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ABSTRACT

HYBRID ROUTING AND BRIDGING STRATEGIES FOR LARGE SCALE MOBILE AD HOC NETWORKS

by Sheng Xu

Multi-hop packet radio networks (or mobile ad-hoc networks) are an ideal technology to establish "instant" communication infrastructure for military and civilian applications in which both hosts and routers are mobile. In this dissertation, a position-based/link-state hybrid, proactive routing protocol (Position-guided Sliding-window Routing - PSR) that provides for a flat, mobile ad-hoc routing architecture is described, analyzed and evaluated. PSR is based on the superposition of link-state and position-based routing, and it employs a simplified way of localizing routing overhead, without having to resort to complex, multiple-tier routing organization schemes. A set of geographic routing zones is defined for each node, where the purpose of the ith routing zone is to restrict propagation of position updates, advertising position differentials equal to the radius of the (i-1)th routing zone. Thus, the proposed protocol controls position-update overhead generation and propagation by making the overhead generation rate and propagation distance directly proportional to the amount of change in a node's geographic position. An analytical model and framework is provided, in order to study the various design issues and trade-offs of PSR routing mechanism, discuss their impact on the protocol's operation and effectiveness, and identify optimal values for critical design parameters, under different mobility scenarios. In addition an in-depth performance evaluation, via modeling and simulation, was performed in order to demonstrate PSR's operational effectiveness in terms of scalability, mobility support, and efficiency. Furthermore, power and energy metrics, such as path fading and battery capacity considerations, are

integrated into the routing decision (cost function) in order to improve PSR's power efficiency and network lifetime. It is demonstrated that the proposed routing protocol is ideal for deployment and implementation especially in large scale mobile ad hoc networks.

Wireless local area networks (WLAN) are being deployed widely to support networking needs of both consumer and enterprise applications, and IEEE 802.11 specification is becoming the de facto standard for deploying WLAN. However IEEE 802.11 specifications allow only one hop communication between nodes. A layer-2 bridging solution is proposed in this dissertation, to increase the range of 802.11 base stations using ad hoc networking, and therefore solve the hotspot communication problem, where a large number of mobile users require Internet access through an access point. In the proposed framework nodes are divided into levels based on their distance (hops) from the access point. A layer-2 bridging tree is built based on the level concept, and a node in certain level only forwards packets to nodes in its neighboring level. The specific mechanisms for the forwarding tree establishment as well as for the data propagation are also introduced and discussed. An analytical model is also presented in order to analyze the saturation throughput of the proposed mechanism, while its applicability and effectiveness is evaluated via modeling and simulation. The corresponding numerical results demonstrate and confirm the significant area coverage extension that can be achieved by the solution, when compared with the conventional 802.11b scheme. Finally, for implementation purposes, a hierarchical network structure paradigm based on the combination of these two protocols and models is introduced.

HYBRID ROUTING AND BRIDGING STRATEGIES FOR LARGE SCALE MOBILE AD HOC NETWORKS

by
Sheng Xu

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May 2004

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APPROVAL PAGE

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CHAPTER 1

MOBILE AD-HOC NETWORKS AND ROUTING CHALLENGES

1.1. Introduction

Mobile wireless networking has enjoyed dramatic increase in popularity over the last few years. The advances in hardware design, the rapid growth in the communications infrastructure, and the increased user requirement for mobility and geographic dispersion, continue to generate a tremendous need for dynamic ad hoc networking. Multihop packet radio networks (or mobile ad hoc networks) are an ideal technology to establish "instant" communication infrastructure for military and civilian [1, 2] applications in which both hosts and routers are mobile. There are many existing military networking requirements for robust communications in a variety of potentially hostile environments, that may require the rapid deployment of mobile radio networks (commonly referred to as packet radio networks) [3, 4], as well as future military applications and requirements for IP-compliant data services within mobile wireless communication networks [5]. Moreover mobile ad hoc networking technology can provide extremely flexible method for establishing communications for operations in disaster areas resulting from flood, earthquake, or other scenarios requiring rapidly deployable communications with survivable dynamic networking. Some other applications of mobile ad hoc networking technology could include industrial and commercial applications involving cooperative mobile data exchange. In addition mesh-based mobile networks can be operated as robust, inexpensive alternatives or enhancements to cell-based mobile network infrastructures. The goal of mobile ad hoc networking is to extend mobility into the realm

of a set of wireless mobile nodes, where themselves form the network routing infrastructure in an ad hoc fashion.

In such mobile ad hoc networks there are no dedicated base stations as in conventional commercial cellular networks, and all nodes interact as peers for packet forwarding. This distributed nature eliminates single points of failure and makes those packet radio networks more robust and survivable than the commercial cellular networks. At the same time, mobile ad hoc networks result from the fact that not every pair of nodes is within the transmission range of each other, and as a result they present dynamic, sometimes rapidly changing, random, multihop topologies.

The vision of mobile ad hoc networking is to support, with robustness and efficiency the various operations in mobile wireless networks, by incorporating routing functionality into the mobile nodes. In such mobile ad hoc networks a routing strategy (or system) can be defined as a set of several component functions including the following: monitoring network topology; locating end-points and performing mobility management; distributing this information for use in route construction; constructing and selecting routes. An efficient peer-to-peer mobile routing mechanism (protocol) in a purely mobile, wireless domain must: provide for effective operation over a wide range of mobile networking environment with its corresponding set of characteristics; provide algorithms and methods for allowing newly arrived nodes to be incorporated into the network and become an integral part of the network automatically, without manual intervention (self-organizing); react efficiently to topological changes and traffic demands while maintaining effective routing in a mobile networking environment; and address effectively the issue of scalability. Additional issues associated with the routing strategies

in mobile ad hoc wireless networks stem from the fact that those networks are plagued with problems such as, variable quality of the links, the hidden terminal problem, and particularly the inaccuracies in the routing information due to the mobility of the nodes [6].

At the same time wireless local area networks (WLAN) are being deployed widely to support networking needs of both consumer and enterprise applications, while IEEE 802.11 specification [7] is becoming the de facto standard for deploying WLAN. The 802.11 specifications include a Media Access control protocol specification and various PHY layer specification. Two modes are specified by 802.11: the infrastructure mode or centralized mode, in which all the mobile nodes communicate to a centralized node called the access point (AP) (e.g. base station); and the ad hoc mode in which the mobile nodes communicate directly with each other.

IEEE 802.11 specifications support only single hop communication between nodes in both modes. In an infrastructure based mode the mobile nodes will have to be within the range of the access point to communicate with the access point. Work has been done to increase the range of the WLAN by using multiple hops between the mobile node and the access point. This problem has been addressed mainly as a routing problem in the literature (e.g [8, 9]). Furthermore the problem of extending the network coverage in WLAN has recently received significant industrial attention as well [10, 11].

1.2. Dissertation Outline and Contributions

In this dissertation, address the problem of establishing end to end communication paths in large-scale mobile ad hoc networks in an efficient way is addressed, by designing hybrid routing and bridging techniques that operate at the network layer and data link

layer, respectively.

In Chapter 2 a new position-based routing protocol is introduced and described, namely the Position-guided Sliding-window Routing (PSR), which is a position-based/link-state hybrid proactive routing protocol that provides for a flat, mobile ad-hoc routing architecture, and can be implemented in large-scale ad hoc networks. In Chapter 3 an analytical model and framework is provided in order to study the design issues and trade-offs of PSR routing mechanism, evaluate their impact on the protocol's operation and effectiveness, and identify the corresponding critical design parameters that optimize the protocol's operation under different mobility models and scenarios. Chapter 4 contains the performance evaluation of the proposed strategy. One of the main features of PSR protocol is that it is based on the superposition of link-state and position-based routing, and it employs a simplified way of localizing routing overhead, without having to resort to complex, multiple-tier routing organization schemes. The proposed protocol controls position-update overhead generation and propagation by making the overhead generation rate and propagation distance directly proportional to the amount of change in a node's geographic position. PSR protocol is self-paced, in the sense that it automatically adjusts the generation of routing control packets depending on the mobility characteristics of the network. Overall, it is demonstrated, that PSR provides the features of scalability, routing effectiveness and mobility support, and therefore is an ideal routing protocol for deployment in large scale mobile ad hoc networks. Furthermore, a power/energy aware extension of the PSR protocol is proposed and evaluated, in order to prolong the operation of the ad hoc network, by integrating into the routing decision various power and energy metrics, such as path fading and battery capacity considerations.

Since wireless LANs is a significant component of mobile ad hoc networks and IEEE 802.11 specifications are becoming the de facto standard for their deployment, in Chapter 5 of this dissertation, a novel layer-2 bridging solution to increase the range of an 802.11 access point using multi-hop ad hoc networking is proposed. One of the main difficulties in solving the multi-hop extension using conventional spanning tree based layer-2 bridging solutions, is the number of times spanning tree update will have to be done in a mobile ad hoc network. The innovative solution proposes a framework that avoids the requirement of rebuilding the whole spanning tree protocol frequently. It only re-builds connections locally with its direct neighbors, therefore no updates need to be broadcasted through the bridging tree. In Chapter 6 an analytical model to evaluate the asymptotic throughput that can be achieved by the proposed bridging solution is designed and developed. In Chapter 7 the applicability and effectiveness of the proposed solution are evaluated and some results that demonstrate the access point area coverage extension that can be achieved is presented, when compared with the conventional 802.11b scheme. It should be noted that the proposed bridging architecture mainly aims to address and solve the hotspot communication problem, where a large number of mobile users require Internet access through an access point. Extending the coverage area of each access point in WLAN, results in far less requirement for handoffs between APs and in significant performance improvements, while at the same time allows for increased degree of mobility. Finally, Chapter 8 concludes the dissertation, by summarizing the main contributions and discussing directions for future work.

CHAPTER 2

POSITION-GUIDED SLIDING-WINDOW ROUTING (PSR) PROTOCOL DESCRIPTION AND OPERATION

2.1. Introduction and Overview

In this chapter the operation of a position-based/link-state hybrid, proactive routing protocol (Position-guided Sliding-window Routing – PSR) is introduced and described, which provides for a flat, mobile ad-hoc routing architecture. PSR is based on the superposition of link-state and position-based routing, and it employs a simplified way of localizing routing overhead, without having to resort to complex, multiple-tier routing organization schemes. A set of geographic routing zones is defined for each node, where the purpose of the ith routing zone is to restrict propagation of position updates advertising position differentials equal to the radius of the (i-1)th routing zone. Thus, the proposed protocol controls position-update overhead generation and propagation by making the overhead generation rate and propagation distance directly proportional to the amount of change in a node's geographic position. In the following chapters, an analytical model and framework in order to study the various design issues and trade-offs of PSR routing mechanism is provided, their impact on the protocol's operation and effectiveness, and identify optimal values for critical design parameters under different mobility scenarios are discussed thereafter. The performance evaluation results of the protocol demonstrate its operational effectiveness in terms of scalability, mobility support, and efficiency.

2.2. Related Work and Motivation

Recently, the use of geographic position as a means of routing has become increasingly

popular in mobile ad hoc networks [12]. One important advantage of using position for routing is its inherent ability to alleviate the need for the development of separate complicated techniques for mobility management. In addition, position-based routing strategies, since they do not require the exchanges of routing tables, are especially attractive in highly mobile environments where topological changes are frequent and routing tables become obsolete very quickly [13]. In order to implement these protocols, a node is assumed to be able to determine its location in some way. There are several systems for position location and/or position updates [14, 15, 16]. For example the NAVSTAR Global Positioning System (GPS) [16] is a position location system that is capable of global coverage. In general using geographic position as a means of routing/mobility management, has the following advantages [17]: a) It makes feasible the realization of a flat routing architecture, thus, eliminating the complexities associated with maintaining rigid, multiple-tier hierarchical architectures, therefore making the network robust and 'fluid' in nature, b) it minimizes the amount of initial manual configuration required to set-up the network, thus making the network completely self-organizing, and c) it makes feasible the process of routing packets with geographic destinations.

In [18] a localized routing algorithm, named loop-free hybrid single-path/flooding routing was proposed. In this scheme a 2-hop position based routing is used to avoid common failures when the next hop becomes the one from which the packet came from, while flooding is used as a solution to avoid packet dropping at a concave node, thus guaranteeing the packet delivery. Position information can be used in conjunction with 'on-demand' routing protocols in order to limit the scope of the flood search that occurs

when a source attempts to find a route to a destination. Location-Aided Routing (LAR) [19] couples Dynamic Source Routing (DSR) [20] with knowledge of position, by using the last known destination position as the origin of an uncertainty circle, which is called the 'request zone', and limiting the flood search for a destination route within that request zone. In [21], global node position knowledge is used as a means of constructing a network connectivity graph, which is subsequently used to construct a source route from a given source to a given destination; thus, there is no need to perform flood search as in DSR. However, it should be noted that the connectivity graph constructed using exclusively knowledge of position might not necessarily correspond to the actual network connectivity due to the existence of terrain obstructions. In addition, the drawback associated with source routing in general, is that the route computed originally at the source may become obsolete as the packet is 'in transit', resulting in packet loss.

Furthermore, using geographic position as a means of routing provides for an efficient way of extending the concept of the 'routing event'. In general, a routing event is the change in status of a link connecting two neighbors, or the acquisition of a new neighbor. Using position as a means of conveying routing information allows us to treat changes in position as routing events. Moreover, 'magnitudes' to these events can be assigned: the larger the change in position, the larger the 'magnitude' of the routing event. This is because the larger the change in position, the larger the population of nodes that gets 'affected' by that change. Consequently, the magnitude associated with a routing event can be used to determine the dissemination radius of the update advertising the routing event. The dissemination radius of updates associated with 'larger' (hence, more significant) events will be bigger than the dissemination radius of updates associated with

'smaller' (less significant) events. Thus, the accuracy of the routing information maintained by a node for each potential destination, is proportional to the distance of the node from the potential destination. This effect is referred as the 'near-far' routing effect in this dissertation. More significantly, the existence of multiple routing events associated with multiple update dissemination radii serves as a soft (implicit) hierarchical mechanism, and therefore, using position as a means of routing facilitates the realization of a flat routing architecture.

DREAM (Distance Routing Effect Algorithm for Mobility) [22] and FSR (Fisheye State Routing) [23] are two protocols that are based on the existence of multiple routing events, and the exploitation of the 'near-far' routing effect. DREAM is a position-based routing protocol that utilizes an array of position-update triggering timers, where timer[k] has a larger period (expiration interval) than timer[k-1]; therefore, position updates triggered by the expiration of timer[k] have a larger dissemination radius than the updates triggered by the expiration of timer[k-1]. FSR is a link-state routing protocol that utilizes the same update triggering/dissemination mechanism, but instead of position updates, it sends link-state updates.

In this chapter, a new position-based routing protocol, namely the Position-guided Sliding-window Routing (PSR) [24, 25], is introduced and designed, which exploits the 'near-far' routing effect. PSR, however, differs from DREAM and FSR in that it actively combines link-state routing with position-based routing, therefore providing a framework for the implementation and support of Quality of Service (QoS) in mobile ad hoc networks.

2.3. Background Information and Notation

As mentioned before the Position-Guided Sliding Window Routing Protocol (PSR) is based on the superposition of link-state and position-based routing, and it employs a simplified way of localizing routing overhead, without having to resort to complex, multiple-tier hierarchical routing architectures [24, 25]. This is achieved by 'joining' the processes of routing and mobility management, via combining the use of geographic position with the adaptation of a hierarchical organization concept used for location-database updating in cellular PCS networks [26].

Specifically, for each node X a set of geographic routing zones (circles) is defined, where the ith routing zone is a geographic circle with radius R(i) meters. The geographic circle radii satisfy the following inequality:

$$R(0)=R(1)<R(2)<...<R(i-1)<R(i)<R(i+1)$$

Before describing in detail how does the protocol operate and how the geographic routing zones are utilized by the protocol, some notation specific to the operation of the protocol is given as following:

L(X,t) ≡ Location (x,y,z) of node X at time t.

Z(X,i,t) ≡ Node X's zone i at time t = geometric circle with area equal to $\pi*[R(i)]^2$, centered at C(X,i,t) for i>0, centered at L(X,t) for i=0.

C(X,i,t) ≡ Center of Z(X,i,t). For i=0, C(X,i,t) = L(X,t). For i>0, normally $C(X,i,t) \neq L(X,t)$.

R(i) ≡ Radius of zone i, in meters.

$R_{meters}(0)$ ≡ Radius of zone 0 (core zone), in meters.

$R_{hops}(0)$ ≡ Radius of zone 0 (core zone), in hops.

ZRT(X,i) ≡ Zone Refresh Timer of node X's zone i. The purpose of the Zone Refresh Timer is to periodically 'refresh' node X's position in the position databases of all nodes included by Z(X,i+1,t).

ZRT_Residual(X,i,t) ≡ Time remaining until ZRT(X,i) expires.

GPU(X,i) ≡ Geographic Position Update of node X, advertising a position-differential equal to R(i) meters. GPU(X,i) is only propagated within a circle with radius equal to R(i+1) meters, centered at C(X,i+1,t), which, in general, is different than L(X,t).

2.4. PSR Operation

The overall operation of the protocol can be divided into three components: a) Link-State Update Propagation, used within the core zone of each node, b) Position Update Generation/Dissemination, used for the generation and dissemination of routing updates within any zone-i, such that i>0, and c) Data Packet Forwarding, which deals with the mechanism used to forward a packet from source to destination.

2.4.1. Link-State Update Propagation

Routing zone Z(X, 0, t) is referred to as the *core zone* of node X at time t, and R(0) as the core zone radius (e.g.Figure 2.1). The functionality of the core zone in the protocol is similar to the functionality of the routing zone in the Zone Routing Protocol [27]. A node K is said to be within node X's core zone if either one of the following conditions is satisfied:

a) $\text{Distance}_{\text{meters}}[\ L(X,t), L(K,t)\ ] \leq R_{\text{meters}}(0)$

b) $\text{Distance}_{\text{hops}}[\ X, K\ ] \leq R_{\text{hops}}(0)$

Thus, the core zone of node X includes all nodes that satisfy anyone of the above

conditions. The protocol supports the proactive maintenance of the core routing zone through its link-state Core-zone Routing Protocol (CRP). Through the link-state CRP, each node learns the identity of and the least-cost route to all the nodes in its core routing zone. The choice of the link-state CRP is arbitrary; however, the chosen link-state protocol needs to be modified to:

a) ensure that the scope of its operation is restricted to the radius of a node's core routing zone;

b) a field containing the node's position is added to the link-state CRP protocol packets.

It should be noted that the center of a node's core zone is always the same as the instantaneous position of the node. In other words, the node is always the center of its core zone. In addition, a set of Core-zone Border Routers (CBR) is defined for each node; CBRs are nodes whose minimum distance to the node in question is equal to the core zone radius. The nodes in the CBR set are sorted according to their angular distance from the node's geographical y-axis. It should be noted here that the purpose of the link-state component of PSR is to: a) guarantee the reliable forwarding of data packets through terrain obstructions while 'en route' to the final destination vicinity; b) achieve the accurate delivery of the data packets to the final destination, once the packet is close to the vicinity of the final destination; and c) provide a framework for the implementation and support of QoS requirements.

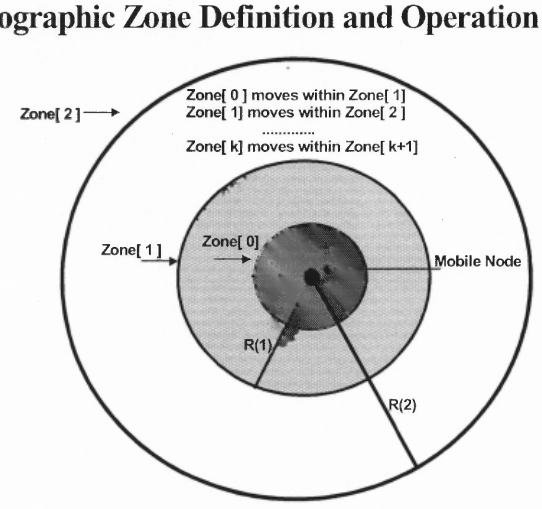


Figure 2.1 PSR Zone Definition and Operation.

2.4.2. Position Update Generation/Dissemination

When node X's position, relative to C(X,i,t), changes by more than R(i) meters, or the Zone Refresh Timer associated with Z(X,i,t) expires then: a) a routing/position update GPU(X,i) is generated and propagated throughout Z(X, i+1, t+Dt), and 2) a new geographic zone Z(X, i, t+Dt) is defined for node X, where (t+Dt) denotes the time that the above event occurred . In consistency with the notation defined above, this operation is described by the following algorithm:

IF {Distance [L(X, t), C(X, i, t)] > R(i) OR ZRT_Residual(X,i,t) = 0 }, given i>0

a) C(X, i, t+Dt) := L(X, t); A new zone Z(X,i,t+Dt) is defined (or refreshed) for node X

b) Construct GPU(X, i) packet with dissemination area equal to Z(X, i+1, t+Dt)

As can be seen, the geographic zone radii and the values of the corresponding Zone

Refresh Timers are set so that the accuracy of the knowledge of a node's position is proportional to the geographic distance from that node.

The GPU(X,i) packet contains the following fields:

1) Source ID, 2) L(X,t+Dt), 3) GPU type, 4) sequence number, 5) C(X, i+1, t+Dt).

At any time t, a node F that received (from a neighbor G) a GPU(X,i) packet (generated by node X), will propagate that packet if all of the following conditions are true:

1) Node F has been designated as a flooding-relay by neighbor G

2) Distance[L(F, t), C(X, i+1, t)] < R(i+1), and

3) Received_GPU_sequence_number > latest GPU sequence number associated with node X.

It should be noted that according to condition 2, the propagation of a GPU(X,i) packet is not done with respect to the current position of node X, but with respect to C(X, i+1, t), which was node X's position when Z(X, i+1, t) was (re)defined.

2.4.3. Data Packet Forwarding

In the following a complete view of the routing protocol's operation is presented by outlining the main steps implemented by the router module of any node (current_node) in the network that needs to route a packet. The first node (current_node) that implements the following procedure is the source node of the packet (node that originally generated the packet).

Step 1: The current_node checks whether the destination is within its core routing zone. If so, the path to the destination is completely specified via the link-state CRP, and no further route processing is required; go to step 4. Otherwise go to step 2.

Step 2: The current_node looks up the destination's geographic position, picks the CBR

that minimizes the Euclidean distance between itself (i.e. the CBR) and the destination, and forwards the packet towards the selected CBR via the least-cost path specified by the current node's link-state CRP. This node is the next hop recipient (next_hop_node).

Step 3: The next hop recipient (next_hop_node) continue forwarding the packet to the CBR unless itself is the CBR as indicated in the packet in which case, it executes the same procedure: that is: current_node:=next_hop_node; go to step 1.

Step 4: Stop.

Steps 1, 2 and 3 may be repeated until the packet reaches the boundaries of the destination's core routing zone; at this point, the packet is picked-up by the link-state CRP instance running in the vicinity of the destination.

Figure 2.2 graphically illustrates the operation of the protocol. Assume that node X is the destination, and node S is the source, which is physically located inside Z(X,4,t) (not shown) and outside Z(X,3,t). Given the above, node X's perceived position at node S is equal to C(X,3,t). In other words, nodes outside Z(X,3,t) know X's position within a radius of R(3) meters. Thus, the packet is being forwarded towards C(X,3,t), according to the Data Packet Forwarding procedure described above. The dashed, overlapping circles that are superimposed on top of the routing trajectory represent overlapping core routing zones (sliding-window effect), where local, link-state knowledge is available. As soon as the packet reaches a router within Z(X,3,t), it is re-directed toward C(X,2,t), since nodes within Z(X,3,t) know X's position within a radius of R(2) meters. Similarly, as the packet enters Z(X,2,t), another course-correction happens: the packet is re-directed towards C(X,1,t), since nodes within Z(X,2,t) know X's position within a radius of R(1) meters. After the packet enters Z(X,1,t), at some point it 'hits' Z(X,0,t), where it gets

picked up by the core zone link-state routing protocol running in the vicinity of node X.

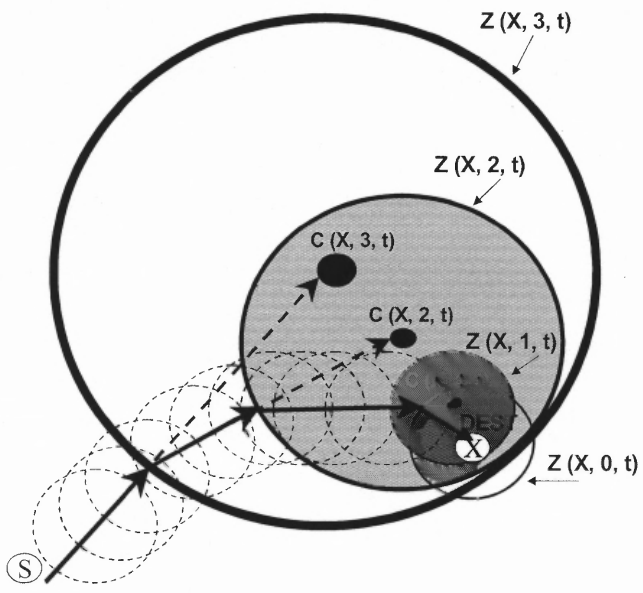


Figure 2.2 Graphical Illustration of the Position-guided Sliding-window Routing (PSR) Protocol.

2.5. Energy Aware PSR Extension

There is no doubt that over the past twenty years there has been steady progress towards making computers more mobile. Several efforts have been devoted to achieve higher processor integration levels and develop high-performance batteries. At the same time with the rise of packet-oriented wireless networks and powerful mobile terminals, various applications/services are under development, such as location-aware navigation guides, financial applications, personal assistance services and entertainment, etc. However these features should be integrated and achieved with energy efficiency in all phases of the system design, especially given the weights and size limitations of mobile devices, which in turn constraints the capacity of the battery and amount of available power/energy.

In mobile ad hoc networks the overall network connectivity depends on the capability

and availability of the nodes between source and destination to relay data packets. As a result the depletion of batteries in certain mobile nodes may result in the disconnection of the network, and/or affect significantly the overall network performance. In order to prolong the operation of an ad hoc network, power/energy consumption should be taken into consideration in various phases of the mobile radio network design, including the routing protocol development phase.

Some research efforts to improve the energy efficiency of location-based routing protocols have been reported in literature (e.g.[28, 29]). In [28], the authors consider the problem of finding a path between a given pair of nodes with the maximum life or maximum battery energy level, while the cost of the path does not exceed a pre-specified bound. In LAPAR [29], the concept of relay region was introduced and defined. Any node located within this region can relay the packet for the packet transmitter, with less power than direct transmission between the transmitter and the receiver. A forwarding node constructs its relay regions based on the position of its neighbors, and forwards a data packet to the specific neighboring node whose relay region covers the destination. If there is more than one neighbor that is able to cover the destination, the algorithm makes greedy choices – e.g. the node that requires the least transmission power from the point of view of the transmitter is selected - to determine the next hop to forward the packet.

In the following, with reference to the PSR protocol, let us consider a scenario where a source node S wants to transmit packets to destination node D, and lets denote by i and j the current node holding the packet and the next CBR in the corresponding path, respectively. Let P_{jD} denotes the path loss between node j and node D, and d_{jD} be the distance between them. Furthermore E_j denotes the percentage of the energy left at node j

at a given time, in which $0 < E_j \leq 1$. The remaining capacity of the battery of each node is one of metrics used in the literature, to measure the lifetime of the network [30]. In the following, for simplicity in the representation and without loss of generality, considering that the channel path loss model is inversely proportional to the *n-th* power of the distance between two nodes, that is: $P_{jD} \sim (1/d_{jD}^n)$ (where typical values for exponent n could range between 2 and 4 depending on the environment).

As described before, in the second step of the data packet forwarding procedure, PSR chooses the next hop for data forwarding as the CBR j that minimizes the Euclidean distance between itself and the final destination D, i.e. the one that minimizes the distance: d_{jD}. However, in this section an extension of the basic PSR operation is described, by modifying the forwarding procedure of PSR, in order to take into consideration additional factors, such as the power and energy efficiency. This is achieved by introducing and defining a new routing cost function, which is a weighted cost function of the following metrics: path loss (distance) and current energy levels. Then, the routing is made based on this cost function. Specifically, if the cost function for local node i is denoted by $f_i(P_{jD}, E_j)$ when trying to identify the CBR j to forward the packet to, then the following optimization should be performed: $Min_{j \in A_i}\{f_i(P_{jD}, E_j)\}$, where A_i denotes the set of the CBR nodes of local mobile host i. It should be noted that parameter P_{jD} is incorporated into the cost function to take into account the power transmission consumption related to the distance between the CBR and the destination. Furthermore, metric E_j is utilized into the cost function so that PSR always attempts to avoid the use of CBR nodes with low battery capacity left (unless these nodes present the only choices). This procedure attempts to distribute the load as evenly as possible among

the CBR nodes, and utilize the energy of the whole network more fairly, thus extending the overall network lifetime. For instance a cost function can be defined as: $f_i(P_{jD}, E_j) = P_{jD}{}^{w1}(\frac{1}{E_j})^{w2}$, where w_1, w_2 are positive weighting indices for the two cost metrics.

2.6. Fault Tolerant Routing in PSR

As mentioned before, PSR is in principle, a position based routing strategy, and as such, it is possible for some packets to end up in a loop operation due to potential path deadlock/loop occurrences. Following is an example network/graph that demonstrates the occurrence of a deadlock/loop event during the routing path creation in PSR. In the graph, node 1 and node 5 represent the source and destination respectively, while

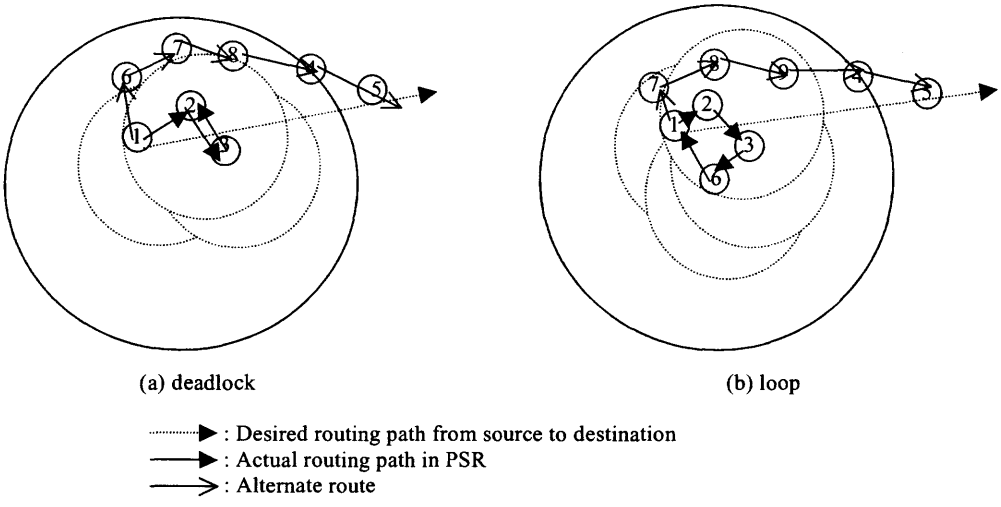


Figure 2.3 Deadlock/loop in PSR.

solid arrow lines show the packet flowing based on PSR routing approach. Dashed circles represent the transmission ranges of each node. In Figure 2.3(a), since nodes 2 and 3 are the closest neighbors to each other, the data packet will be routed between them

indefinitely under the PSR operation (or until is dropped). However, if the deadlock between nodes 2 and 3 could be observed in advance, the packet could follow path 1-6-7-8-4-5, and therefore delivered to final destination. Similarly in Figure 2.3(b), if packets are not allowed to be sent back to recently visited node, then nodes 1, 2, 3, 6 formulate a loop, and the packet will follow this path until the hop count limit is reached.

Therefore a mechanism that can alleviate or minimize these occurrences and routing failures is needed, and improve the routing reliability and fault tolerance performance of PSR. In this section an enhancement to the basic PSR is introduced, by adding an additional level of hierarchy (on the cluster level which is of much smaller scale), thus improving its operational effectiveness and alleviating some of the drawbacks associated with the nature of position-based protocols (such as routing deadlock occurrences).

There are many cluster algorithms for ad hoc networks that have been proposed in the literature [31, 32, 33, 34, 35, 37, 38]. These cluster algorithms can be divided into two main categories. The first type uses cluster-head [33, 38] as the central control point or local coordinator for each cluster. These cluster-heads themselves can further be built up as a higher-level mesh to improve the coordination between clusters. The other type [31, 35] uses distributed and dynamic algorithms to adaptively create clusters, without having to resort to the use of cluster-heads. The advantage of the cluster-head based algorithms is the ease of cluster management and load balance. However, the cluster-heads may become the bottleneck of the cluster and constrain the total performance. Therefore the use and integration of the second class of clustering algorithms with the position based routing strategies is investigated, in order to provide fault tolerant routing in mobile ad hoc networks. It should be noted here that by avoiding the use of cluster-heads and

providing multiple routing paths, high level of fault-tolerance is achieved.

These cluster-based approaches did not investigate in detail the problem of optimal clustering (cluster construction) and its use in providing fault tolerant routing. The main advantage of the proposed procedure, compared to basic position-based routing, is preventing of deadlocks (for example, if there are holes in a network graph, as shown in the figure above). At the same time, no additional information, compared to information about node positions is required.

The proposed enhancement is the integration of a position-based cluster scheme to the PSR protocol. According to the algorithm, all nodes are divided into clusters (number of clusters is much less than the total number of nodes in the system) based on mobile node's geographical positions. Routing procedure consists of two phases – routing inside cluster and routing between clusters. Each node has information about the structure of cluster it belongs to, based on PSR operation, as well as the structure of interconnection graph between clusters (cluster connectivity graph) and information about routing paths to the neighboring clusters (gateways). If the destination node belongs to a cluster, which differs from the source node's cluster, first the routing path in terms of clusters is constructed between source and destination cluster. Clusters and cluster connectivity graph can be reconstructed either when some nodes move a significant distance, or when a fault occurs.

2.6.1. Clustering in PSR

Clusters are constructed based on information about node positions. It is assumed that all nodes within given radius can communicate with each other. Furthermore, in the proposed structure there is no need to disseminate all small changes in node positions to

the whole network. In some sense, the overhead generation rate and propagation distance is directly proportional to the amount of change in a node's geographic position. For example, as long as a node stays in the same cluster, only nodes within this cluster may be updated. If necessary, this idea can be used in a hierarchical manner (using clusters of clusters etc).

2.6.1.1.Fixed Grid-cluster Construction:

The simplest way to partition the network into clusters based on geographical position is to grid it. In this scheme, the whole network is divided into a square-rootable number of clusters. For example, according to the size of the network, it can be divided it into 4, 9, 16 clusters. Figure 2.4 shows an example network partitioned into 4 clusters.

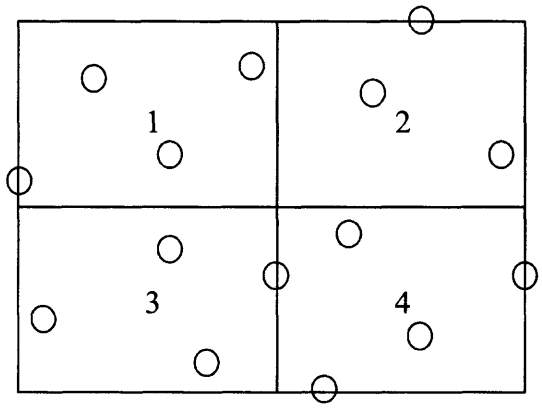


Figure 2.4 Grid-cluster Scheme

Advantages of using fixed grid-cluster based on geographical positions include:

Only position information, which is already propagated by the underlying PSR protocol, is needed in cluster construction and maintenance, so it is simple and no extra overhead is introduced. Furthermore, it makes easy the implementation of geographical multicasting schemes similar to [36] in addition to the traditional group multicasting algorithms.

In fixed cluster construction scheme, each cluster is assumed to have a fixed size. Thus local nodes know exactly which cluster they belong to and how many clusters exist in the network. Nodes that are close to the edge of the cluster calculate the local gateway status and build gateway connections to neighboring clusters. Finally, such information is propagated into the local cluster. A high level description of the cluster construction algorithm is given as in the following.

```
Input number of clusters desired;
Calculate local cluster corner positions;
Mark the cluster number of local node;
Search PSR position table
{       If ((node_id ≠ my_id) & (node_coordinations within transmission range of
local node)
& (node_cluster ID ≠ my_cluster ID))
                {       Mark local node as gateway and add the node to the gateway
list;
                }
If local node is gateway, add such information in GPU packet and propagate to local
cluster.
}
```

Each node runs this algorithm at the beginning to build up clusters and its own gateway connection list, if it is a gateway itself. Gateways that created in this algorithm are mobile nodes that have connection with nodes in neighboring clusters.

2.6.1.2.Cluster Maintenance:

Position information is propagated by the underlying routing protocol. Since the cluster partition is closely related to this information, there is no need to propagate additional information in the cluster level to maintain the cluster structure. The node will automatically recognize its cluster change during its movement. The maintenance is only needed when gateway status of local node changes. Mobile nodes need to verify the new gateway status in the local cluster and distribute this information. The steps of the algorithm used for the cluster maintenance is outlined as following:

For each mobile node, after certain node movement or timer expired;

```
Calculate cluster number of local node.
If (local node qualify for the gateway)
        {Mark the gateway status of local node;
 Check PSR position table, find gateways in neighboring clusters;
 Add such information in GPU and propagate to local cluster;
        }
If (local node was a gateway and doesn't qualify for the gateway any more)
        {
                De-mark local node as a gateway;
                Add such information in GPU and propagate to local cluster;
        }
```

2.6.1.3. Routing in Grid-clustered PSR and Deadlock/Loop Avoidance

Packet routing operation in grid-clustered PSR is the same with the basic PSR, except the mechanism adopted to avoid a deadlock/loop occurrence. As Figure 2.3 shows, deadlock/loops may happen, for instance when the closest neighbor routes the packet back to some nodes along the path. Avoiding a deadlocks as the one presented in Figure 2.3(a) is quite trivial, as long as that the next hop along the path is not the most recently visited node can be guaranteed. However avoiding deadlocks/loops as the one presented in Figure 2.3(b) becomes more complicated, since it may require to upstream to several hops to find out the already visited node. For example, in the loop case in Figure 2.3, three hops from node 6 to node 1 need to be looked up to observe the loop. Even worse, if the deadlock/loop is generated due to a hole in the network, there is a great probability that more deadlocks/loops around this area will be found.

To overcome this drawback that is inherent to the position-based routing schemes, gateways are used as intermediate hops along the path to the destination. When a packet passed the cluster border and arrives to a gateway, some calculations are performed at the gateway to see if there exists a path between the local node to another gateway of local cluster that is closer to the destination. If deadlock/loop is found during this operation, it

is better to request the gateway of the previous cluster to change the path to another cluster or change a different destination gateway in the local cluster. The following figure shows an example that grid-clustered PSR is used to avoid deadlock/loop creation.

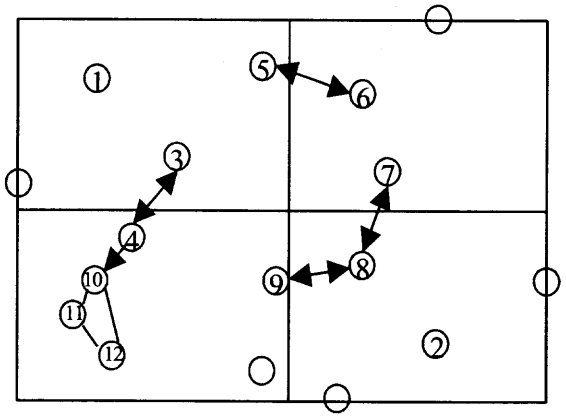


Figure 2.5 Deadlock/loop Avoidance in Grid-clustered PSR.

In this figure, node 1 is the source and node 2 is the destination. Nodes 3-9 are gateways between neighboring clusters. At the source, the next gateway to which packets will be sent is node 3. Since node 3 and 4 are connecting gateways, packets are passed to node 4. At node 4, a loop will be created from node 10 to 12. Thus node 4 informs node 3 to choose another path to transfer the packet. In this example, gateway 5 will be chosen and packet will follow path 5-6-7-8-2 and be delivered to the destination.

CHAPTER 3

MODELING, ANALYSIS AND ZONE OPTIMIZATION OF PSR

In this chapter an analytical model and framework is provided in order to study the design issues and trade-offs of PSR routing mechanism, discuss their impact on the protocol's operation and effectiveness, and identify the corresponding values of the critical design parameters that optimize the protocol's operation under different mobility models and scenarios.

3.1. Modeling and Analysis Framework

The number of the zones defined in the network as well as their respective 'sizes' (i.e. radii of the various zones) are design parameters that are important for the operation and performance of the protocol based on the discussion presented in the previous chapter. Specifically, as the core zone radius becomes larger, the local, link-state overhead increases, but, at the same time, the position-update overhead due to core-zone boundary crossings decreases. In the special case where the radius of the core zone becomes infinite (i.e. there are no zones at all), the performance of PSR becomes the same as that of link state routing. In this special case the amount of overhead is expected to be proportional to node density and the coverage area [30, 40].

In PSR a set of geographic routing zones is defined for each node X (e.g., where the i-th routing zone is a geographic circle with radius R(i) meters. Those routing zones are designed to limit position update propagation, and thus control routing overhead. Intuitively it can be argued that smaller zone radii can further restrict position-update overhead, but lead to larger number of zones, and therefore to a more distorted (curved) routing path, thus increasing the total delay. On the other hand, bigger zone radii can

reduce delay by keeping the routing path closer to a straight line, but this happens at the cost of introducing additional position-update overhead, since position-updates may have to be propagated to a larger area. However at the same time, for a given target area, when the number of zones increases a lot, then the probability that a node movement may result in a crossing of some zone increases, which in turn increases the number of generated and propagated GPU packets. Therefore it is not immediately clear how the control traffic will be affected by the number of zones, and the corresponding zone radii.

As described in the previous chapter, GPUs are generated when the mobile nodes move cross the border of the various level zones. A node disseminates these GPUs to neighbor nodes within its transmission range if it is located within the one level up zone of the crossed zone of the GPU originator and this is the most updated GPU the local node received. Thus the number of GPUs generated is proportional to the number of "zone crossings". If *RAM* denotes the ratio of the active mobile nodes in a given network, and by T_i the hitting (i.e. zone crossing) time of a motion that started at zone-i center, then the average crossing rate $\frac{dC_i}{dt}$ of the i-th level zone per time unit per node is given by:

$$\frac{dC_i}{dt} = \frac{RAM}{E(T_i)} \tag{1}$$

In the following without loss of generality, for representation and demonstration purposes, the following zone configuration is considered:

$$r_{i+1} = r_i Z \qquad i = 1, \cdots N-1 \tag{2}$$

where Z is the ratio of radius between the (i+1)-th level zone and the i-th level zone, and N is the total number of zones in a certain network area. r_1 is assumed to be equal to

R(0), the core zone. Let us also denote by ρ_a the density of the mobile nodes in the network and by T_r the transmission range of a mobile node. Then, if n_n denotes the average number of nodes that are located within the transmission range of a local node (e.g. number of neighboring nodes): $n_n = \rho_a \pi T_r^2$. The total average number of mobile nodes in the (i+1)-th level zone is: $N_node_{i+1} = \rho_a \pi r_{i+1}^2$. Therefore the GPU generation rate of the i-th level zone, expressed in average GPUs generated per time unit per node, due to the crossing of the i-th level zone, is expressed as follows:

$$GPU_i / dt = \frac{dC_i}{dt}(n_n - 1)N_node_{i+1} \tag{3}$$

The total GPU generation rate in the protocol is given by:

$$\begin{aligned} GPU / dt &= \sum_{i=1}^{N} \frac{dC_i}{dt}(n_n - 1)N_node_{i+1} \\ &= \sum_{i=1}^{N} \frac{RAM}{E(T_i)}(\rho_a \pi T_r^2 - 1)\rho_a \pi r_{i+1}^2 \end{aligned} \tag{4}$$

In the following the corresponding average GPU generation rate for three mobility models (i.e. straight-line movement, Brownian (random) movement and Brownian movement with drift) that can be used to model and represent the node movements in typical mobile ad hoc networks is analyzed. Specifically some analytical expressions that present the average GPU generation rate as a function of the various system and zone parameters and configurations are developed. These models and expressions can be used to develop guidelines for the efficient design and tuning of the involved parameters in order to balance the associated protocol tradeoffs.

3.1.1. Straight-line Movement

In this scenario, mobile nodes move in a straight line but in random directions. That is, the initial direction of motion of any node is uniformly distributed over all possible directions. This means that mobile nodes are uniformly distributed on the surface of the network and that the movements of the mobile nodes are not correlated; the initial directions of these movements are uniformly distributed on $[-\pi,+\pi]$.

The average hitting time for Straight-line movement can be expressed as: $E(T_i)=r_i/v$, where v is the average velocity of the mobile node and r_i is the radius of the i-th level zone. Based on this, relation (4) that gives the GPUs generation rate can be expressed as:

$$\begin{aligned} GPU/dt &= \sum_{i=1}^{N} RAMv\rho_a\pi(\rho_a\pi T_r^2-1)\frac{r_{i+1}^{\ 2}}{r_i} \\ &= RAMv\rho_a\pi(\rho_a\pi T_r^2-1)r_1\sum_{i=1}^{N} Z^{i+2} \\ &= RAMv\rho_a\pi(\rho_a\pi T_r^2-1)r_1\frac{Z^2(1-Z^N)}{1-Z} \end{aligned} \tag{5}$$

In a certain given network area, the radius of the biggest zone is r_N. Then according to (2):

$$N=\log_Z Zr_N/r_1 \qquad or \qquad Z=(r_N/r_1)^{\frac{1}{N-1}} \tag{6}$$

and the GPU rate can be easily calculated as:

$$\begin{aligned} GPU/dt &= RAMv\rho_a\pi(\rho_a\pi T_r^2-1)r_1\frac{Z^2(1-Z^N)}{1-Z} \\ &= RAMv\rho_a\pi(\rho_a\pi T_r^2-1)Z^2\frac{r_1-Zr_N}{1-Z} \end{aligned} \tag{7}$$

$$or = RAMv\rho_a\pi(\rho_a\pi T_r^2 - 1)(r_N/r_1)^{\frac{2}{N-1}} r_1 \frac{1-(r_N/r_1)^{\frac{N}{N-1}}}{1-(r_N/r_1)^{\frac{1}{N-1}}} \tag{8}$$

3.1.2. Random Movement (Brownian Motion):

The expectation of e^{-sT_i} which is the Laplace Transform of the pdf of T_i (i.e. the hitting time of a standard Brownian motion started at $x = 0$) for a sphere of radius r_i and centre 0, can be expressed as [41]:

$$\begin{aligned} &E(e^{-sT_i}) = (vr_i)^h / [2^h \Gamma(h+1) I_h(vr_i)] \\ &v = (2s)^{1/2}, \quad h = (d-2)/2 \end{aligned} \tag{9}$$

where d is the dimension number (for 2 dimensions, h = (d-2)/2 = 0) and I_v is the Bessel function "of purely imaginary argument": $I_v = \sum_{m=0}^{\infty} \frac{(\frac{1}{2}z)^{v+2m}}{m!\Gamma(v+m+1)}$. Based on the Moment Theorem [42] for two dimensions $E(T_i)$ can be expressed as:

$$\begin{aligned} E(T_i) &= (-1)\frac{d}{ds} E(e^{-sT_i})\Big|_{s=0} \\ &= (-1)\frac{d}{ds}\left[\frac{1}{\Gamma(1) I_0(r_i\sqrt{2s})}\right]\Big|_{s=0} \\ &= \frac{1}{\Gamma(1)} \frac{1}{I_0^2(r_i\sqrt{2s})} \frac{r_i I_1(r_i\sqrt{2s})}{\sqrt{2s}}\Big|_{s=0} \\ &= \frac{r_i^2}{2} \end{aligned} \tag{10}$$

Following the same steps as before, the average GPU generation rate can be calculated as:

$$
\begin{aligned}
GPU/dt &= \sum_{i=1}^{N} \frac{2RAM}{r_i^2}(\rho_a \pi T_r^2 - 1)\rho_a \pi r_{i+1}{}^2 \\
&= 2RAMNZ^2 \rho_a \pi (\rho_a \pi T_r^2 - 1) \\
&= 2RAM\rho_a \pi (\rho_a \pi T_r^2 - 1) Z^2 \log_Z Zr_N / r_1
\end{aligned} \tag{11}
$$

$$
or \qquad = 2RAM\rho_a \pi (\rho_a \pi T_r^2 - 1) N (r_N / r_1)^{\frac{2}{N-1}} \tag{12}
$$

3.1.3. Random Movement (Brownian Motion) with Drift:

In general the Brownian motion with drift c can be expressed as: $B_t = W_t + ct$, where W_t is the standard Brownian motion. The expectation of e^{-sT_i}, which is the Laplace Transform of the pdf of T_i, can be expressed as [43]:

$$
E_x^c e^{-sT_i} = \left(\frac{\sqrt{v^2 + |c|^2}}{|c|} \right)^h \frac{I_h(|c| r_i)}{I_h(\sqrt{v^2 + |c|^2} r_i)} \tag{13}
$$

$v = (2s)^{1/2}, \quad h = (d-2)/2$

Following similar steps as the ones in the case of the Brownian motion $E(T_i)$ can be expressed:

$$
\begin{aligned}
E(T_i) &= (-1)\frac{d}{ds} E_x^c (e^{-sT_i}) \Big|_{s=0} \\
&= (-1)\frac{d}{ds} \frac{I_0(|c| r_i)}{I_0(\sqrt{2s + |c|^2} r_i)} \Big|_{s=0} \\
&= \frac{r_i I_0(|c| r_i) I_1(\sqrt{2s + |c|^2} r_i)}{\sqrt{2s + |c|^2} I_0{}^2(\sqrt{2s + |c|^2} r_i)} \Big|_{s=0} \\
&= \frac{r_i I_1(|c| r_i)}{|c| I_0(|c| r_i)}
\end{aligned} \tag{14}
$$

When $x>>n$ it can be easily concluded [44] that: $x>>n,\ I_n(x)\approx\frac{1}{\sqrt{2\pi x}}\exp(x)$. Thus $I_n(x)$ becomes unrelated to the order n. Therefore, when $|c|r_i$ is big enough $(|c|r_i>>1)$, $E(T_i)$ reduces to $\frac{r_i}{|c|}$. Based on (4), the GPUs generation rate can be simplified as:

$$\begin{aligned} GPU/_{dt} &= \sum_{i=1}^{N}\frac{RAM|c|}{r_i}\rho_a\pi(\rho_a\pi T_r^2-1){r_{i+1}}^2 \\ &= \rho_a\pi(\rho_a\pi T_r^2-1)RAM|c|Z\sum_{i=1}^{N}r_{i+1} \\ &= \rho_a\pi(\rho_a\pi T_r^2-1)RAM|c|Z^2r_1\frac{(1-Z^N)}{1-Z} \\ &= RAM\rho_a\pi(\rho_a\pi T_r^2-1)|c|Z^2\frac{r_1-Zr_N}{1-Z} \end{aligned} \tag{15}$$

$$or = RAM\rho_a\pi(\rho_a\pi T_r^2-1)|c|r_1(r_N/r_1)^{\frac{2}{N-1}}\frac{1-(r_N/r_1)^{\frac{N}{N-1}}}{1-(r_N/r_1)^{\frac{1}{N-1}}} \tag{16}$$

When $x<<n$ it can be easily concluded [44] that $x<<n,\ I_n(x)\approx\frac{1}{n!}(\frac{x}{2})^n$ and therefore, when $|c|r_i$ is small enough $(0<|c|r_i<<1)$:

$$E(T_i)=\frac{r_iI_1(|c|r_i)}{|c|I_0(|c|r_i)}\approx\frac{r_i^2}{2} \tag{17}$$

In this case it approximates the random movement without drift. Therefore the average GPU generation rate is the same as the random movement:

$$\begin{aligned} GPU/_{dt} &= 2RAM\rho_a\pi(\rho_a\pi T_r^2-1)Z^2\log_Z Zr_N/r_1 \\ or \quad &= 2RAM\rho_a\pi(\rho_a\pi T_r^2-1)N(r_N/r_1)^{\frac{2}{N-1}} \end{aligned} \tag{18}$$

In summary the average GPU generation rate of random movement with drift is:

$$GPU/_{dt} = \begin{cases} RAM\rho_a\pi(\rho_a\pi T_r^2 - 1)|c|Z^2 \frac{r_1 - Zr_N}{1-Z} & (|c|r_i >> 1) \\ 2RAM\rho_a\pi(\rho_a\pi T_r^2 - 1)Z^2 \log_Z {Zr_N}/{r_1} & (0 < |c|r_i << 1) \end{cases} \quad (19)$$

3.2. Optimal Zone Configuration and Discussion

In this section how the analytical models that developed can be used in the evaluation of the various design tradeoffs and the identification of the optimal values of the zone configuration parameters is demonstrated. Specifically a network with fixed density of 0.5nodes/Km^2, where the core zone is r_0=$3Km$ and the largest zone is $r_N = 8.7Km$, is considered. Figure 3.1 presents the average GPUs/node/second generated vs. the radius ratio Z according to relation (7) for the case of straight-line movement for three different mobile node speeds (low=20km/hr, medium=50km/hr and high=80km/hr). From this figure it can be seen that the total number of GPUs per node per time unit generated initially decreases as the zone radius ratio Z increases, while after some point it starts increasing again as the zone radius ratio increases. It should be noted here that for a given target area, when this ratio increases the actual number of zones per node in the system decreases.

The trend presented in the curves in Figure 3.1 is the combined effect of the following two interrelated design parameters and observations: the bigger difference between the radii of two consecutive zones (e.g. the zone ratio) introduces additional position-update overhead, since position-updates may have to be propagated to a larger area; while as the number of zones increases a lot, the probability that a node movement may result in a crossing of some zone increases as well, therefore increasing the number of generated and propagated GPU packets. Thus in Figure 3.1 for the first initial small values of ratio Z the large number of zones is the main contributor to the overhead, while after some point as this ratio increases, the overhead is

overwhelmed by the contribution of the large number of propagated GPUs due to the large area that the generated GPUs have to be propagated because of the large value of Z.

There exists an optimal zone radius ratio that results in the minimum number of GPUs. Based on certain network parameters, this point can be easily obtained and the zone ratio be pre-set in order to control and minimize the overhead generated by PSR. For instance, based on the analysis and the corresponding mathematical relations that developed in the previous section, it can easily be concluded that for the case of low mobility (20km/hr) the optimal operational point of the algorithm is when the zone ratio Z is: $Z_1 = 1.449$.

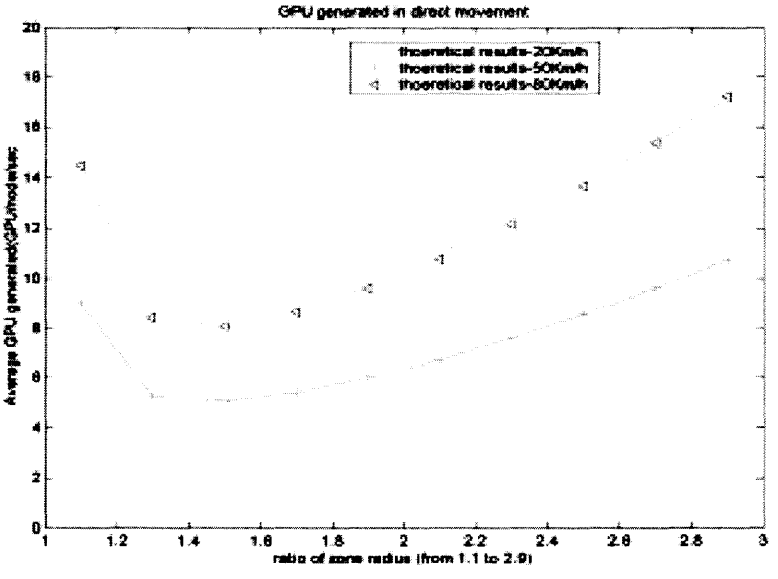


Figure 3.1 Average Number of Routing GPU Packets per Node per Time Unit (sec) (for Low, Medium and High Mobility) as a Function of Zone Radius Ratio in Straight-line Movement.

In Figure 3.2 the average number of routing GPU packets per node per time unit (sec) as a function of zone radius ratio in random movement with drift, with average velocity 20Km/h and for three different drifts: low, medium and high drifty are presented. From

this figure a similar tend as in Figure 3.1 is observed, where initially the GPU generation rate decreases as the zone radius ratio increases, for all the three mobility scenarios, and increases gradually after an optimal point. It should be noted here that in the scenario considered for the results presented in Figure 3.2, $|c|r_i$ is much larger than 1 for all three mobility cases and therefore the results are obtained based on relation (15).

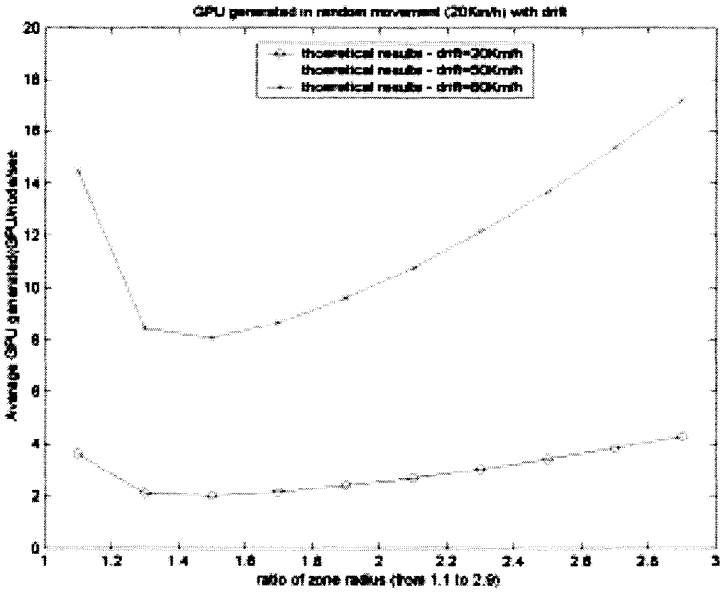


Figure 3.2 Average Number of Routing GPU Packets per Node per Time Unit (sec) as a Function of Zone Radius Ratio in Random Movement with Drift, with Average Velocity 20Km/hr and for Three Different Drifts: Low, Medium and High Drift.

CHAPTER 4

PSR PERFORMANCE EVALUATION

In this chapter, the framework that is used to evaluate the protocol's performance, as well as some numerical performance results, is presented. The emphasis of the protocol performance evaluation is placed on its scalability capabilities and its routing effectiveness.

4.1. Model and Assumptions

The performance evaluation of the protocol is accomplished via modeling and simulation using the Optimized Network Engineering Tool (OPNET). Since the main objective of this evaluation is to develop and evaluate the efficiency of the routing strategy, the simulation study is mainly focused on network layer details, while simplified models are assumed for the data link layer.

The link layer itself provides ideal scheduling of packet transmissions to avoid collisions. Although such a scheme is not feasible in practice, the protocol evaluation is performed assuming such an ideal link layer protocol, because the control traffic performance of the protocol depends very little on the underlying medium access control (MAC) protocol. By reducing the complexity of the MAC layer, simulation of large dense networks of highly mobile nodes becomes feasible.

In addition the use of ideal MAC allows us to isolate impacts and delays associated with particular MAC scheme. Each node is modeled as an infinite-buffer, store-and-forward queuing station. The mobile nodes are assumed to have constant radio range of R m. Therefore, this behavior may be interpreted as follows: any packet can be received error free within the transmission range of a node (i.e. radius of R from the transmitter), but is

lost beyond R. Since packet delivery is guaranteed to any destination in the range of the source, the complexity of the model is further reduced by eliminating retransmissions at the data link layer. Throughout the study, it is assumed that a link fails, or reappears, as a node goes out or in transmission range of another node, due to the mobility of the nodes. Note that in the experiments, it is possible for a node to receive multiple packets from different neighbors simultaneously. All those packets are placed in the node's receiving queue to be served by the node (in an order determined by OPNET).

Mobile nodes are assumed to be moving around, throughout a closed rectangular region of size Y m x Y m, according to a simple mobility model. The basic mobility model used throughout the evaluation is as follows: at any point in time mobile movement is characterized by two parameters, its velocity vector $\boldsymbol{v}$ (value v and direction Φ) and its current position (x, y). The velocity value v is assumed to be constant for the whole duration of the mobile movement, while the movement direction Φ is updated every time interval Δt, according to the model: $\Phi(t+\Delta t)=\Phi(t)+\Delta\Phi$, where $\Delta\Phi$ is a uniformly distributed random variable in $[-\pi/4,+\pi/4]$. Each mobile recalculates a new position (new move) every Δt time units. After each such move, the mobile node X computes its neighborhood and possibly generates the appropriate $GPU(X,i)$ packet for routing update purposes. This model, which provides a variation of the Brownian movement with drift, is utilized in the simulation in order to better and more accurately represent the typical movement of mobile nodes in realistic mobile ad hoc networks.

4.2. Scalability Evaluation

One of the most important design objectives of the development of PSR is the scalability

property. In this section the protocol's scalability (measured by routing overhead) is studied, by calculating the average number of routing packets per node, as a function of the network size (number of nodes) and network density, under various mobility scenarios. While the neighbor discovery mechanism could be considered as additional overhead (i.e. use of hello beacon signals), this additional traffic is independent of both velocity and the protocol design parameters. Furthermore the neighbor discovery process is not an exclusive component of the protocol, and as such the beacons used by the neighbor discovery mechanisms are not counted for in the evaluation. In this work the protocol's operation effectiveness under three mobility scenarios that correspond to low mobility (v=20 km/hr), medium mobility (v=50 km/hr), and high mobility (v=80 km/hr) is investigated. The scalability of the protocol is evaluated under two main scenarios. In the first one the protocol's operation under different network sizes (maintaining the network density constant) is evaluated, while in the second one the network density is varied, for a given number of nodes.

Therefore in the first scenario, since the primary goal is to evaluate the net effect of the network size on the protocol's routing overhead, the following numerical results are obtained by keeping fixed most of the protocol related parameters throughout the simulation and varying only the network size and the moving speed of the mobile nodes. The default values for the protocol related parameters used in these tests are: Node Transmission Range = 3km, $R(0)$=6km, radius of zone[i] = $3*2^i$ (km) for i=1,2,3,4,... (e.g. zone ratio Z=2). For destination nodes (either final destinations or intermediate destinations) within the core zone of a node A, ideal link state routing and communication is assumed. In addition, the Zone Refresh Timers are not utilized in the

current implementation (i.e., timers are set to infinite values). The number of mobiles ranges from 500 to 5000 nodes, while maintaining the network density (number of mobiles per surface unit) constant and equal to 0.25 mobiles/Km^2.

In Figure 4.1 and Figure 4.2 the Average Number of Routing Packets (GPUs) per Node per time unit (sec) for each zone is presented, as well as the Average Number of Total_GPU packets, versus the network size (number of nodes in the network), for the cases of v=20km/hr and v=50km/hr respectively. As seen from these figures, the average number of routing packets transmitted by a node is growing at a rate that is much lower than the corresponding network size increase. For instance, as seen by Figure 4.1, an increase in the network size of five times (i.e., from a network of 1000 nodes to a network of 5000 nodes) results in an increase of only 25% in the corresponding average number of GPU packets per node per time unit, which essentially demonstrates that the protocol is practically insensitive to the network size. This clearly indicates that the protocol possesses the scalability property, which is very critical in mobile ad-hoc networking environments, without having to resort to complicated and vulnerable hierarchical approaches.

As seen by Figure 4.1 and Figure 4.2 the average number of routing packets follows the same trend independent of the mobility pattern. However, as indicated by the numerical values in Figure 4.2, faster mobility leads to the generation of more routing packets per time unit, than the ones generated under the low mobility scenario. This happens because the changes in the topological characteristics of the network due to the mobility are more drastic in that case. In order to keep track with those fast network topological changes the protocol needs to generate routing packets more often. Therefore the protocol is self-

paced, in the sense that it automatically adjusts the generation of routing control packets depending on the mobility characteristics of the network.

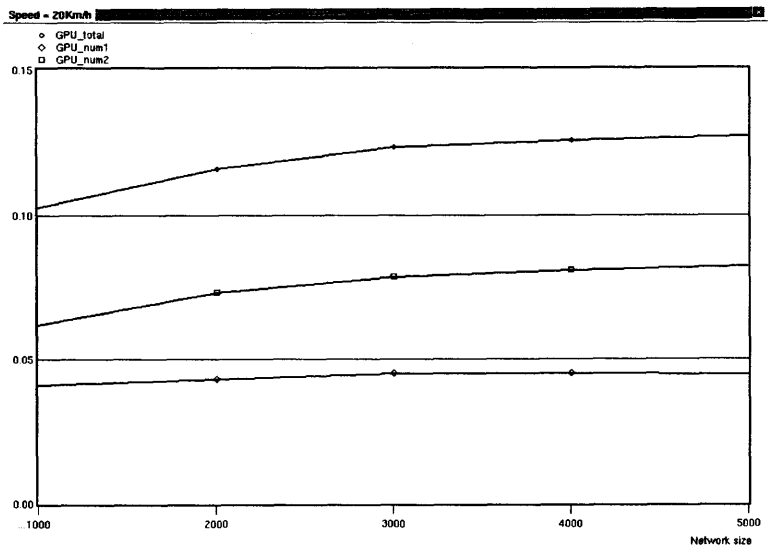


Figure 4.1 Average Number of GPU Packets (for Each Zone and Total) per Node per Time Unit (sec) Packets versus the Network Size (Number of Nodes in the Network) for the Case of V=20 Km/hr.

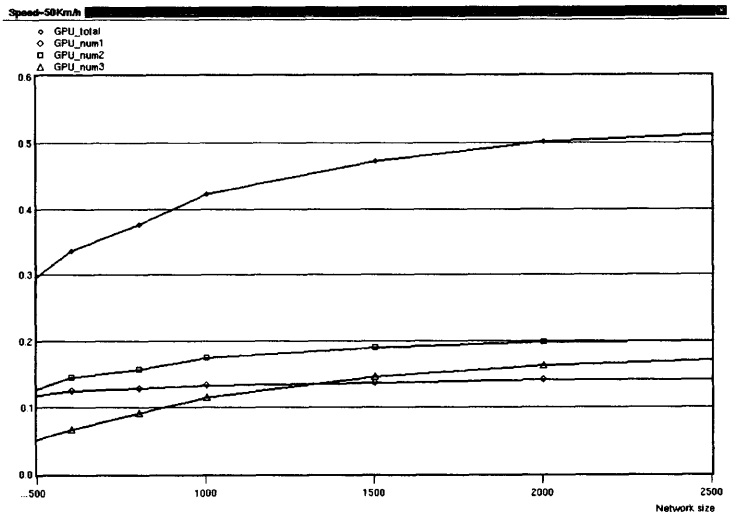


Figure 4.2 Average GPU Packets (for Each Zone and Total) per Node per Time Unit (sec) Packets versus the Network Size (Number of Nodes in the Network) for the Case of v=50 Km/hr.

In the second test scenario of the scalability experiment, the protocol's performance under different network densities is evaluated. Specifically for a fixed network size of 400 mobile nodes the network density is varied from 0.25 nodes/km^2 to 1 node/km^2. Figure 4.3 presents the corresponding results for the low, medium and high mobility scenarios. As seen from Figure 4.3 the number of generated and propagated GPUs increases at a much lower ratio compared to the network density increase.

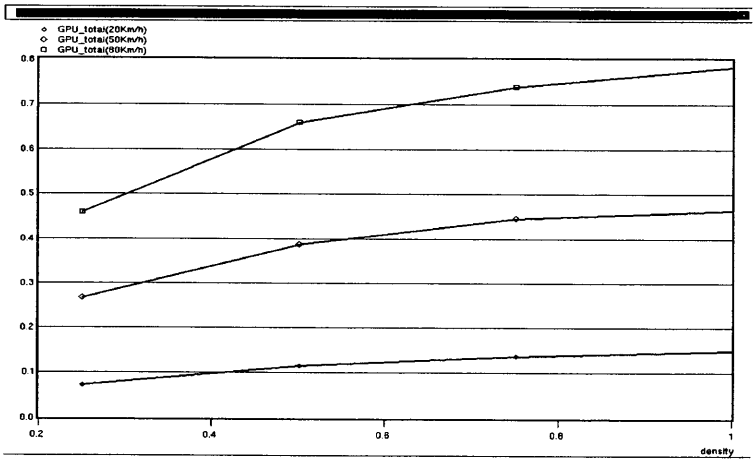


Figure 4.3 Average Number of Total GPU Packets per Node per Time Unit (sec) Packets versus the Network Density (Number of Nodes per Km^2) for Low, Medium, and High Mobility.

4.3. Route Selection Process Evaluation

In this section, some numerical results to evaluate the protocols' route selection effectiveness are presented. Due to the operation mechanism of the PSR, accurate position information is not propagated to nodes beyond the (i+1)th zone when the movement of nodes is within the i-th zone. In this case, positions of other hosts known by the local host may include inaccuracies, and thus the routing path calculated based on this information may not be optimum. Therefore the path that eventually a data packet follows in order to be delivered to the appropriate destination (that itself moves) may

include some deviations from the optimal path (or the shortest path). In the following such deviations are referred as "route distortion". In order to quantify and evaluate the introduced "route distortion" by the protocol, the performance of the PSR protocol with a non-realistic "ideal routing" protocol is compared. In the "ideal routing" case, data packets are routed assuming continuous and accurate knowledge of the exact node position. Every movement of the node in the ad hoc network is recorded and made known for others immediately when it happens. Such a routing scenario would be equivalent to the operation of a centralized routing scheme that assumes continuous and complete network topology knowledge. However such a routing protocol is impossible to be implemented and realized in practice for large-scale mobile networks due to the tremendous overhead involved.

The "route distortion" due to those inaccuracies is evaluated by comparing the number of hops needed to route data under PSR, against the corresponding results obtained for the "ideal routing". Specifically in Figure 4.4 the corresponding results for various network sizes and mobility scenarios (low, medium, high) for a network with density 0.5 mobiles/km^2 are presented The results indicate that for various mobility scenarios PSR has nearly optimum data routing characteristics. As can be seen from Figure 4.4 the "route distortion" measured in hop numbers is less than 5% for all the various mobility scenarios that were considered.

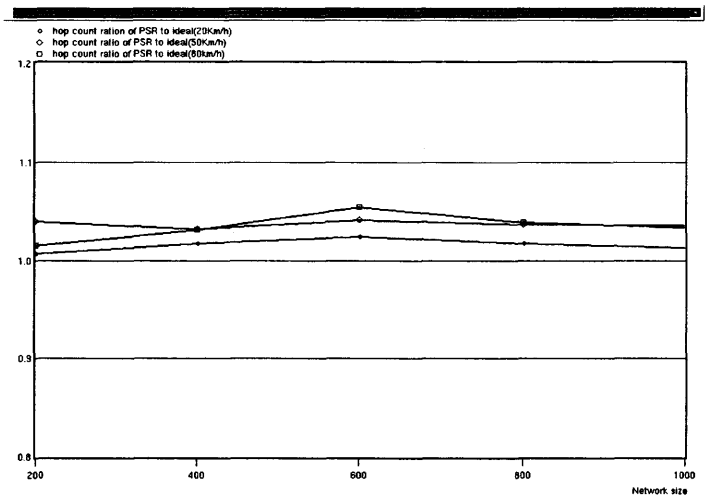


Figure 4.4 Average Hop Count Ratio of PSR versus "Ideal Routing" for Low Mobility (v=20 Km/hr), Medium Mobility (v=50 Km/hr) and High Mobility (v=80 Km/hr).

4.4. Zone Configuration

Table 4.1 Multi-Zone Configuration for Figure 4.5 (Core Zone = 6Km)

In this	zone sizes (km)
2	{6,40}
3	{6,18,40}
4	{6,12,24,40}
5	{6,11,19,35,40}
6	{6,9,14,20,30, 40}

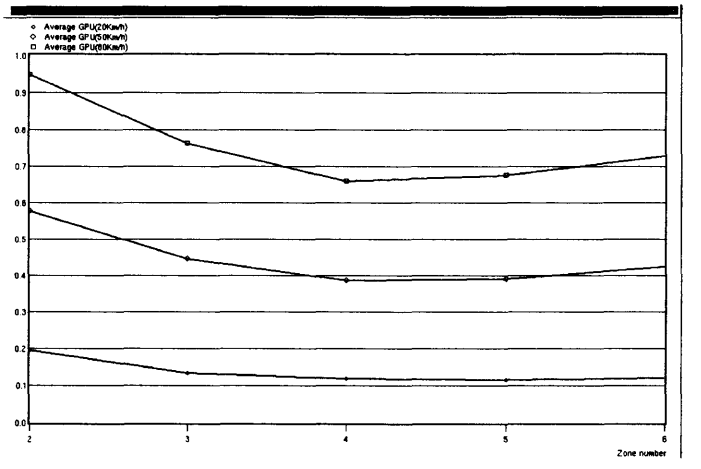


Figure 4.5 Average Number of Routing GPU Packets per Node per Time Unit (sec) (for Low, Medium and High Mobility) as a Function of the Number of Zones (Core Zone = 6Km).

Those results demonstrate the dependence of the optimum zone configuration (i.e. number of zones and corresponding radii) on network configuration and node behavior (i.e. mobility). As seen from Figure 4.5, as mobility increases the number of GPU increases as expected, and at the same time the optimal point of operation moves towards a smaller number of zones with larger radii. This is justified by the fact that as mobility increases the advantage of limiting the propagation of control packets to a restricted zone is overwhelmed by the often generation of GPU packets and the need to propagate that information to large areas, in order to keep track of a node's new position, as discussed in section 3.2.

Similarly, Figure 4.6 presents the corresponding results for the same network with the core radius set to 9km. The following Table 4.2 summarizes the various network configurations used to obtain the results of Figure 4.6. As seen from those figures, the larger the core zone the smaller the impact of the actual configuration of the number and sizes of the other zones defined in PSR protocol, for a given network.

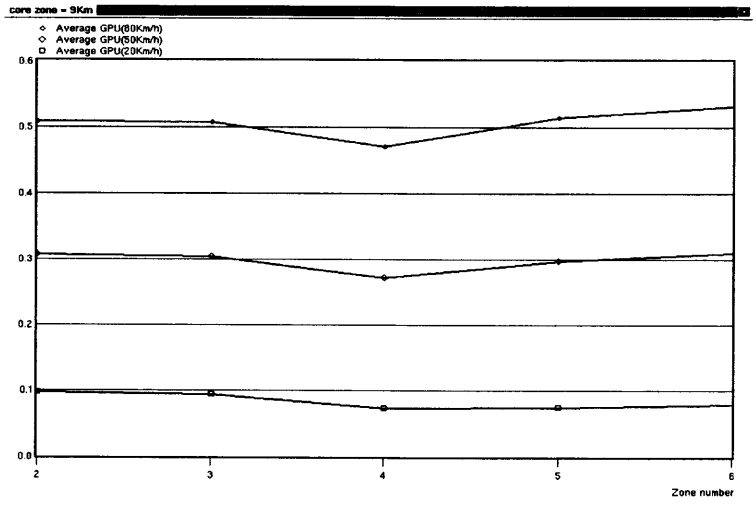


Figure 4.6 Average Number of Routing GPU Packets per Node per Time Unit (sec) (for Low, Medium and High Mobility) as a Function of the Number of Zones (Core Zone = 9km).

Table 4.2 Multi-Zone Configuration for Figure 10 (Core Zone = 9Km)

# of zones	zone sizes (km)
2	{9,40}
3	{9,27,40}
4	{9,16,29,40}
5	{6,14,20,30,40}
6	{9,12,18,24,35, 40}

4.5. Performance of the PSR Power Extension

The power/energy aware PSR extension is designed to extend the lifetime of the ad hoc network by integrating power/energy metrics, when selecting the next CBR node. In this experiment, the lifetime of the ad hoc network under the power/energy aware PSR extension is compared with the pure PSR that considers only the Euclidean distance between the CBR and the destination as the cost metric.

Depending on the network topology and the corresponding applications, several definitions of the network lifetime have been reported in the literature. Some of them define the network lifetime as the time interval from the point that the mobile ad hoc network starts its operation, until the point that the coverage falls below than a pre-specified threshold, or until the point that the number of active nodes is less than a pre-specified threshold. Alternatively other definitions have defined the network lifetime, as the time interval from the point that the network starts its operation until the point that the first node exhausts its energy. In this study, without loss of generality and for demonstration purposes, the latter definition is adopted, and therefore the network lifetime is defined here, as the time when the first node runs out the battery. Such events may lead to path breakages and network partitions.

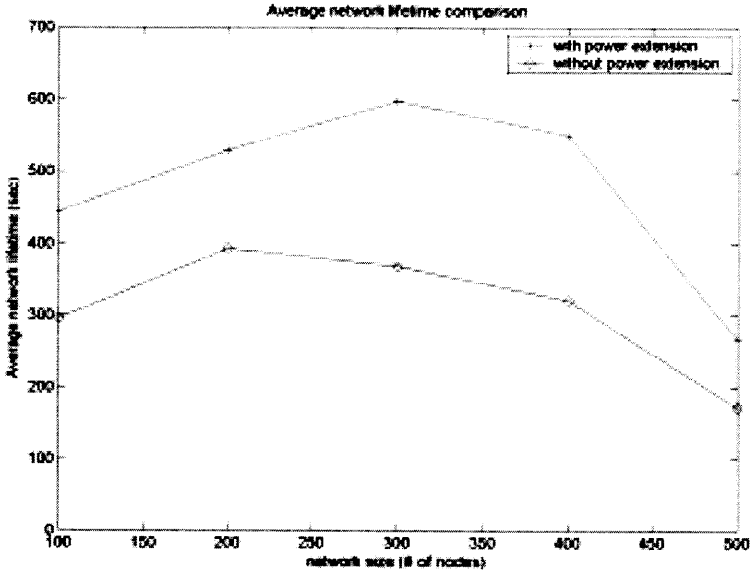


Figure 4.7 Average Network Lifetime Comparison with/without Power Extension.

Figure 4.7 presents the average network lifetime under the basic PSR and the power/energy aware PSR extension. In this experiment the network density is 0.5nodes/Km^2 while 100% traffic load is assumed, that is, every node is the source and could be the destination of a communication session. From Figure 4.7 it can be seen that the network lifetime has been greatly extended by using the PSR power/energy extension. The extension of the network lifetime is achieved because the improved PSR tends to choose the next CBR with more available energy, rather than making its decision depending only on the distance to the destination. This in fact results in distributing the traffic more evenly in the various nodes, therefore protecting certain CBR from having their battery energy depleting very fast. It can be also noted in this figure, that for large networks, the network lifetime decreases as the network size increases, for both basic PSR and the power/energy aware PSR extension. This happens because, as the network size increases, the number of traffic sources, as well as the total traffic in the network are

increasing too, especially when the average number of hops that a packet has to go through in the network increases. Therefore, the overall traffic generated and transmitted in the network increases significantly, which could result in utilizing the energy of certain nodes faster and more easily.

In the next experiment, the hop count performance of the PSR after applied the power/energy extension is evaluated and compared with the original PSR. As indicated in the cost function in section 2.5, the battery level in the CBR, is integrated into the cost function to distribute the traffic evenly and avoid using the CBRs with low battery capacity left. The net effect of this scheme is that the chosen CBR may no longer be the one that has the shortest Euclidean distance to the destination. Therefore, more hop counts may be introduced for the data forwarding process, from the source to the destination.

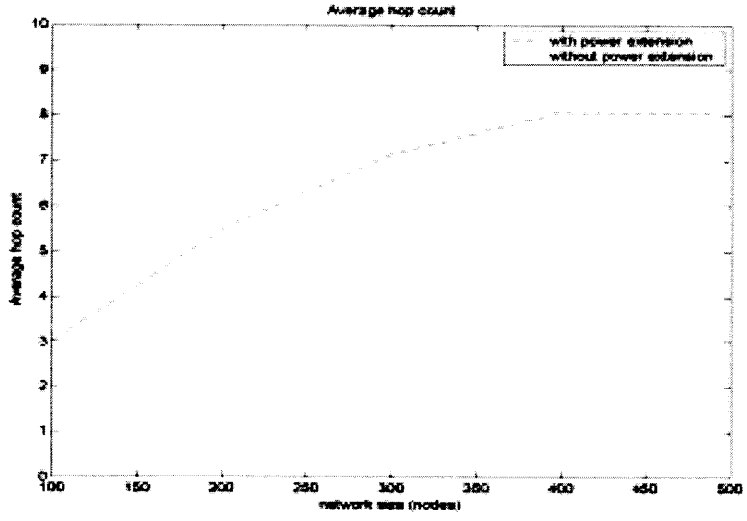


Figure 4.8 Average Hop Count Comparison with/without Power Extension.

As seen from Figure 4.8, the average hop count for the PSR with the power extension is

larger than the original PSR, as expected. However, this increase is negligible for small size networks, and less than one hop for network sizes as large as 500 nodes.

CHAPTER 5

LAYER-2 BRIDGING FRAMEWORK AND PROTOCOLS

5.1. Introduction and Overview

Wireless local area networks (WLAN) are being deployed widely to support networking needs of both consumer and enterprise applications [45]. IEEE 802.11 specification [46] is becoming the de facto standard for deploying WLAN. However the high data rates achieved by contemporary WLAN technologies are restricted to very short ranges [47, 48]. IEEE 802.11 specification supports only single hop communication between nodes. Work that has been reported in the literature to increase the range of the WLAN by using multiple hops between the mobile nodes and the access point (AP), has mainly addressed the ad hoc multi-hop communication only as a routing problem (e.g. [8, 9, 49, 50]). In [51] the Wireless Mesh Routing protocol is proposed, which routes packets based on the distance between the local nodes to the access point (AP). A DSR (Dynamic Source Routing) [49] like routing inquiry and reply path discovery scheme are implemented and link qualities are considered in the path selection procedure to provide Quality of Service (QoS) support.

The problem of extending the network coverage in WLAN has recently received significant industrial attention as well [10, 11]. The Mesh Enabled Architecture (MEA) [10] mobile broadband solution of Meshnetworks, Inc. is based on its patented ad hoc peer-to-peer routing technology and QDMA (Quadrature Division Multiple Access) radio protocol, to enable every device in the network to act as a router and repeater for all other devices in the network. This Multi-Hopping™ capability eliminates the need for cell

towers and creates a robust, interconnected network that automatically routes around congestion and line-of-sight obstacles, while improving throughput as subscriber density increases.

In this chapter the operation of a novel layer-2 bridging architecture to increase the range of an 802.11 access point using multi-hop ad hoc networking is proposed and described. The saturation throughput analysis and the performance evaluation of the proposed scheme are presented in Chapter 6 and Chapter 7 respectively. It should be noted that the proposed bridging architecture mainly aims to address and solve the hotspot communication problem, where a large number of mobile users require Internet access [52] through an access point. In cellular networks several protocols have been proposed to solve the mobility problem [53, 54]. However, the basic operational principles of these approaches indicate frequent handoffs, which are preventing them from providing satisfactory solution, especially for multimedia applications. If the coverage area of each access point in WLAN can be extended, there will be far less requirement for handoffs between APs which will result in significant performance improvements, while at the same time will allow for increased degree of mobility [47].

In this work, due to the lack of infrastructure in mobile ad hoc networks (they do not have fixed routers and/or hosts) and due to the fact that as nodes move, addresses may not imply anything about the logical or physical attachments to the network, bridging techniques that rely on the data link layer to forward packets in the network is proposed. One of the main difficulties in solving the multi-hop extension using conventional spanning tree based layer-2 bridging solutions, is the number of times spanning tree update will have to be done in a mobile ad hoc network. Therefore, neither 802.1D

spanning tree protocol [55] nor the 802.1w (Rapid spanning tree protocol) [56] amendment to it can be used here, as the topology changes in an ad-hoc network can be too frequent for these protocols to converge in time. However, the requirements are slightly different in the problem with respect to the standard bridging requirements. The differences are: a) The root of the spanning tree is fixed at the AP; b) A next hop in the forwarding table can be a group of nodes rather than a single node, as every node in the network can potentially act as a bridge. The innovative solution proposes a framework that avoids the requirement of rebuilding the spanning tree protocol frequently.

In the proposed framework nodes are divided into levels based on their distance (hops) from the AP. Layer-2 bridging tree is built based on the level concept - node in certain level only forwards packets to nodes in its neighboring level, either to lower-level uplink or higher-level downlink. The forwarding problem basically now becomes identifying the right node in a level up in upstream direction and level down in downstream direction.

A node's hierarchical level, starting from the access point that has the lowest level, is defined according to the following rules:

a) The access point is the first level

b) If the lowest level of a given node's neighbors is i, then the local node's level is i+1

Following two different approaches (tree establishment algorithms): single path and multi-path are presented, which are differentiated by uplink construction.

5.2. Uplink Single Path Tree Scheme

In the single path scheme, mobile node chooses one, and only one, node in parent level as the bridge towards to the AP based on certain criteria. To establish the level structure and build the forwarding tree, each node broadcasts hello message to its neighbors with the

following format:

Level (i)	My_ID	Parent_ID	AP_flag

The definition of these fields is as follows:

Level (i): the level of the transmitting node

My_ID: local node's identification (MAC address)

Parent_ID: identification (MAC address) of the designated parent of local node

AP_flag: Boolean value of local AP setting

Initially, level (i), parent_ID are set to 0, while My_ID is the local MAC address. AP_flag is set to 0 except by the access point which sets it to 1. Throughout the operation of the algorithm, a local node updates its level based on the level information received from its neighbors and following the rules described above. Parent_ID is the node ID from which the local node obtained its level. If more than one nodes reported the same level to the local node, then only one of these nodes will be selected as the parent ID. Although in the following it is assumed that in this case the parent node is randomly chosen among the candidates, other more enhanced heuristics that take into consideration different parameters such as the available battery power, etc. may be used as well. Furthermore, as explained later in this chapter, multi-path tree extensions to this approach can be considered where there is no single parent limitation.

5.2.1. Forwarding Tree Establishment

Based on the hierarchical level definition and the rules described above, each node builds a neighboring status table in the following format, assuming that the local node is at level i:

Level	Neighbor nodes	Child_flag
i-1	ID_1(i-1)	0
	ID_2(i-1)	0
	⋮	⋮
I	ID_1(i)	0
	ID_2(i)	0
	⋮	⋮
i+1	ID_1(i+1)	0
	ID_2(i+1)	1
	.	0
	ID_j(i+1)	1
	.	.
⋮	⋮	⋮

Child_flag is set when a received hello message has the local node ID set as the Parent_ID. Entries shall be automatically removed after a specified time has elapsed since the entry was created or updated. In the above table, ID_2(i+1), …, ID_j(i+1) are child nodes. A separate entry that has single field of parent node ID is created as explained before. Thus a single path tree rooted at the access point is established from node to access point direction. It should be noted that if the parent node moves out of reach of the current local node, this field is updated with another one of the available parent options (i.e. another node that the local node may obtain its level from). Figure 5.1 demonstrates the forwarding tree establishment procedure. The forwarding tree for node 14 will be: 14→7→3→1 (AP).

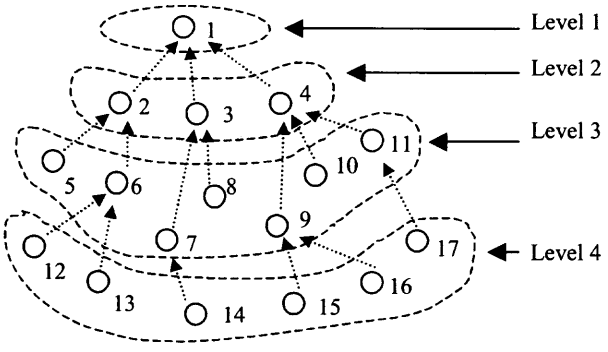


Figure 5.1 Single Path Forwarding Tree Establishment.

Following is the pseudo code of the uplink forwarding tree establishment in the single tree scheme:

```
If (hello_timer expires)
{       create a new neighbor_hello packet;
        broadcast the neighbor_hello packet;
}
if (neighbor_hello packet received with: rcv_level, rcv_id, rcv_parent, rcv_AP)
{
search local neighbor status table;
        if (rcv_id found)
        {
                update rcv_level;
update AP if changed;
        }
        else if (!rcv_id found)
        {
                create a new entry in neighbor status table;
        }
        if(rcv_parent == local_node_id)
        {
                set child_flag;
        }
        if (rcv_level is the smallest)
        {
                update local node level to rcv_level+1;
        }
        if(rcv_level == local_level-1)
        {
```

```
                set parent_node_id = Random (node in local_level-1);
        }
}
```

5.2.2. Data propagation

A transmitting node, which can be either the original source or an intermediate node in the upstream direction towards the AP that may act as a relay node, needs to make the forwarding decision in order to propagate the data to the AP. There are two options that can be followed, that are different from implementation point of view.

Option 1: The transmitting node includes the intermediate destination node address, as this is determined by the established forwarding tree, in all the data packets it forwards. Then every node that receives the packet compares the intermediate destination ID in the packet with its own_ID to determine if the packet should be picked up and processed. This method requires the transmitting node to include the intermediate destination address in the forwarding packets which enlarge the header size of the packet, however simplifies the receiving decision processing of the involved intermediate nodes that receive the packet. It should be noted that the MAC format in IEEE 802.11 standard defines four address fields. The intermediate ID will use the Receiver Address (RA) field to store the intermediate destination ID.

Option 2: The transmitting node transmits the packet to its neighbors without including any intermediate destination node address. Every neighboring node that receives a data packet determines if the packet should be picked up and processed by this node, based on the transmitter MAC address. Only the neighbor node, for which the transmitter MAC address is equal to one of its recorded child_IDs, will pick up and relay the packet towards AP. The other nodes will discard the packet. This does not require the transmitter

to include the intermediate destination address and therefore saves the corresponding processing time and effort, however the receiving nodes need to search their recorded child_ID spaces to determine if they should pick up the packet.

5.3. Uplink Multi-path Tree Scheme

The difference between the multi-path tree and single path tree scheme is that there is no single parent node limitation. The neighbor_hello message exchanged between neighbors for the multi-path tree case is defined as:

Level (i)	My_ID	AP_flag

Initially, level (i) is set to 0, My_ID is the local MAC address, and AP_flag is set to 0 except for the access point, which sets it as 1.

5.3.1. Forwarding Tree Establishment

The neighboring status table is built in a similar way as before. No child_flags are defined in multi-path tree scheme, thus any node that belongs to the level i-1 can be selected as the next hop on a per packet basis. Therefore, multi-path from the source to the AP becomes possible if more than one neighbor node exist in parent level.

Figure 5.2 shows an example of multi-path forwarding tree establishment. From this figure it can be seen that node 6, 10, 12 and 13 all have multiple parent nodes. Thus for these nodes, there may exist multiple paths in the uplink direction.

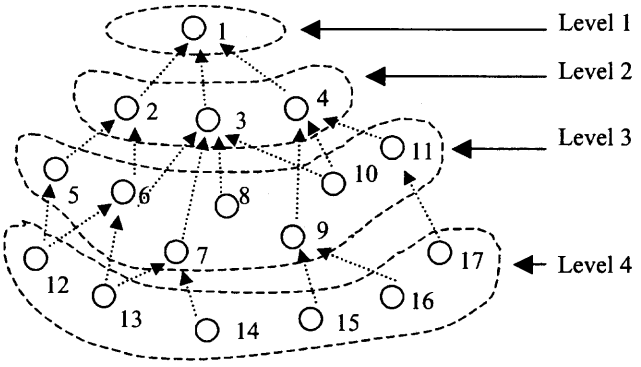


Figure 5.2 Multiple Path Forwarding Tree Establishment.

Following is the pseudo code of uplink forwarding tree establishment in multiple path scheme:

```
If (hello_timer expires)
{
        create a new neighbor_hello packet;
        broadcast the neighbor_hello packet;
}
if (neighbor_hello packet received with: rcv_level, rcv_id, rcv_AP)
{
        search local neighbor status table;
        if (rcv_id found)
        {
                update rcv_level;
update AP if changed;
        }
        else if (!rcv_id found)
        {
                create a new entry in neighbor status table;
        }
        if (rcv_level is the smallest)
        {
                update local node level to rcv_level+1;
        }
}
```

5.3.2. Data Propagation

The transmitting node, which can be either the original source or an intermediate node in

the upstream direction towards the AP that may act as a relay node, chooses one of nodes of parent level as intermediate destination. The choice can depend on many different optimization parameters and criteria, and can range from random selection to load balancing and power balancing considerations. Then when a local node senses a packet sent from a node of higher level, it will pick it up if itself is the immediate destination or transmitter MAC address matches one of its child node ids.

5.4. Downlink Path Establishment and Data Forwarding

5.4.1. Downlink Path Establishment

To achieve the downlink communication (e.g. from AP to the end nodes) in an efficient way, source information is cached during the uplink packet forwarding. As mentioned before the bridging algorithm proposed in this chapter mainly aims to address and solve the hotspot communication problem, where a large number of mobile users require access through an access point, to information provided by a small and finite number of sites. Peer to peer communication is rare and also depends on local cache for downlink forwarding. Information that is cached at a local node along the uplink route data forwarding includes: source node address of the packet (i.e. address of the node that originated the packet) and the intermediate node address from which the packet is forwarded to the local node. The structure of the cached data is presented as following:

Source address 1	Previous bridge 1	Timer 1
	Previous bridge 2	Timer 2
	⋮	⋮
	Previous bridge n	Timer n
Source address 2	Previous bridge 1	Timer 1
	Previous bridge 2	Timer 2
	⋮	⋮
	Previous bridge n	Timer n

⋮	⋮	⋮
Source address N	Previous bridge 1	Timer 1
	Previous bridge 2	Timer 2
	⋮	⋮
	Previous bridge n	Timer n

For the single-path level tree algorithm described in the previous sections, only one previous bridge (node) for each source address will be cached. That means, both uplink and downlink paths are the same once the single-path level algorithm becomes stable. For the case of multi-path tree algorithm, since packets may follow different uplink paths to the AP, there may exist more than one previous bridge cached for each source node. In this case different strategies can be used to select the cached previous bridge to become the next bridge in downlink path forwarding (that may range from random selection to other more sophisticated ones). It should be noted that in the previous table each entry is associated with an expiration timer that is initialized at some value and decreases as time evolves. The corresponding timer is refreshed (reset) every time the entry is successfully used or when a packet in the uplink direction redefines it. Therefore in the multi-path tree algorithm, the cached previous bridge that becomes the next bridge in downlink path forwarding, could be determined by the highest timer value (e.g. most recently updated entry).

5.4.2. Data Forwarding

A transmitting node, which can be either the AP or an intermediate node that acts as a relay node in the downstream direction towards the final end node destination, needs to make the forwarding decision in order to propagate the data to the destination: the local node first checks its cached table to see if it contains the corresponding source address. If the source address can be found in the cached table, then one of the previous bridges

cached will be chosen to be the next bridge to forward the packet towards the final destination.

As explained before, for single-path algorithm, only one previous bridge should have been cached and be chosen as the intermediate destination to forward the packet. In case that there is no acknowledgement received after certain times of re-transmissions in local node, the link established during the uplink formation procedure probably is broken.

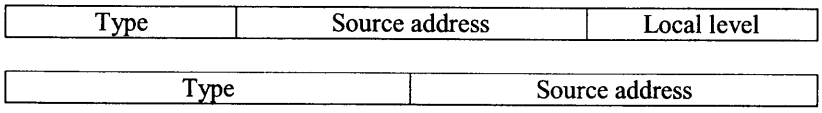
5.4.3. Downlink Repair Mechanism in the Bridging Algorithm

When no acknowledgement has been received after certain times of re-transmissions, a bridge_discovery packet will be broadcasted that contains the source node address and the local node's level. Neighbor nodes that have smaller level will drop it to avoid loop and limit the broadcast. As a neighbor node with higher level receives this packet:

Its local cache table is searched according to the source address. If this source address was cached before, then the local node becomes the new next bridge for the downlink forwarding. If no source address was cached locally, the bridge_discovery is cached locally and broadcasted again to the downlink neighbors until it arrives a node with the source cached. To let its parent node know about this, a new bridge_response packet with the source address encapsulated will be sent back to the source of the bridge_discovery packet and let nodes along the path update the cache table with the new previous bridge. After this exchange of bridge_discovery and bridge_response packets, a new path is found and thus the broken downlink path is fixed.

If no bridge_response packet is received within a certain time period, the packet will be dropped and the recovery operation fails. In this case a new path will be re-established (according to the rules and procedures described above) when the uplink becomes active.

In the following, the structure of the bridge_discovery and bridge_response messages are presented, respectively.



CHAPTER 6

THROUGHPUT ANALYSIS OF THE BRIDGING ALGORITHM

It is well known that systems with large number of stations that operate based on random access schemes, may exhibit unstable behavior, especially when the traffic load increases significantly. As the traffic load increases the throughput increases up to a maximum value, while further increases of the offered load may result in decrease in the throughput. In this chapter an analytical model and framework to evaluate the asymptotic throughput (or saturation throughput) that can be achieved by the proposed bridging solution is investigated and developed. This throughput practically represents the limit reached by the system throughput as the offered load increases, and is the maximum throughput the system can maintain under stable conditions. Therefore a fixed number of nodes is assumed, with each one of them having always a packet available for transmission, and ideal channel conditions.

It should be noted that some analytical efforts to evaluate the asymptotic throughput under simplified unrealistic assumptions regarding the backoff window mechanisms have been reported in the literature [60, 61, 62, 63]. In [64] the performance analysis of IEEE 802.11 distributed coordination functions was performed by including more realistic details regarding the backoff mechanism used.

However in conventional IEEE 802.11 network, most nodes in the network are neighbors among each other, and the total number of nodes in the network may affect the throughput performance. In the proposed bridging algorithm, normally the number of neighbors of the local node is much smaller than the number of total nodes in the network, and thus there are fewer nodes competing for the channel access. However, the

total integrated traffic load is much higher in bridging network, since each communication session from source to destination will be transmitted several times, as it travels along the path through multiple hops. This in effect increases the local traffic load, and also increases the collision probability. As a result these tradeoffs may impact the final throughput. In this chapter, a model to investigate the asymptotic throughput of the enhanced bridging solution that is introduced in Chapter 5 is developed.

6.1. Throughput Modeling and Analysis

Throughout the analysis a discrete time backoff scale is employed [57]. That is, time is slotted in slots of size σ and a station is allowed to transmit only at the beginning of each time slot. The station may proceed with its transmission if the medium is sensed idle for an interval larger than the distributed inter frame space (DIFS). If the medium is busy the station defers until after a DIFS idle period is detected and then generate a random backoff period before transmitting. The backoff timer counter is decremented as long as the channel is sensed idle, frozen when the channel is busy, and resumed when the channel is sensed idle again for more than a DIFS. Each station is assumed to operate in the standardized request-to-send/clear-to-send (RTS/CTS) mode [45].

Let $b(t)$ be the stochastic process representing the backoff time counter for a given station at slot time t. This discrete time scale does not directly relate to the system time. The slot time is referred to as the constant value σ and the time interval between two consecutive backoff time counters may consist of variable number of slot times. Since the value of the backoff time counter of each station depends also on its transmission history (e.g., how many retransmission the head-of-line packet has suffered), the stochastic process $b(t)$ is non-Markovian. Let also $s(t)$ be the stochastic process representing the

backoff stage $(0,...,m)$ of the station at time t. With the approximation that the probability p that a transmitted packet collides within a slot time regardless of the number of retransmissions suffered already, is constant and independent of the station state $s(t)$, it is possible to model the bi-dimensional process $\{s(t),b(t)\}$ with the discrete-time Markov chain depicted in Figure 6.1.

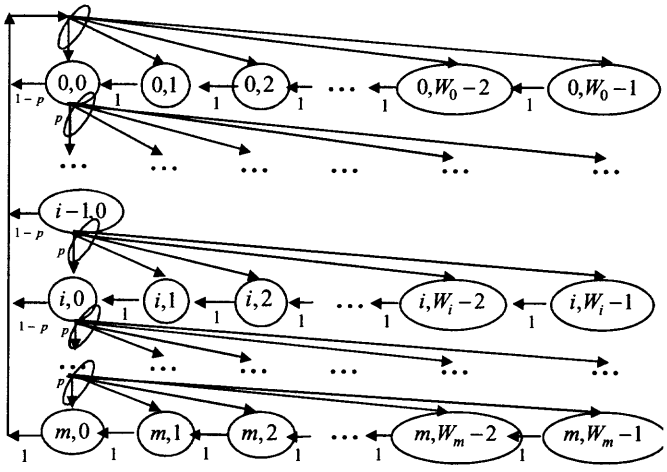


Figure 6.1 Markov Chain Model for Backoff Window

Following the procedures and specifications in 802.11 the backoff time counter window W_i at stage i is as follows:

$$\begin{cases} W_i = 2^i W & i \le m' \\ W_i = 2^{m'} W & i > m' \end{cases} \tag{20}$$

where $W = (CW_{\min} + 1)$, and $2^{m'} W = (CW_{\max} + 1)$. Here m' is the maximum stage defined by local physical layer in IEEE 802.11. For example, for Direct Sequence Spread Spectrum (DSSS), $CW_{\min}$ and $CW_{\max}$ equal to 31 and 1023 separately, and therefore $m' = 5$. In the following, m denotes the "maximum backoff stage" that can be reached during the IEEE 802.11 operation. In fact m also means the maximum retransmission count, which could

be larger than m' and is different for data frame and RTS frame, i.e., 5 and 7 separately. In this Markov chain, the only non-null one-step transition probabilities are[1]

$$\begin{cases} P\{i,k \mid i,k+1\}=1 & k\in[0,W_i-2] \quad i\in[0,m] \\ P\{0,k \mid i,0\}=(1-p)/W_0 & k\in[0,W_0-1] \quad i\in[0,m-1] \\ P\{i,k \mid i-1,0\}=p/W_i & k\in[0,W_i-1] \quad i\in[0,m] \\ P\{0,k \mid m,0\}=1/W_0 & k\in[0,W_m-1] \end{cases} \tag{21}$$

These transition probabilities account, respectively, for:

a) The decrements of the backoff timer

b) A new packet following a successful packet transmission starts with backoff stage 0, and thus the backoff is initially uniformly chosen in the range $(0,W_0-1)$.

c) An unsuccessful transmission makes the backoff stage increase and the new initial backoff value is uniformly chosen in the range $(0,W_i-1)$

d) At the maximum backoff stage, the CW will be reset if the transmission is unsuccessful, or restart the backoff stage for new packet after a successful transmission.

A packet transmitted in the network between two neighboring nodes (at any hop throughout the transmission) will encounter a collision when either or both of the two following events happen in one time slot: a) at least one of the transmitter's neighbors transmit; b) at least one of the receiver's neighbors transmit. In the following τ denotes the probability that a station transmits in a randomly chosen slot time, by n_n the average number of a transmitter's neighbors except the receiver, and by n_n' the average number of nodes located beyond transmitter's transmission range but within receiver's transmission range. The latter n_n' nodes represent additional contenting stations to the receiver, which may lead in collisions as well. As mentioned before probability p is the probability of a

[1] $P\{i_1,k_1 \mid i_0,k_0\}=P\{s(t+1)=i_1,b(i+1)=k_1 \mid s(t)=i_0,b(t)=k_0\}$

collision seen by a packet being transmitted on the channel. The fundamental independence assumption given above regarding probability p implies that each transmission sees the system in the same state. Then at steady state each remaining station transmits a packet with probability τ.

It should be noted that one of the basic assumptions of the throughput analysis presented in [57, 58] is the fact that there are no hidden terminals. The same approach does not apply directly here for the bridging scheme due to its multi-hop transmission characteristics and the fact that neighbor terminals of the receiver are hidden from the transmitter (e.g. $n_n^{'}$ nodes). However, under the saturation condition, terminals always have queued packets to send regardless of the source of the packet. Therefore, a similar approach to calculate the transmission probability is used, that is the probability that a station transmits in a randomly chosen slot time. The hidden terminal effect however is included in the calculation of the collision probability p by calculating the collisions around the receiver as well, as shown in relation (22). Therefore:

$$p = 1-(1-\tau)^{n_n}(1-\tau)^{n_n^{'}} = 1-(1-\tau)^{n_n+n_n^{'}} \tag{22}$$

Probability τ can be expressed as follows:

$$\tau = \frac{1-p^{m+1}}{1-p} b_{0,0} \tag{23}$$

where $b_{0,0}$ is the initial state of the corresponding Markov chain used to model the bi-dimensional process $\{s(t), b(t)\}$, and m is the maximum retransmission count defined by IEEE 802.11 standard. Therefore (22) and (23) represent a nonlinear system in the two unknown τ and p, which can be solved using numerical methods. If T_r is the

transmission range of a transmitter and ρ denotes the network density, then $n_n^{'}$ is equal to $\rho A^{'}$, where $A^{'}$ is the shaded area shown in Figure 6.2.

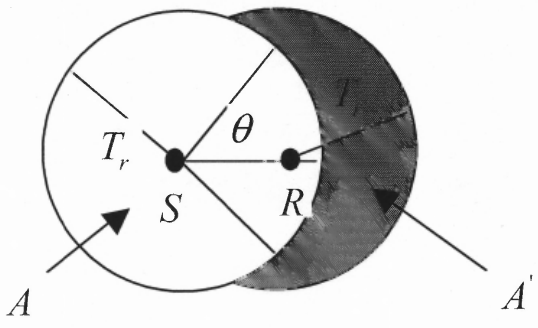


Figure 6.2 Contention Area of Receiver.

The average size of $A^{'}$ can be calculated as:

$$\int_{\frac{\pi}{3}}^{\frac{\pi}{2}} T_r^2\theta[\pi - 2\theta + \sin(2\theta)]d\theta \cong \pi \times (0.8012T_r)^2 \tag{24}$$

Let P_{tr} be the probability that there is at least one transmission in the considered slot time within the total area covered by A and $A^{'}$. Let also P_s be the successful transmission probability for the transmitter under consideration (Figure 6.2) (this is the probability that only the transmitter transmits given that there is at least one transmission in the time slot in the area $A + A^{'}$). Then it can be easily obtained:

$$P_{tr} = 1 - (1-\tau)^{n_n + n_n^{'}} \tag{25}$$

$$P_s = \frac{\tau(1-p)}{P_{tr}} \tag{26}$$

Thus the average number of successful transmissions per time unit per node, N_u, is expressed as:

$$N_u = \frac{P_s P_{tr}}{[(1-P_{tr})\sigma + P_s P_{tr} T_s + (1-P_s)P_{tr} T_c]} \tag{27}$$

where σ is the duration of an empty time slot, T_s and T_c denote the average time the channel is sensed busy because of a successful transmission or a collision respectively, $backoff_succ$ is the average back off time after a successful transmission and $backoff_fail$ is the average back off time after a failed transmission. Parameters T_s and T_c are calculated as follows:

$$\begin{cases} T_s = RTS + SIFS + \delta + CTS + SIFS + \delta + H + E[P] + SIFS + \delta + ACK + DIFS + \delta + backoff_succ \\ T_c = RTS + SIFS + \delta + CTS + DIFS + \delta + backoff_fail \end{cases} \tag{28}$$

where SIFS is the short inter-frame space, H is the packet header, and δ is the propagation delay [45]. If $CW_{\min}$ and $CW_{\max}$ further denote the minimal and maximal contention windows respectively, then average $backoff_succ$ time and $backoff_fail$ time can be calculated as:

$backoff_succ = 0.5 * CW_{\min} * \sigma$ and $backoff_fail = 0.25 * (CW_{\min} + CW_{\max}) * \sigma$

If the total number of nodes in the network is n, then the total network integrated throughput is:

$$S_{total} = nN_u E[P] = \frac{nP_s P_{tr} E[P]}{[(1-P_{tr})\sigma + P_s P_{tr} T_s + (1-P_s) P_{tr} T_c]} \tag{29}$$

where E[P] denotes the average packet payload size.

However it should be noted that in bridging scheme, a packet transmitted from a randomly selected source to the AP and then forwarded by AP to a randomly selected destination is going through multiple hops. That is, a communication session between a certain source and destination pair includes multiple transmitter – receiver transmissions.

The integrated throughput given by the latter relation (29) contains all these transmissions. Therefore in order to obtain the average effective throughput, from the source point of view, the integrated throughput should be divided by the average path length of the communication sessions. By dividing the expected distance between a random source-destination pair, by the expected progress $\bar{z}$ in one hop, the expected number of hops to reach an arbitrary destination (average path length) can be calculated. The expected progress is given by [59]:

$$\bar{z} = T_r - \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-\rho_a T_r^2 (\theta - \sin 2\theta)} d\theta \tag{30}$$

It should be noted that here only positive progress and connected network are considered due to bridging algorithm characteristics. If it is assumed that the network is situated inside a disc of radius R, then the expected distance d between the access point and any point randomly located within this disc can be obtained as:

$$d = \frac{1}{\pi R^2} \int_0^R 2\pi x^2 dx = \frac{2}{3} R \tag{31}$$

where:

$$R = \left(\frac{n}{\rho_a \pi} \right)^{1/2} \tag{32}$$

Therefore, the average number of hops $\bar{h}$ for each source and destination pair is:

$$\bar{h} = \frac{2d}{\bar{z}} \tag{33}$$

Thus the effective saturation throughput is:

$$S_{effect} = S_{Total} / \bar{h} \tag{34}$$

6.2. Model Validation

To validate the model developed in the previous section, its results with the corresponding ones obtained by simulation are compared. The values of the parameters used to obtain the numerical results for both the analytical model and simulation are summarized in Table 6.1. The system parameter values, such as PHY header, Slot time, SIFS and DIFS, are the ones specified by the physical layer, Direct Sequence Spread Spectrum (DSSS) 45. The channel bit rate for each node is 1Mbits/sec while the AP capacity is assumed 11Mbps.

Table 6.1 System and Other Parameters Used for the Validation of the Saturation Throughput Model

Packet payload	1024 bytes
MAC header	272 bits
PHY header (DSSS)	192 bits
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
Channel Bit Rate	1 Mbits/s
AP Max. Capacity	11Mbits/s
Propagation Delay	1 μs
Slot Time (DSSS)	20 μs
SIFS (DSSS)	10 μs
DIFS (DSSS)	50 μs

In Figure 6.3 the saturation throughput as function of the number of nodes for two different networks with density of 250 nodes/km^2 and 350 nodes/km^2 are presented, respectively. From this figure it can be seen that the analytical and simulation results agree and therefore the analytical model is very accurate. The difference between the analytical and simulation results for small networks (e.g. 100 nodes) is mainly caused by the border effect of the rectangular shape of the simulated network.

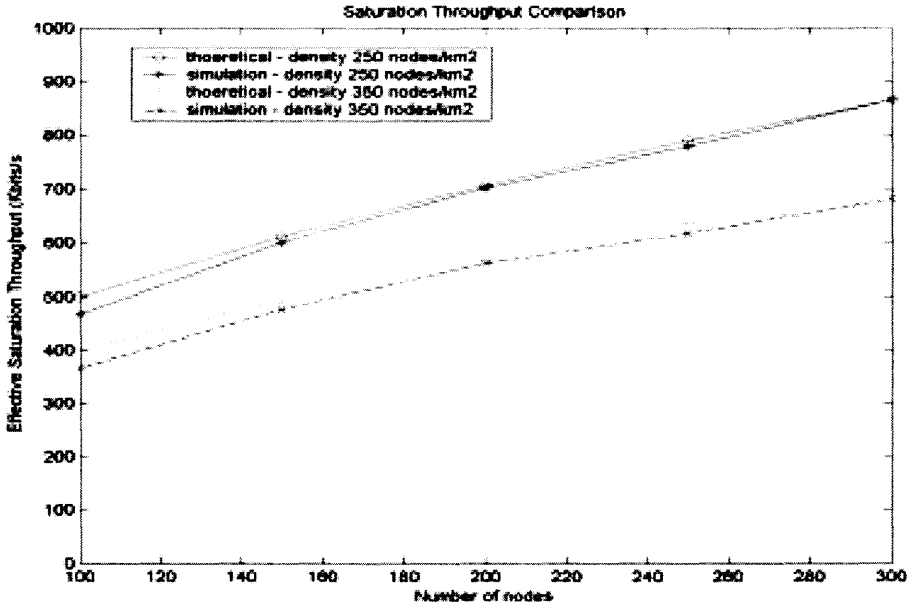


Figure 6.3 Saturation Throughput (Analytical Model and Simulation).

CHAPTER 7

PERFORMANCE EVALUATION OF LAYER-2 BRIDGING SOLUTION

7.1. Introduction

In this chapter, in order to evaluate the applicability and effectiveness of the proposed solution, some results that demonstrate the access point area coverage extension that can be achieved are presented, when compared with the conventional 802.11b scheme. To achieve this the OPNET modeling and simulation environment is used. In order to design and deploy an efficient and effective solution in realistic wireless ad hoc networking environments it is necessary to consider the broadcast nature of the radio links. In a radio environment, transmissions can be heard by any node within radio range of the transmitting node (realistically the radio range will be determined by many factors, power, antenna gain, propagation losses, etc.). Generally, this number of nodes within range will have a direct relationship to the density of the network (nodes/km^2). In dense networks channel access becomes problematic while in sparse networks maintaining a connected network may be difficult.

7.2. Models, Assumptions and Performance Metrics

A network consisting of one access point and N nodes randomly distributed in a closed rectangular region of size Y m x Y m is considered here. The transmission range of a single node is assumed to be 300 meters, the maximal transmission range defined in IEEE 802.11b. The performance of the proposed solution is evaluated in terms of packet loss and end-to-end delay, as a function of the various dimensions such as area coverage and network density. *Packet loss ratio* is the ratio between the total number of packets

dropped during the transmission between source(s) and destination(s) and the total number of packets generated by the source(s). This metric is extremely important in IEEE 802.11 ad hoc network because of its media sharing characteristics. By using this metric, the efficiency of the scheme can be evaluated. It should be noted here that throughout the simulation packets might be lost in the network either due to excessive number of unsuccessful transmission attempts, or due to the lack of connectivity between the source and the destination. *End-to-end delay* is the amount of time it takes for a data packet to travel from source to destination. Furthermore in addition to obtaining the overall average values of the previous parameters, with respect to the proposed bridging solution additional metrics based on the node source-level are collected and presented.

Two different scenarios are considered here. In the first one the nodes are static. Stationary topologies allow the investigation of the protocol's ability to cope with varying topology related parameter changes, such as range coverage and network densities, since their usage eliminates the potential impact of mobility on the results. However since one of the most distinct characteristics of mobile ad hoc networks is mobility, using the stationary topologies as a starting point, individual nodes are set in motion, according to Brownian mobility model with speed of 5km/sec.

7.3. Numerical Results and Discussions

7.3.1. Range Extension: Comparison between Proposed Scheme and IEEE 802.11b

In order to evaluate the range extension improvement achieved by the proposed solution, the performance metrics for a network with a given density of 250 nodes/Km^2 is calculated first as a function of the network size, considering the uplink communication

for both the single-path and multi-path solutions. Figure 7.1 and Figure 7.2 present the packet loss for the case where each node generates on the average 32 Kbps (assuming bursty traffic) and 66% of the nodes are selected as sources for the duration of the simulation (e.g. 66% activity ratio), for the conventional IEEE 802.11b scheme and the proposed single-path bridging and multi-path bridging solutions respectively. It should be noted here that, since the network is of fixed density there is a direct relation between the number of nodes in the network and the network size (or area) covered by the network. From this figure it can be easily observed that the solution achieves to significantly extend the WLAN area coverage using a single access point, while still maintains a low packet loss ratio for most of the experiments. For instance under the bridging scheme packet loss is less than 0.5% for network size of 625mx625m while in 802.11 presents packet loss ratio of about 20%, and less than 4% for a network size of 750mx750m while 802.11 presents packet loss ratio over 40%. It should be noted that in conventional IEEE 802.11b the packet loss ratio increases significantly as the number of nodes increases as a result of the lack of connectivity between some of the nodes and the AP due to their increased distance from the AP. However the proposed algorithm, due to its multi-hop nature, achieves to extend the coverage significantly, while maintaining a low packet loss. In this case the packet loss ratio is used as a measure to compare the range of the scheme with conventional 802.11b. Furthermore, as mentioned before although only 66% of the nodes generate traffic, the protocol takes advantage of the other nodes in the network as they are assumed to act as relay nodes if required.

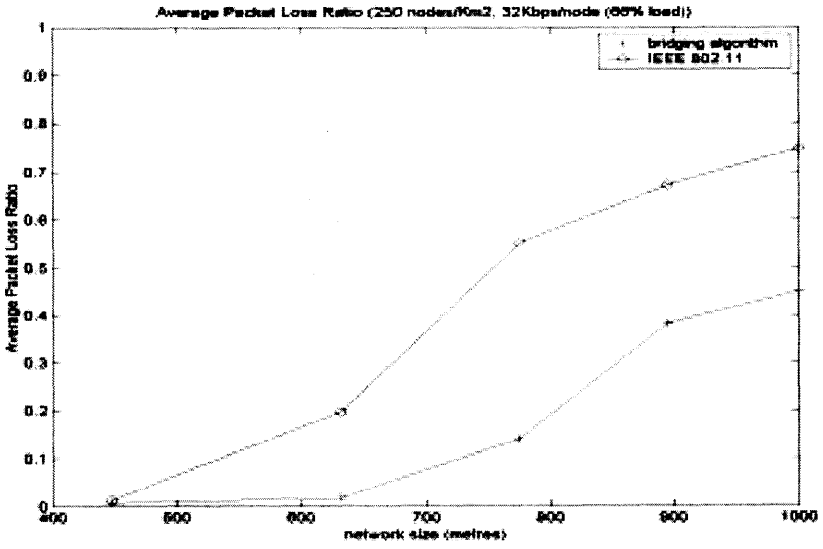


Figure 7.1 Packet Loss as a Function of Network Size for a Network with Density 250nodes/Km^2 – Single-path Bridging.

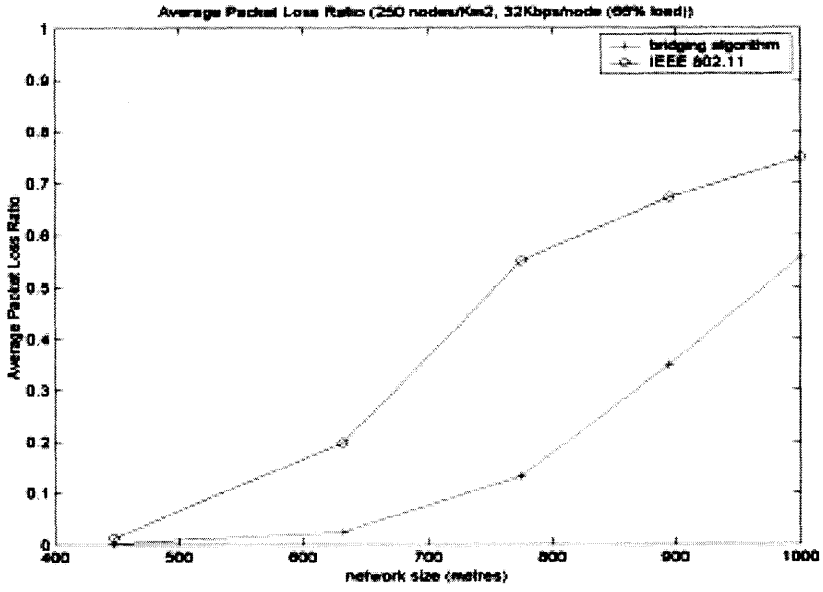


Figure 7.2 Packet Loss as a Function of Network Size for a Network with Density 250nodes/Km^2 – Multi-path Bridging.

In Figure 7.3 and Figure 7.4 the corresponding end-to-end delay for the cases under consideration are presented. Specifically from these figures it can be concluded that when the network size is up to approximately 800mx800m, the protocol achieves very low packet loss while still maintaining very low delay that is comparable to IEEE 802.11b. When the number of nodes increases a lot and therefore the corresponding area covered by the AP increases (e.g. for networks larger than 800mx800m), the performance improvement in packet loss happens at the cost of increasing delay, as can be seen from Figure 7.3. This increased delay is caused mainly by the fact that as the network size increases, the number of hops from some sources to the AP increases, and therefore at every hop the packet in transit has to contend for channel access.

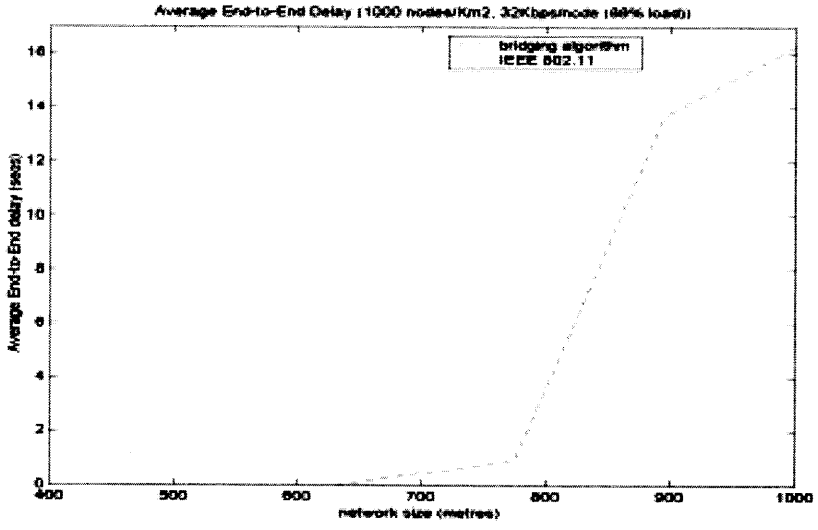


Figure 7.3 End to End Delay as a Function of Network Size for a Network with Density 250nodes/Km^2 - Single-path Bridging.

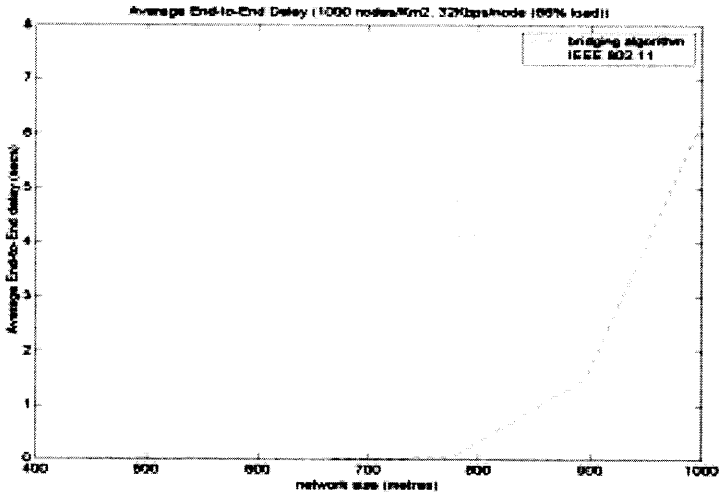


Figure 7.4 End to End Delay as a Function of Network Size for a Network with Density 250nodes/Km^2 - Multi-path Bridging.

In order to gain some insight about the capability of the proposed solution to deal with frequent topology changes, in Figure 7.5 the corresponding packet loss results for a network are presented, where individual nodes are set in motion according to Brownian mobility model (described in section 7.2) with speed of 5km/hr. Each node generates on the average 32 Kbps and 66% of the nodes are selected as sources for the duration of the simulation (e.g. 66% activity ratio). Comparing these results with the corresponding ones presented in Figure 7.1 for a stationary topology with the same traffic characteristics, it is observed that both the proposed solution and the conventional IEEE 802.11a present a slight increase in the achievable packet loss. However it can be seen that the corresponding curves follow a similar trend as the one presented in Figure 7.1, where the solution achieves to significantly extend the WLAN area coverage using a single access point, while still maintains a much lower packet loss ratio compared to the conventional protocol. This demonstrates the improvement and robustness of the proposed solution,

even in scenarios where more frequent topology changes occur.

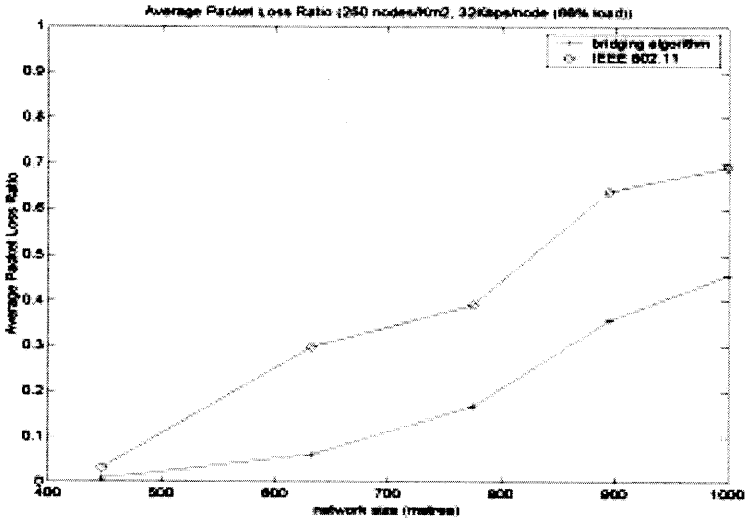


Figure 7.5 Packet Loss as a Function of Network Size for a Moving Network with Density 250nodes/Km^2 .

7.3.2. Performance Evaluation of the Bridging Solution Based on Source Levels

In the following some results are presented in order to gain some insight about the operational details of the proposed bridging scheme. Since one of the basic characteristics of the proposed solution is the introduction and definition of the multiple levels, in this section in addition to obtaining the overall average values of the previous parameters, with respect to the proposed bridging solution, additional metrics based on the node source-level are collected and presented. For this purpose a network consisting of 100 nodes randomly distributed in a closed rectangular region of size Y m x Y m is considered here. The graphs presented in the following are plotted as a function of the overall transmission range (horizontal axis), which is expressed in multiples of the single node transmission range. That means that for a topology representing a square area of YxY m, Y=Transmission range*Node range. Please note that as a result of this definition

for the topology under consideration in this experiment the Transmission range gets values from 2 to 5. The node transmission range here is considered to be 300 meters, the maximum transmission range defined in IEEE 802.11 standard.

From Figure 7.6 and Figure 7.7 it is observed that, as expected, the packet loss ratio increases as the source node's distance from the AP increases (higher level). This happens because, since each communication session from source to destination will be transmitted several times, as it travels along the path through multiple hops, the further the source node from the access point the more hops the corresponding packets have to go through, and as result the packet loss probability may increase. Furthermore, comparing the results of the moving networking topology with the corresponding ones for the stationary topology, it is observed a slight increase in the achievable packet loss, for the different source levels. When the source level goes up to 5 times of the transmission range, the packet loss ratio ranges from 10% to 35%, depending on the scheme used and mobility status of the local node. Based on these results, although in principle the protocol can support any number of levels, for practical purposes and in order to obtain satisfactory performance, the number of levels should be constrained.

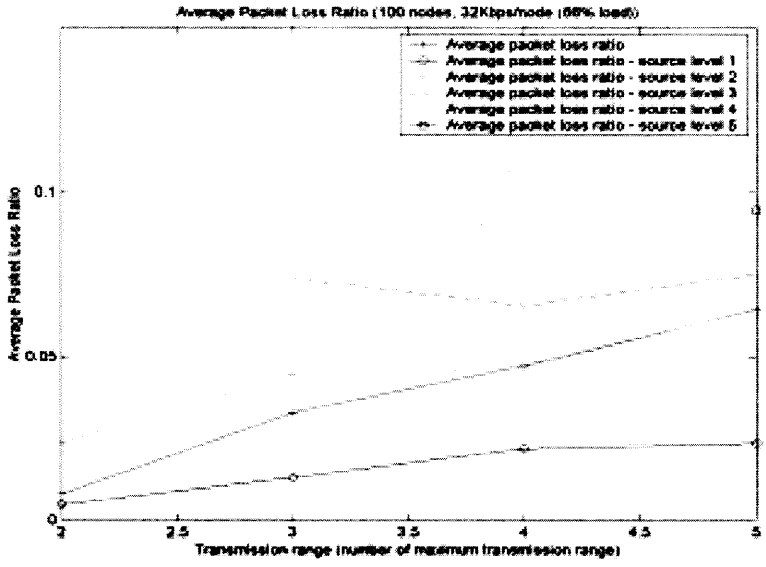


Figure 7.6 Packet Loss for Different Source Levels.

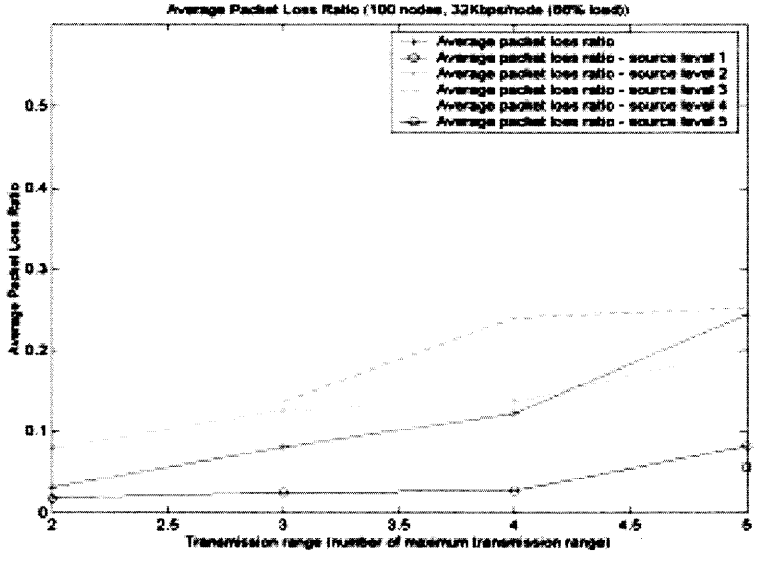


Figure 7.7 Packet Loss for Different Source Levels for a Moving Network.

CHAPTER 8

CONCLUSIONS

In this dissertation the problem of establishing end to end communication paths in large-scale mobile ad hoc networks in an efficient way is considered, by designing hybrid routing and bridging techniques that operate at the network layer and data link layer, respectively. In this chapter the dissertation is concluded by: 1) summarizing the main contributions; 2) providing a network paradigm for next generation mobile networks, based on the combination of the proposed PSR and bridging solutions; 3) discuss directions for future work.

8.1. Summary of Contributions

The operation of Position-guided Sliding-window Routing (PSR) protocol in large-scale mobile ad hoc network deployments is introduced, designed and described. PSR provides a position-based integrated proactive routing and mobility management strategy that makes feasible the realization of a flat single-tier routing architecture in mobile ad hoc networks. It provides an alternative, simplified way of localizing routing information overhead, without having to resort to complex, pyramid-like, hierarchical routing organization schemes.

One of the main features of PSR protocol is that it is self-paced, in the sense that it automatically adjusts the generation of routing control packets depending on the mobility characteristics of the network. Furthermore, the proposed protocol controls position-update overhead generation and propagation, by making the overhead generation rate and propagation distance directly proportional to the amount of change in a node's geographic position.

By enhancing the packet relay/forwarding mechanism of PSR to take into account the various nodes' energy/power considerations and limitations, it was demonstrated that the energy efficiency of PSR is enhanced and the network lifetime is extended. This is achieved by introducing and defining a new routing cost function, which is a weighted cost function of the following metrics: path loss (distance) and current energy levels.

An analytical model was developed and provided, in order to study the design issues and trade-offs of PSR routing mechanism, discuss their impact on the protocol's operation and effectiveness, and identify the critical design parameters that optimize the protocol's operation. Specifically, since the radii and the number of the various zones are important design parameters for performance of PSR, analytical expressions are developed that present the average GPU generation rate as a function of the various system and zone parameters and configurations for different mobility scenarios. These outcomes can be used as guidelines for the efficient design and tuning of the involved parameters in order to balance the associated protocol tradeoffs.

The performance evaluation of PSR demonstrated that it possesses the scalability property which is among the primary design objectives of any routing protocol for mobile ad hoc networks, and indicated the high routing effectiveness of PSR, even under high mobility, therefore providing an ideal protocol for deployment in large scale mobile networks.

Since the IEEE 802.11 standard has been widely deployed in existing wireless local mobile networks, the problem of increasing the range of a 802.11 access point using multi-hop ad hoc networking was also investigated in this dissertation. A novel layer-2 bridging solution was introduced, and the mechanisms for the corresponding forwarding

tree establishment as well as for the data propagation were described in detail.

The proposed bridging architecture mainly aims to address and solve the hotspot communication problem, where a large number of mobile users require Internet access through an access point. Extending the coverage area of each access point in WLAN, results in far less requirement for handoffs between APs and in significant performance improvements, while at the same time allows for increased degree of mobility.

An analytical framework to estimate the achieved throughput of the proposed bridging solution has been developed and validated by simulations.

The performance evaluation process and the corresponding numerical results presented in this dissertation, demonstrated the effectiveness of the proposed bridging solution, in improving significantly the area that can be supported by a single access point, therefore making the proposed novel mechanisms an alternative attractive and cost efficient solution to the WLAN coverage extension problem.

8.2. Network Paradigm of PSR and Bridging Network

Based on the description and analysis presented in this dissertation, it is clear that PSR provides an efficient routing algorithm, which is operational independent of the underlying link state and physical layer settings, and can be deployed in large-scale networks by supporting up to thousands of mobile nodes. At the same time although the proposed bridging scheme provides a simple and efficient layer-2 mechanism to extend the area coverage of a local mobile network, its performance degrades significantly when the distance between a source and the AP is longer than 4 hops, and as a result by itself is not appropriate for large networks. It is believed that the integration of PSR and the bridging scheme will provide a new routing paradigm to enable anywhere, any time

communication in mobile ad hoc networks. For practical purposes, this new routing paradigm is envisioned in the context of a two-level hierarchical ad hoc communications. In this new routing paradigm, mobile nodes can be grouped into a subnet that is administered and managed by the Access Point (AP). The APs can be either static nodes or slow moving nodes, and can act as the network backbone to support communication between subnets. The concept of subnet used in this paradigm differs from the subnet currently deployed in the Internet in that they are not defined by the addressing scheme but by the geographical locations. Mobile nodes can join a subnet by discovering and examining the hello messages received from their neighbors. A node will choose an AP to be associated with (i.e. the closest to itself) and then decide its level based on the bridging mechanism. Figure 8.1 presents the structure of an ad hoc network paradigm.

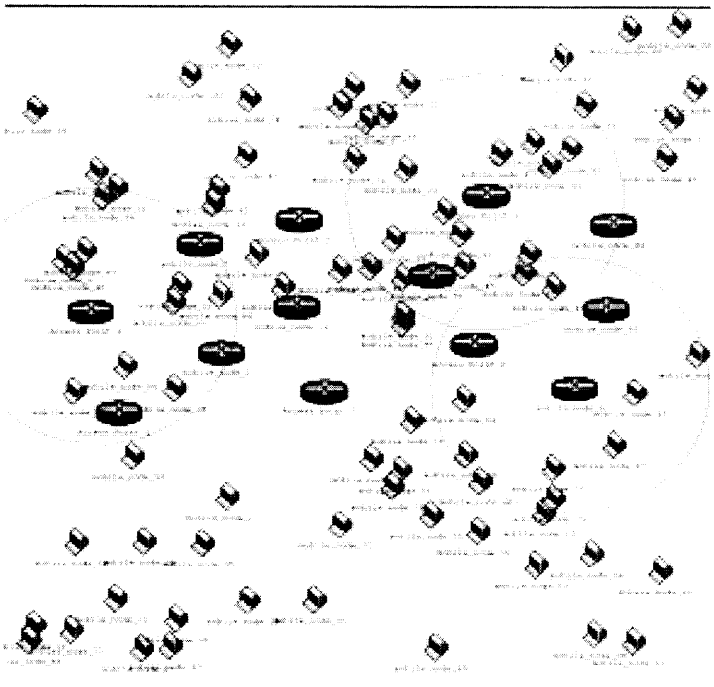


Figure 8.1 Ad Hoc Network Paradigm by PSR and WLAN Bridging.

In this figure, the large blue nodes represent the APs while the small nodes correspond to the mobile hosts that could represent notebooks, handheld devices, etc. Circles around the APs denote their corresponding transmission ranges. The APs among themselves support and communicate using the PSR protocol as this has been described in this dissertation. The mobile nodes, although could run themselves the complete PSR protocol, they may use the bridging solution to gain access to an AP and support only limited functions of the PSR. A mobile node will generate GPUs when it crosses a certain level zone, evaluate the higher level zones based on current position and propagate the updates within the higher level zone.

8.3. Future Work

Research work reported recently in the literature 66 has shown that multi-hop networks using IEEE 802.11 wireless LANs, based on RTS/CTS MAC, may exhibit throughput degradation when the node density increases. This happens because RTS/CTS based MAC schemes do not allow simultaneous transmissions, even if these are feasible in principle, due to the collision avoidance mechanism that they adopt. One of the key points in improving the existing mechanisms, is to allow concurrent scheduling of two neighboring transmitting or receiving nodes, and thus relaxing some of the unnecessary restrictions in IEEE 802.11 collision avoidance mechanism. The future research in this area, will focus on the enhancement of the proposed bridging approach, by allowing concurrent transmissions as mentioned above, in order to further increase the achievable throughput.

Furthermore, as explained in section 2.5, the energy aware PSR extension, implicitly tends to distribute the traffic more evenly among the various nodes, by possibly utilizing

different routes for different packets, depending on the energy levels of the candidate forwarding nodes. This demonstrates that the PSR provides a natural and simple vehicle for the implementation of diverse and/or multipath routing, and can significantly contribute to the performance improvement of the network, through load balancing and QoS provisioning. Another advantage of such an approach is the provisioning of enhanced routing security through the traffic dispersion mechanism, so that the possibility of unauthorized information leakage induced by attacks along the information path is minimized.

Finally, since for some applications in mobile ad hoc networks many nodes are inclined to group-oriented communication, the investigation of the applicability of the developed methods in the cases of multicast routing, is a topic of high research and practical importance.

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