers all of the disjoint paths in the network and distributes the packets according to the specified distribution. At the destination node, the percentage of successfully received packets is calculated by counting the number of received packets.

Simulation network topology used in the simulations presented in this section is given in Figure 5.1. There are three disjoint paths and each path consists of two nodes with individual parameters specific to the selected simulation scenario.

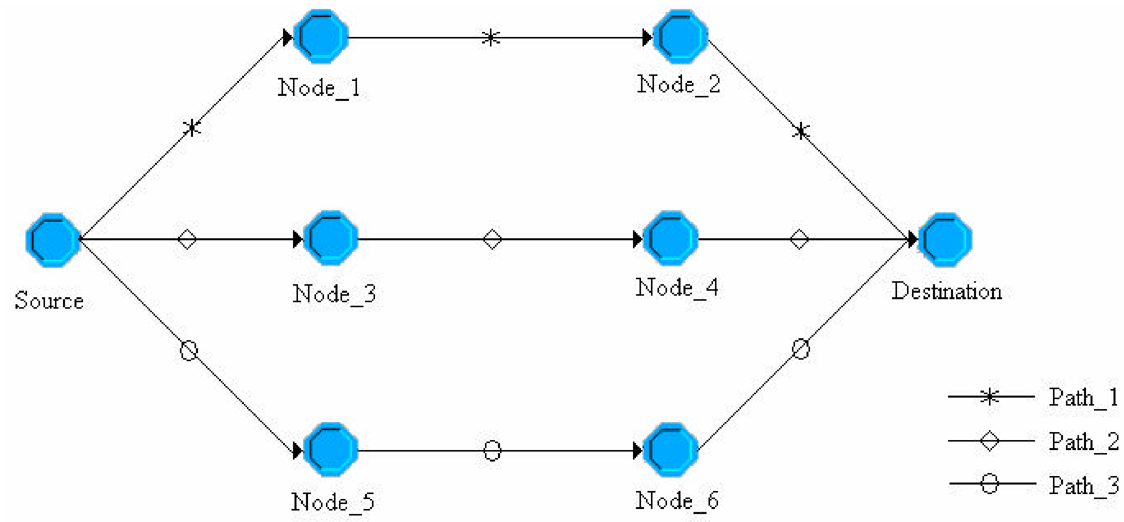

Figure 5.1 Simulation network topology

Two scenarios have been previously discussed in Section 3.4. These scenarios have investigated the behavior of the proposed model for approximating the path reliability and selecting the optimum traffic allocation scheme that maximizes the probability of receiving at least *K* of *N* packets at the receiver node.

In this section, other scenarios have been considered to investigate the model behavior for different cases. Simulation network topology is common for all the scenarios, where the node parameters are subject to change.

5.1.1. Scenario1

Node parameters for Scenario1 are given in Table 5.1.

	Alpha	Beta	P0	P1
Node_1	0.05	0.2	0.8	0.2
Node_2	0.05	0.45	0.9	0.1
Node_3	0.1	0.1	0.5	0.5
Node_4	0.1	0.4	0.8	0.2
Node_5	0.15	0.35	0.7	0.3
Node_6	0.2	0.3	0.6	0.4

Table 5.1 Node parameters for scenario1

Path parameters for Scenario1 are given in Table 5.2.

	$Alpha^{Path}$	$Beta^{Path}$	$P0^{Path}$	$P1^{Path}$
Path_1	0.0975	0.2507	0.7200	0.2800
Path_2	0.1900	0.1267	0.4001	0.5999
Path_3	0.3200	0.2317	0.4200	0.5800

Table 5.2 Path parameters for scenario1

Success probabilities of receiving at least K = 60 packets of 100 packets are given in Figure 5.2. In this scenario, "*N1*=100,*N2*=0,*N3*=0" was found as the optimum distribution and the simulation results support this selection. As the number of packets transmitted over the first path decrease, the success probability dramatically decreases.

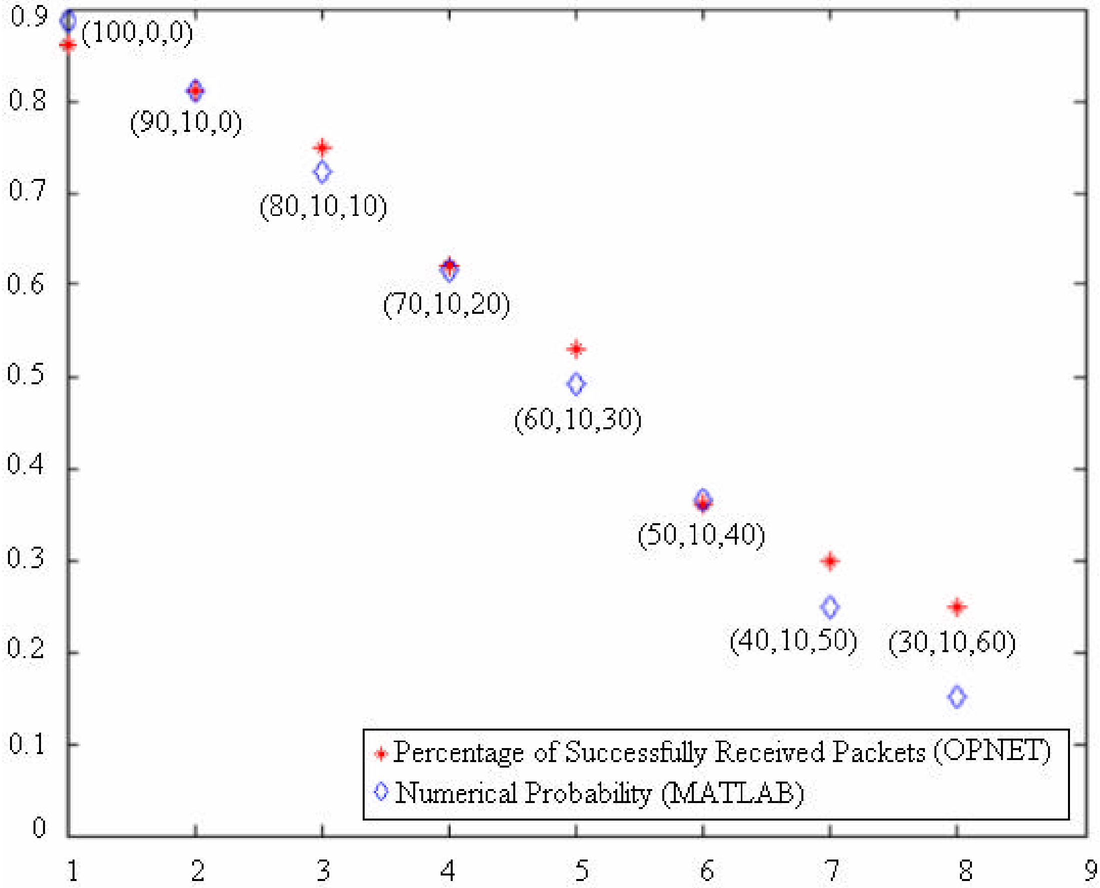

Figure 5.2 Probability of receiving K = 60 out of 100 packets

5.1.2. Scenario2

Node parameters for Scenario2 are given in Table 5.3.

	Alpha	Beta	P0	P1
Node_1	0.1465	0.3535	0.7071	0.2929
Node_2	0.1465	0.3535	0.7071	0.2929
Node_3	0.2929	0.7071	0.7071	0.2929
Node_4	0.2929	0.7071	0.7071	0.2929
Node_5	0.4101	0.9899	0.7071	0.2929
Node_6	0.4101	0.9899	0.7071	0.2929

Table 5.3 Node parameters for scenario2

Path parameters for Scenario2 are given in Table 5.4.

	$Alpha^{Path}$	$Beta^{Path}$	$P0^{Path}$	$P1^{Path}$
Path_1	0.2715	0.2715	0.5	0.5
Path_2	0.5	0.5	0.5	0.5
Path_3	0.6520	0.6520	0.5	0.5

Table 5.4 Path parameters for scenario2

This scenario has been used to show the strategy of allocating packets if paths' state probabilities (*P0, P1*) are equal. Note that, expected (average) number of packets that the destination receives out of all transmitted packets (*N*), from a path with average success probability (or state probability) *P0* is *NP0.* Recall the results obtained in Section 4.4. If the minimum number of packets required for fully reconstruction of the original information (*K*) is less than the expected number of packets, using a path with higher *Alpha* and *Beta* values gives higher probability of success. If *K* is more than the expected number of packets than a path with smaller *Alpha* and *Beta* values performs better. Otherwise, all possible distributions perform the same and any *Alpha* and *Beta* value would be accepted. Simulation results support the idea of the proposed strategy which are given in Table 5.5.

K of N	N1 N2 N3	Probability (Analytical)	Probability (Simulation)
30 of 100	0 43 57	1	1
40 of 100	0 0 100	0.9969	0.947
50 of 100	33 33 34	0.5	0.519
60 of 100	100 0 0	0.1111	0.16
70 of 100	100 0 0	0.026	0.03

Table 5.5 Simulation results for scenario2

5.1.3. Scenario3

Node parameters for Scenario3 are given in Table 5.6.

	Alpha	Beta	P0	P1
Node_1	0.05	0.95	0.95	0.05
Node_2	0.05	0.95	0.95	0.05
Node_3	0.05	0.45	0.05	0.45
Node_4	0.05	0.45	0.05	0.45
Node_5	0.01	0.19	0.95	0.05
Node_6	0.01	0.19	0.95	0.05

Table 5.6 Node parameters for scenario3

Path parameters for Scenario3 are given in Table 5.7.

	$Alpha^{Path}$	$Beta^{Path}$	$P0^{Path}$	$P1^{Path}$
Path_1	0.0975	0.9025	0.9025	0.0975
Path_2	0.0975	0.4157	0.8100	0.1900
Path_3	0.0199	0.1842	0.9025	0.0975

Table 5.7 Path parameters for scenario3

Success probabilities of receiving at least *K* = 80 packets of 100 packets are given in Figure 5.3. We see that the steady state probabilities are equal for *Path_1* and *Path_3*. Although, the optimum distribution of 100 packets among the possible three paths is "*N1*=100, *N2*=0, *N3*=0". Simulation results also show that this alternative has the best probability when compared to other selected alternatives. In addition, it would be expected that the packets will be distributed equally between *Path_1* and *Path_3* because of the equal steady state probabilities. However, "*N1*=50, *N2*=0, *N3*=50" is not better than the distribution of "*N1*=100, *N2*=0, *N3*=0".

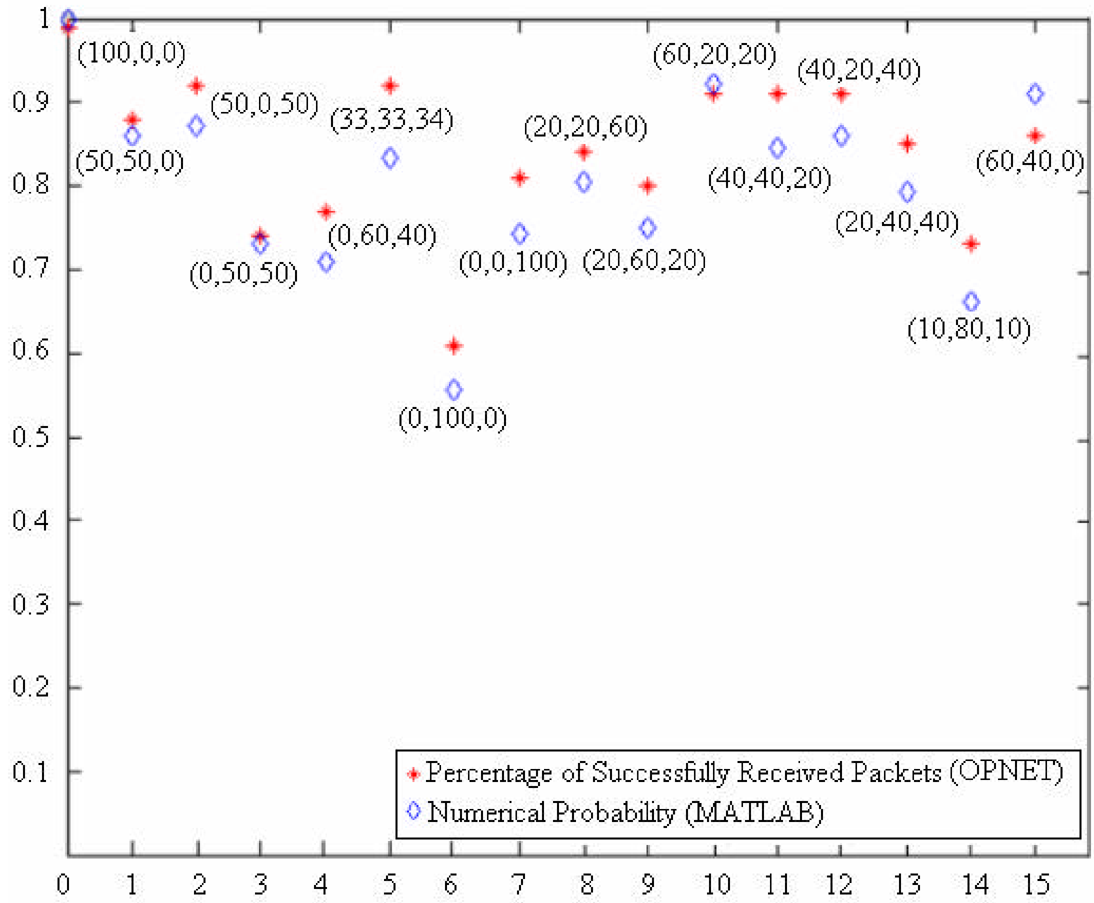

Figure 5.3 Probability of receiving K = 80 out of 100 packets

5.2. Performance Evaluation

Recall that, in Section 2.3, network reliability is defined as the probability of correctly reconstructing the original information at the destination. K out of N transmitted packets is enough in order to reconstruct the original information. $M=N-K$ packets are the redundant packets added by the diversity coding. Therefore, there is an overhead arising from coding. Let us define an overhead factor, h in order to quantify this overhead. Overhead factor, h is defined as the ratio of the number of packets transmitted to the number of packets required for successful reconstruction; $h = \frac{N}{K}$.

In Chapter 2, we present a model for time correlated path failures which captures the bursty characteristics of losses occurring as a result of the failures. In Chapter 3, we propose a multipath routing strategy in order to improve the network reliability. Our multipath routing strategy is based on the model presented in Chapter 2, thus it considers the correlation among path failures. On the other hand, in a simple failure model, it is assumed that the probability of failure on a particular path at time slot $t+1$ is independent of the probability of failure at time slot t. Thus, these kinds of models overwhelm the correlation between successive failures by using a single probability of success parameter for each path which is the average success probability of the corresponding path. When the multipath routing strategy is designed upon that assumption, the performance of the strategy may be worse than the expected in situations where the failures are correlated.

We compare the performance of our multipath routing strategy with the mutlipath strategy which does not consider the correlation. Performance of both strategies is also compared with single path routing. Due to the space limitations, simulation results are given only for four different overhead factors.

The number of disjoint paths used in the simulations presented in this section is five. In figures, 'P$_{success}$' corresponds to the network reliability and 'Path Success Probability' corresponds to the *mean* success probability of the paths used in the simulation. The *mean* success probabilities of all paths are the same.

In Figure 5.4, P$_{success}$ corresponds to the probability of receiving 90 out of 100 packets. The overhead factor is approximately 1.12. Mean success probabilities of the paths are located in the horizontal axis. Each point in the horizontal axis corresponds to a different path success probability vector. For example, '0.9' represents a vector with elements; [0.9, 0.9, 0.9, 0.9, 0.9] since there are five paths with equal success probabilities.

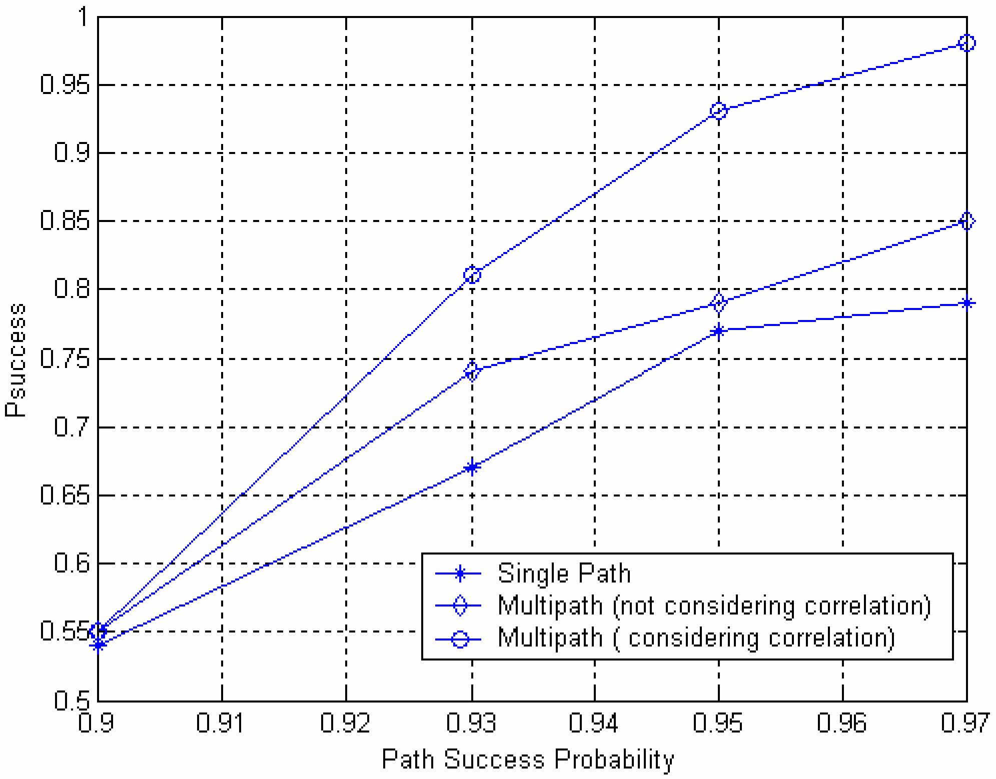

Figure 5.4 Comparison of three different strategies for overhead factor 1.12

Figure 5.5 shows the simulation results where the path success probability vector ranges from 0.8 to 0.97. $P_{success}$ corresponds to the probability of receiving 80 out of 100 packets. The overhead factor is approximately 1.25.

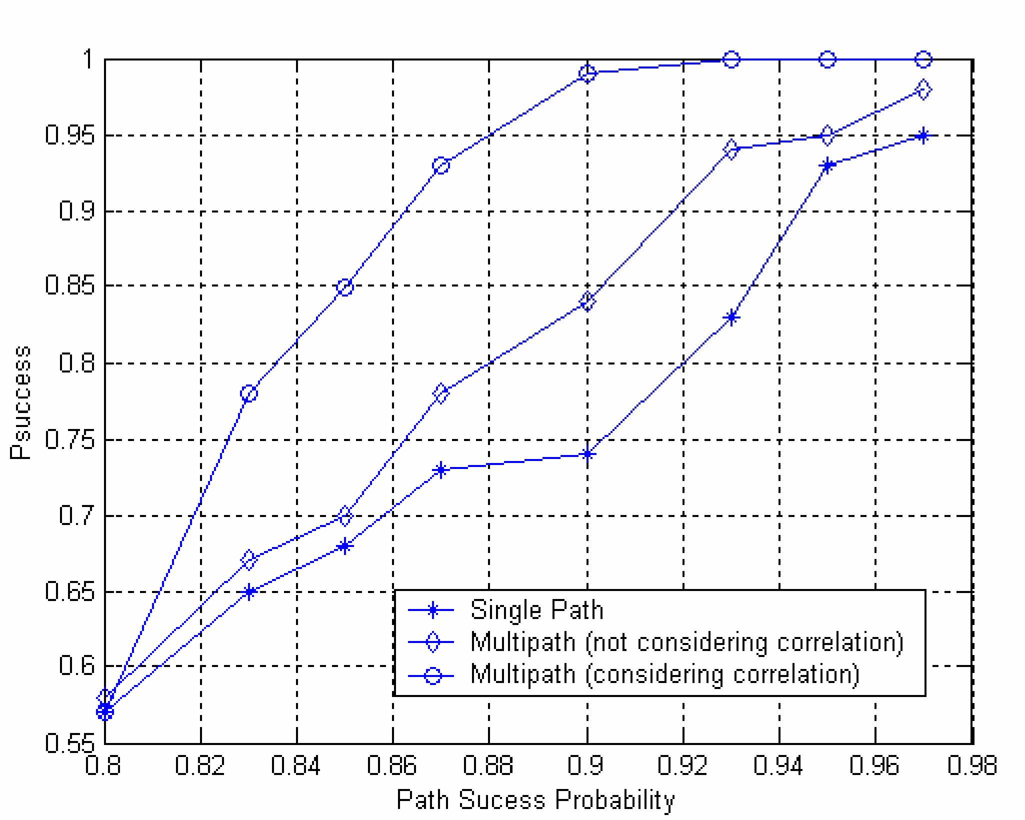

Figure 5.5 Comparison of three different strategies for overhead factor 1.25

In Figure 5.5, all of the three strategies have very same similar $P_{success}$ values when path success probability is 0.8. This is an expected result. Recall the results obtained in Section 4.4. If *K*, the minimum number of packets required for successful reconstruction of the original information equals to the expected number of packets, then $P_{success}$ is independent of Markov parameters (a, b). In this case, $K=80$ and expected number of packets which is the product of the number of packets sent and the path success probability, is also 80. As the path success probability increases, the performance improvement in Multipath (considered time correlation) routing relative to Multipath (not considered time correlation) routing and single path routing increases. In high path success probabilities, i.e. 0.98, $P_{success}$ values of all three strategies again become closer. This is because $P_{success}$ value is inherently quite high, in high path success probabilities.

Figure 5.6 compares three routing strategies for different path success probabilities ranging from 0.8 to 0.87. $P_{success}$ corresponds to the probability of receiving 70 out of 100 packets. The overhead factor is approximately 1.43. The performance improvement when time correlation is considered in the multipath routing is quite high for this range of success probabilities and overhead factor.

Figure 5.7 illustrates the simulation results when the average success probabilities are quite low. Since low overhead factors should not give satisfactory performance, a higher overhead factor which is approximately 2.85 is used in this scenario. In Figure 5.7, since the overhead factor is quite high, all of the schemes converge to high $P_{success}$ quickly, i.e. in low path success probabilities.

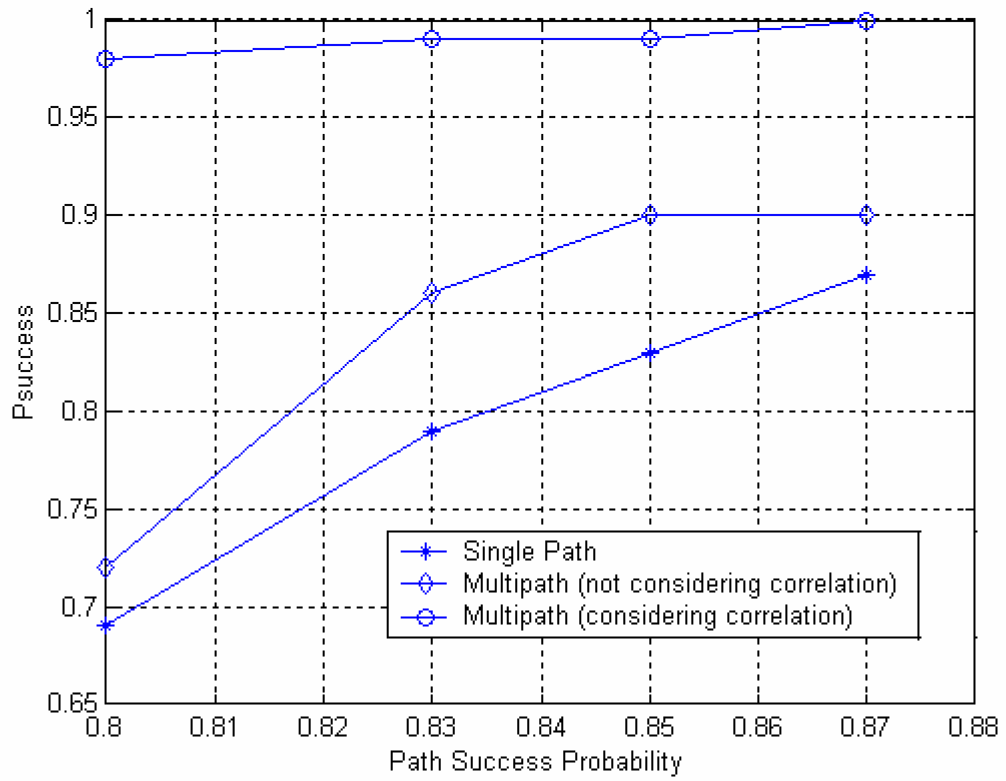

Figure 5.6 Comparison of three different strategies for overhead factor 1.43

From Figure 5.7, it can be inferred that also in quite high overhead, performance improves when time correlation is considered.

Simulation results show that in a wide range of average success probabilities of paths, multipath routing strategies outperforms single path routing. This is a result of the advantage that path diversity offers. Performance improvement depends on both path success probability and the overhead. Besides, in all of the scenarios presented in this section, our strategy has a better performance that the multipath routing strategy which do not consider time correlation.

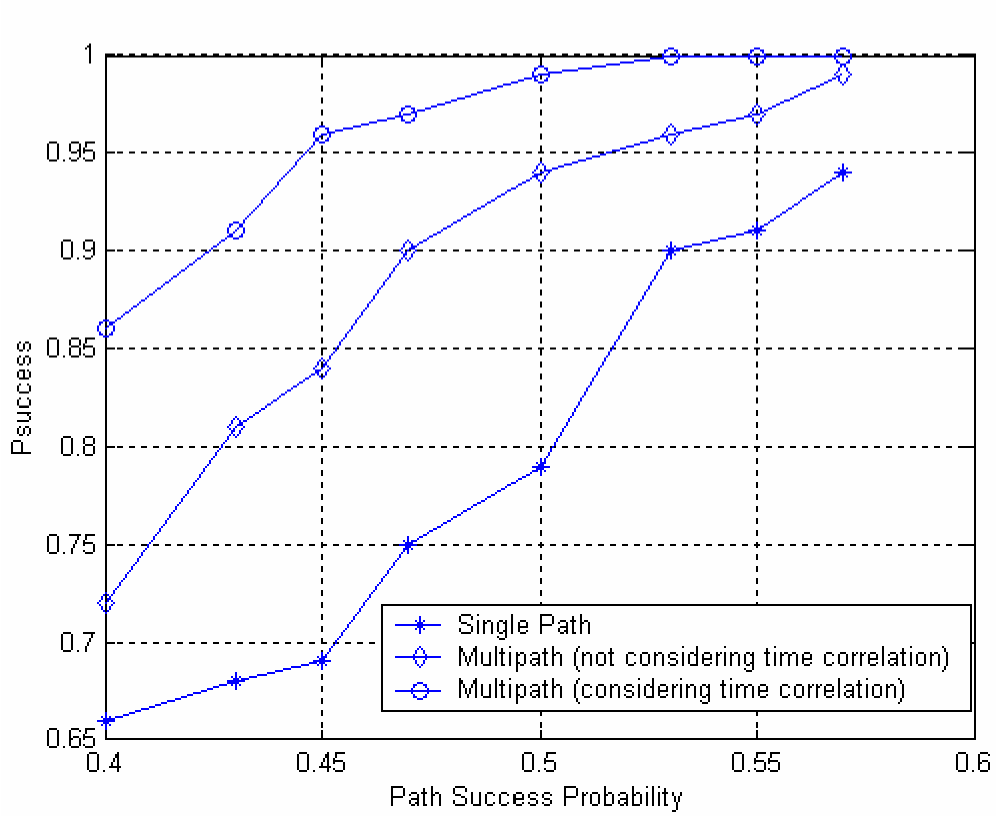

Figure 5.7 Comparison of three different strategies for overhead factor 2.85

As stated in Section 1.4.3, a recent study closest to our work is [55]. However, this study treats paths as pure erasure channels. Recall that, pure erasure channel means that when the channel is On state, all of the packets assigned to this channel are transmitted, and when it is in Off state all of the packets assigned to this channel are lost.

In [55], based on pure erasure channel assumption, a strategy for distributing the packets among available paths is proposed. In order to see the performance of their strategy when the paths are not pure erasure channels, we conducted simulations in which the paths are modeled as two state Markov. Since the states of the paths can change between successive packets, any number of packets could be transmitted over that path. We select a scenario which is considered in [55], where there are nine disjoint paths between the source and destination and the steady state probabilities of paths are 0.85, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7 correspondingly.

We compare the performances of our strategy and the strategy in [55] for different overhead factors in Figure 5.8. The horizontal axis is the inverse of the overhead factor which is *K/N*. For example, when *K/N* = 0.7, $P_{success}$ corresponds to the probability of receiving at least %70 of the packets. If the packet distribution strategy proposed in [55] is used, $P_{success}$ is 0.58 for this overhead, while if our packet distribution strategy is used, $P_{success}$ is 0.82.

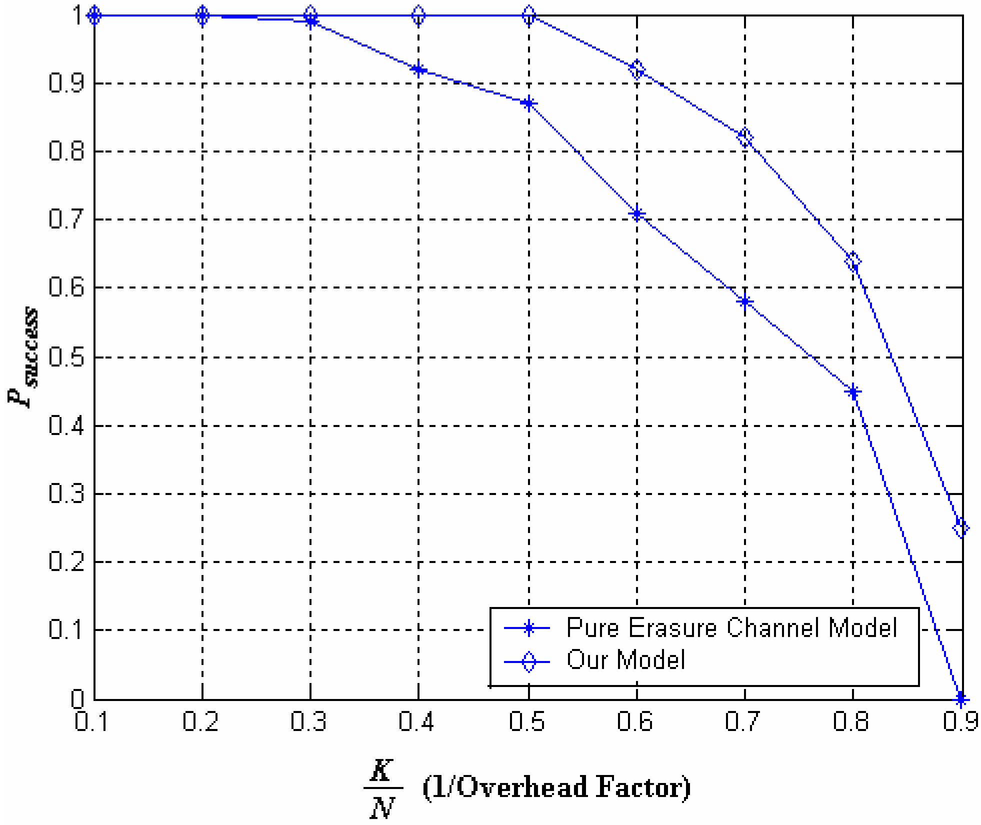

Figure 5.8 Pure Erasure Channel Model vs Our Model

When the overhead is quite high, both of the strategies give high $P_{success}$ values. As the overhead decreases, the difference in the performances of two strategies also increases. Our strategy attains the performance of the strategy in [55] in lower overhead values. For example, the strategy in [55] gives $P_{success}$ value of 0.92 when K/N is 0.4. Our strategy attains the $P_{success}$ value of 0.92 when K/N is 0.6.

6. CONCLUSIONS AND FUTURE WORK

In this thesis, we proposed a strategy for using multiple disjoint paths between the source and destination in order to increase the end to end connection reliability in wireless mobile ad hoc networks. Our scheme uses diversity coding technique that exploit the diversity of paths. Diversity coding [63] is a channel coding scheme proposed for nearly instantaneous recovery from link failures in digital communication networks. Burst of errors occurring on the wireless links and the topology changes due to the mobility of nodes are the two main sources of link/node failures occurring on the path, decreasing the packet delivery ratio. Motivated by the bursty characteristics of packet losses, node availability (or similarly link availability) is modeled by *First Order Markov Model* in which current state of the node (or the link) corresponds to its availability for transmission or not. Node/link availability model is also extended to the path availability model.

It is a well known fact that sending multiple copies of the same packet over multiple paths increases packet delivery ratio. In order to improve network reliability, we take the advantage of path diversity. However, we do not send multiple copies of the same packet since it increases the overhead unnecessarily. Instead, we split the original information into K subpackets; M subpackets of redundancy which is obtained from the original K subpackets by linear transformations are added and totally $N=K+M$ subpackets are sent to the destination, where reception of any K packets is enough to reconstruct the original data. This scheme corresponds a (N,K) code which has a overhead factor of N/K. Our goal is to maximize the network reliability, i.e. probability of receiving any of K packets out of N packets. Based on our path availability model that captures the bursty characteristic of packet losses, we express the network reliability, $P_{success}$ analytically. In order to maximize the network reliability, we define an optimization problem which can be solved by numerical methods.

The proposed scheme offers increased reliability since it allocates the subpackets to the multiple paths in an effective manner. We conducted simulations for different scenarios in which different path failure statistics and different overhead factors are considered. Simulation results support the accuracy and effectiveness of our model and show that our strategy increases network reliability.

Additionally, our scheme can also be used when there is a QoS requirement in terms of network reliability. Given the QoS requirement and the number of disjoint paths established by a route discovery mechanism, the optimal distribution of subpackets can be found.

Although we are concentrated on ad hoc networks, our scheme can be used in any type of wired or wireless network with channels that are subjected to bursty losses. Transparency of our scheme from the transmission methods permits the incorporation of our scheme to any routing protocol.

Possible future research direction may be the development of polynomial-time algorithms instead of using numerical techniques in order to find the optimal distribution of the subpackets among paths that maximizes network reliability. The algorithm developed must be as efficient as possible so that it can adapt to changes in the path failure statistics in real-time. A second direction may include the incorporation of our scheme to existing well established routing protocols such as DSR [1], AODV [2].

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