Modelling Collaborative Motion in Mobile Ad Hoc Networks

by

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Declaration

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Abstract

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In this thesis, a pricing mechanism to stimulate cooperation between nodes in ad hoc networks is explored. The model incorporates incentives for users to act as transit nodes and carry the traffic between other nodes on multi-hop paths, and to be rewarded with their own ability to send traffic. The thesis investigates the consequences of this pricing model by means of simulation of a network and illustrates the way in which network resources are allocated to users according to their geographical position. Moreover, since modelling node movements is an important aspect in ad hoc network simulation, a collective mobility model, the adaptive mobility model, is used to maximise the area coverage of the nodes.

Uittreksel

Modellering van meewerkende beweging in ad hoc netwerke

("Modelling Collaborative Motion in Mobile Ad Hoc Networks")

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Tesis: MSc (Rw)

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In hierdie tesis word 'n koste meganisme gebruik om samewerking te stimuleer tussen nodusse in ad hoc netwerke. Die model inkorporeer trekpleisters deur gebruikers te beloon om verkeer te stuur deur op te tree as transito nodusse, en verkeer tussen nodusse op multi-skakel paaie te dra. Die tesis ondersoek die gevolge van die koste model deur die simulering van 'n netwerk, en demonstreer die manier waarop die netwerk hulpbronne geallokeer word aan gebruikers gebaseer op hulle geografiese posisie. Siende dat die modellering van nodus bewegings 'n belangrike aspek is in ad hoc netwerk simulasie, word 'n kollektiewe mobiliteits model sowel as 'n veranderlike mobiliteits model gebruik om die dekkings areas van die nodusse te maksimeer.

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Chapter 1

Introduction

1.1 Overview

A mobile ad hoc network (MANET) [1] is a complex system of wireless mobile nodes that can dynamically self-organise into arbitrary and temporary network topologies. People and devices can inter-network in areas without any pre-existing infrastructure, e.g. disaster recovery environments and battlefield communication. The ad hoc network concept has existed in various forms for over 20 years, when military tactical networks were the only application domain that followed the ad hoc paradigm. Recently, new technologies such as Bluetooth, HiperLAN and IEEE 802.11 have been introduced in the field of wireless networks. These technologies enabled commercial MANET deployments outside of the military domain.

In a MANET, nodes can move and can arbitrarily organise themselves without relying on an established infrastructure. Thus the topology of the network may change rapidly and unpredictably. Because of the limited transmission range of the nodes, routes between nodes may require multiple hops. Each node can communicate directly with any other node within its transmission range. For communicating with nodes that reside beyond its transmission range, the node needs to use intermediate nodes (transit nodes) to relay its packets hop by hop [1].

The multi-hop nature and the lack of fixed infrastructure add a number of complexities and constraints that are specific to ad hoc networks [1].

Autonomous and infrastructure-less: A MANET is an autonomous self-organised network without infrastructure support where a node operates in a distributed peer-to-peer mode. Each node acts as an independent router and also generates independent data. Nodes in a MANET perform network management and routing functions. This brings added difficulties in fault detection and management.

Multi-hop routing: Routing paths in MANETs may contain multiple hops since every node in a MANET can act as a router. This means that nodes forward each other's packets to enable information sharing between mobile hosts. This implies that no default router is available, and a node has to find and establish a route every time before it sends its data.

Dynamic topologies: Because nodes can move arbitrarily in MANETs, the topology of the network may change in an unpredictable way, resulting in route failures and possibly packet losses.

Limited energy: Since the battery carried by each mobile node in a MANET has a limited power supply, the services and the applications that can be supported by each node should be energy-efficient. However, a node in a MANET acts as a source, destination and transit node. This becomes a bigger issue where additional energy is required, for transit nodes, to forward packets between nodes.

Due to the fact that there is no infrastructure in a MANET and the transmission range of nodes is limited, a node has to rely on neighbour nodes to route a packet to the destination node. In particular, all network functions are based on node cooperation. However, nodes in MANETs may not be willing to spend their resources such as CPU cycles, energy and network bandwidth, to forward packets on behalf of other nodes, even though it expects other nodes to forward packets on its behalf. Without node cooperation no packets are forwarded, which could make communication over multiple hops impossible. The solution is to stimulate nodes to cooperate by rewarding cooperative behaviour.

The research that has been done in the area of cooperation mechanisms shows two main different approaches that are already applied in ad hoc networks. The first one is based on a watchdog and a reputation system. In this approach, nodes monitor their neighbours and assign their reputations according to the observed information. If nodes detect a misbehaving node, they will isolate the misbehaving node. This can be done by not serving the misbehaving node's requests. The second approach is based on a virtual currency. This virtual currency can be used to charge/reward the packet forwarding service. The virtual currency system must compensate a node that cooperates in order to motivate this node for future cooperation [2].

The use of pricing mechanisms for allocating resources in communication networks has received much attention in recent years. In particular, the work by Crowcroft *et al.* [3; 4] shows that this pricing scheme can be used to achieve (in equilibrium) a weighted proportional fair rate allocation of flows. In this thesis incentives for collaboration are introduced into the architecture of a MANET. This leads to the use of pricing mechanisms, which have found application in rate control [5; 6; 7] and resource control [8; 9] in wireless networks.

Moreover, modelling the motion of the nodes is an important aspect in MANET simulation, where realistic motion models are needed to evaluate system and protocol performance. In this thesis, some mobility models are briefly discussed and a simple motion model is used to evaluate an incentive for cooperation in a MANET. In addition, some collective mobility models are also presented. One of these collective motions, the adaptive mobility model [10], is used to maximise the area coverage of the nodes.

1.2 Organisation of the Thesis

In this thesis, node cooperation problems are studied by using the pricing model of Crowcroft *et al.* [3; 4]. The remainder of the thesis is organised as follows. Chapter 2 provides a brief introduction to MANETs. In Chapter 3, node cooperation in MANETs is discussed, where the pricing model of Crowcroft et *al.* is used to study node cooperation. In Crowcroft's model, a node spends credits to pay for the bandwidth and power congestion costs incurred when it sends its own traffic; a node earns credits when forwarding traffic on behalf of other nodes. In Chapter 4, several synthetic mobility models are presented. These models were proposed for (or used in) the performance evaluation of ad hoc network protocols. One of these mobility models, the adaptive mobility model [10], is used to maximise the area coverage of the nodes. In Chapter 5, the simulation results for the proposed pricing model are discussed. In addition, maximising the area coverage of the nodes is also simulated. Chapter 6 summarises the thesis and discusses future research.

Chapter 2

An Overview of Wireless Ad Hoc Networks

2.1 Introduction to Ad Hoc Mobile Networks

A mobile ad hoc network (MANET) [11] is formed dynamically by a system of mobile nodes connected by wireless links. In this network, nodes send packets to each other without using a fixed infrastructure such as access points or base stations. The nodes are free to move and organise themselves arbitrarily. Thus the network wireless topology may change rapidly and unpredictably. Because of the limited transmission range of the nodes, the routes between nodes in a MANET may include multiple hops. Each node can directly communicate with another node that resides within its transmission range. To communicate with nodes that reside beyond its transmission range, a node needs to use intermediate or transit nodes to relay the packets hop by hop [1]. Fig 2.1 illustrates a MANET of three mobile nodes using wireless network interfaces. Node C is not in wireless transmission range of node A, as indicated by the circle around A. Also, node A is not within the wireless transmission range of node C. If nodes A and C want to communicate with each other, they require node B to forward packets for them because node B is within the transmission range of both node A and node C.

In this chapter, a brief introduction to wireless ad hoc networks is provided where Section 2.2 discusses the application area of MANETs. Section 2.3 presents some technologies for ad hoc networks. Section 2.4 describes some popular routing protocols in MANETs. Finally, Sections 2.5 and 2.6 present a brief introduction to the cooperation among nodes and the mobility of nodes in MANETs.

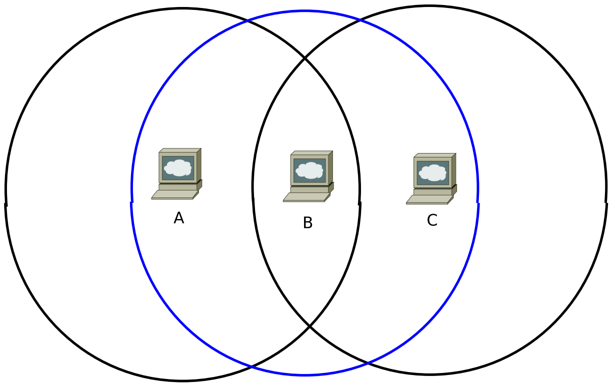

Figure 2.1: An ad hoc network with three wireless mobile nodes

2.2 Application Areas

Mobile ad hoc networks were first used to establish wireless communications for tactical military networks in battlefield communications [1]. Because of the dynamic nature of military operations, the military cannot rely on access to a fixed communication infrastructure in a battlefield. The history of MANETs can be traced back to 1972 where the US military was in need of a communication network that would not depend on a fixed communication infrastructure. Radio communication introduces some limitations for radio frequencies higher than 100MHz. These frequencies do not propagate beyond the line of sight [11]. Moreover, in the military domain, security, reliability, latency, intentional jamming and recovery from failure are important requirements. Military networks are designed to maintain a low probability of interception and a low probability of detection. A failure to fulfil any of these requirements may degrade the performance and dependability of the network [11; 1]. One of the earliest applications of MANETs was the DARPA Packet Radio Network (PRNet) project in 1972 [12; 1]. This application was primarily inspired by the efficiency of packet switching technology, such as bandwidth sharing and store-and-forward routing, and its possible application in mobile wireless environments. PRNet is based on a distributed architecture consisting of a network of broadcast radios with minimal central control. A combination of Aloha [12; 1] and carrier sense multiple access (CSMA) protocols was used to support the dynamic sharing of the broadcast radio channel. In addition, the radio coverage limitation was removed by using multi-hop store-and-forward routing techniques. This effectively enabled multi-user communications within a large geographic area.

In addition to the PRNet project, DARPA also developed the Survivable Radio Network (SURAN) [12; 1] in 1983. This network was created to deal with issues in PRNet in the areas of network scalability, security, processing capability and energy management. The primary aims of SURAN were to develop network algorithms. These algorithms had to support a network that could scale to tens of thousands of nodes and withstand security attacks, as well as the use of small, low-cost, low-power radios that could support sophisticated packet radio protocols [12; 1]. Low-cost Packet Radio (LPR) technology was designed in 1987 [13]. This network is based on a digitally controlled direct sequence spread-spectrum (DSSS) radio with an integrated Intel 8086 microprocessor-based packet switch. In addition, a family of advanced network management protocols was developed, and a hierarchical network topology based on dynamic clustering was used to support network scalability. Other improvements in radio adaptability, security, and increased capacity were achieved through management of spreading keys [14; 1].

2.3 Technologies for Ad Hoc Networks

Currently, three main communication standards with ad hoc capabilities are available in the market, each addressing a specific range of commercial applications. These standards include the IEEE 802.11 family of protocols [15], the high-performance LAN (HiperLAN) protocols [16] and the Bluetooth specifications [17] for short range wireless communications [18; 19].

The IEEE 802.11 standard [1] is a platform to implement a single hop WLAN ad hoc network. Furthermore, the IEEE 802.11 technology can be exploited to build multi-hop networks covering areas of several square kilometres.

The IEEE 802.16 family of protocols [20; 1] is a standard for local and metropolitan area network (MAN) fixed broadband wireless access. The IEEE 802.16 standard is titled “Air Interface for Fixed Broadband Wireless Access Systems", where the primary advantages of IEEE 802.16 systems over wired systems include cost savings, quick setup and more complete coverage. While IEEE 802.16 systems are expensive, the costs are much less than those associated with wired systems.

In addition to the IEEE standards, the European Telecommunication Standard Institute (ETSI) has developed the HiperLAN (High Performance Radio Local Area Network) family of standards for WLANs [16]. The most interesting member of this family is HiperLAN/2. The HiperLAN/2 technology deals with a high-speed wireless network with data rates ranging from 6 to 54 Mbit/s. Infrastructure-based and ad hoc networking configurations are both supported in HiperLAN/2.

On a smaller scale, technologies such as Bluetooth can be used to build ad hoc wireless Body and Personal Area Networks, which connect devices on the person, or placed around a person within a radius of $10m$.

2.3.1 Bluetooth

Bluetooth [17; 1] is based on a Wireless Personal Area Network (WPAN). Its advantages include low power consumption and low cost per node. Bluetooth technology is mainly used in cable-replacement, and has many applications for example synchronisation between a mobile phone and a PC.

A Bluetooth network consists of one “master" station and other “slave" stations. The master decides which slave should have access to the channel. Upon receiving a polling message from the master, a slave is allowed to deliver a single packet to the master. A master station with up to seven slaves form a piconet. A piconet is the central building block of a Bluetooth network where the piconet is formed by units sharing the same channel. A piconet has a bit rate of 1 Mbit/s which is the channel capacity including the overhead introduced by the adopted protocols and polling scheme. Inside a piconet, Bluetooth stations can establish up to three 64 Kbit/s synchronous (voice) channels or an asynchronous (data) channel supporting data rates of maximally 723 Kbit/s asymmetric or 433 Kbit/s symmetric [1].

Piconet interconnection, or scatternet, depends on the Bluetooth specification. In an ad hoc network, a scatternet can be dynamically constructed in the sense that some nodes simultaneously belong to more than one piconet. When a node belongs to more than one piconet, it must time share, spending a few slots on one piconet and a few slots on the other. A node cannot be a master of two different piconets. The current specification also limits the number of piconets within a scatternet to 10 piconets.

2.3.2 IEEE 802.11 Ad Hoc Networks

The IEEE 802.11 MAC [15] defines the most common WLAN currently in use. To provide a low cost and high bandwidth network communication, the IEEE 802.11 technology applies the packet broadcast radio to the licence-exempt Industrial, Scientific and Medical (ISM) frequency bands. The first physical layers defined in IEEE 802.11 were an infrared specification such as the Direct Sequence Spread Spectrum (DSSS) and the Frequency Hopping Spread Spectrum (FHSS) radios. Only the DSSS physical layer, which provides raw bandwidth of up to 2Mbit/s, was widely implemented [21]. Later amendments to the protocol have provided for bandwidths of 11Mbit/s [22], and 54Mbit/s (also supporting the 5GHz ISM band) [23; 24]. Currently, the IEEE 802.11 distributed coordination function (DCF) [25; 26] defines the contention based access standard.

The core 802.11 protocol uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) medium access control method. In the IEEE 802.11 protocol, two access schemes are provided, the basic scheme and the request to send/clear to send (RTS/CTS) scheme. In the basic scheme, the source and the destination nodes only exchange data frames and acknowledgement (ACK) frames, while an RTS/CTS dialog which preceeds the data frame to reduce the probability of collisions on the channel [26] is added by the RTS/CTS scheme.

In the RTS/CTS scheme, a node first reserves the channel before it transmits any data frame. To do this, it sends an RTS frame to the destination node through the network. After receiving the RTS frame, the destination replies with a CTS frame if it is ready to receive data. If the source node successfully receives the CTS frame, it then starts to transmit the data frame. After receiving the data frame, the destination replies to the source node with an ACK frame. If the source does not receive the CTS frame, it waits for a CTS mandatory inter-frame space (IFS) time interval called CTS-IFS. It then adopts the binary exponential back-off (BEB) algorithm to compute a new random back-off time with a higher range in order to retransmit the RTS frame with lower collision probability [26].

The back-off time is uniformly chosen in the range (0, $CW - 1$), where CW is the size of the contention window depending on the number of failed transmissions for the RTS frame. At the first retransmission attempt, CW is equal to the minimum contention window CW_{min}. After each unsuccessful transmission, CW is doubled up to the maximum value CW_{max}, above which CW remains the same. The RTS frame is dropped after seven failures [26].

The 802.11 wireless networks operate in one of two modes: ad-hoc node or infrastructure mode. The IEEE standard defines the ad-hoc mode as Independent Basic Service Set (IBSS), and the infrastructure mode as Basic Service Set (BSS). In the ad hoc mode, each client communicates directly with the other clients within the network. Ad-hoc mode is designed so that only the clients within transmission range (within the same cell) of each other can communicate. If a client in an ad-hoc network wishes to communicate outside of the cell, a member of the cell must operate as a transit node and perform routing. In infrastructure mode, each client sends all of its communications to a central station, or access point (AP). The access point acts as an Ethernet bridge and forwards the communications to the appropriate network that can be the wired network, or the wireless network.

2.3.3 IEEE 802.16

The IEEE 802.16 protocol [20; 27; 28; 29] was specifically developed to provide “last-mile" wireless broad-band access to relatively immobile subscriber stations. The protocol is promoted by the Worldwide Interoperability for Microwave Access (WiMAX) Forum [20; 28], and it has been extended, in the 802.16e amendment [30; 31], to applications involving mobile terminals in contrast to 802.16 (certified as WiMAX) which targets fixed broadband access. WiMAX defined the interoperability certification profiles similar to those for IEEE 802.11 by the Wi-Fi Alliance. New technologies, such as Mobile WiMAX and WiBro, have been developed based on the IEEE 802.16e standard. The ranges of the physical layers defined in the 802.16 standards include the use of Frequency Division Duplex (FDD) or Time Division Duplex (TDD), in the 2-11GHz or 10-66GHz operation ranges, to support data-rates of up to 70Mbit/s. Current certification profiles for Mobile WiMAX specify the use of TDD in a range of bands from 2.3GHz to 3.8GHz [29].

The IEEE 802.16 standard is intended for use in a point-to-multipoint network topology, and it has been updated to be applied in a mesh topology. In this standard, a base station (BS) transmits to multiple subscriber stations (SS) in a cellular coverage area. For the transmission from BS to SS, on the uplink channel, the MAC layer controls medium access via a demand assignment multiple access (DAMA)-TDMA system, while on the downlink, transmission to the SSs is by use of time division multiplexing (TDM). On the other hand, when the SS transmits to BS, the SS uses Time Division Multiple Access (TDMA), on the uplink, to transmit to the BS in its allotted time slot. Time allotment to each SS is done cyclically by the BS. The BS periodically accepts bandwidth requests from the SSs, granting them transmission opportunities based on service agreements negotiated during the connection setup, and then assigning time-slots to them on the uplink channel. In other cases, the BS may provide certain time slots on the uplink that are available to all SSs for contention so that the SSs may use that to transfer data or to request for dedicated transmission opportunities [27].

The uplink channel is divided into a stream of mini-slots, so that a SS that wants to transmit on the uplink requests transmission opportunities in units of mini-slots. Also, the system divides time into physical slots (PS), and in the IEEE 802.16 standard, the time frames are in sizes of 0.5, 1 or 2ms. Each PS has duration of four modulation symbols and a mini-slot consist of two PSs. Every SS, which wants to transmit, sends requests to the BS over a period of time, and the BS accepts requests by creating an allocation map (MAP) message, which describes the channel allocation for a certain period into the future called the MAP time. In addition, this MAP message may also allocate some open slots for contention based transmission. The MAP is broadcast on the downlink to all SSs. In spite of the time allocation, the transmission opportunities are liable to collide, and these collisions are resolved using the Binary Exponential Back-off algorithm [27; 29].

The 802.16e amendment to the standard defines mechanisms to support operations critical for mobile operations such as the hand-off of mobile stations between base stations and low power modes. These mechanisms are implemented by state machines which communicate using the MPDU (MAC Protocol Data Unit) delivery service. A security sub-layer is included to provide authentication and encryption services for the 802.16 stations - authentication allows control of station access to network resources, and encryption provides a degree of privacy for packet payloads [29].

2.3.4 The HiperLAN/2

HiperLAN/2 (H/2) [16; 32; 33] is a wireless LAN system designed for the 5.2 GHz range. It is frequently applied in low-mobility scenarios and affords data rates of up to 54 Mbit/s. It consists of several stations, and one of these stations serves as the central controller (CC). The CC is responsible for the allocation of time slots between stations that wish to communicate with each other, and it assigns slots in a periodically repeated frame to any requesting station which wants to communicate with another station. Therefore, the H/2 system uses a connection-oriented, centrally-scheduled TDMA to organise the medium access. This makes data traffic collision-free and provides simple support for priorities or QoS requirements.

Scheduling occurs based on a frame which is divided into different phases (the phases are themselves made up of cells of fixed length). The first phase contains administrative information from the CC, the broadcast channel (BCH), and the frame control channel (FCCH), which determines the particular terminal that is allowed to transmit, at what specific time, for what period, and to which other terminal.

The FCCH (Frame Control Channel) is a directory located in the first part of every H/2 MAC frame and it contains information on what action will occur in that MAC frame. The FCCH is consists of slots called Information Elements (IE), each of which is assigned to one particular transmission for one terminal, and every device within a cell gets information on all the data transfers of the MAC frame after reading its FCCH. The last part of the first phase is the access channel (ACH), which provides feedback to newly registered terminals.

This information is made available to all terminals in order to organise a complete channel access – the first phase in which the CC sends information to terminals (the downlink phase), and the second phase in which terminals transmit to the CC (the uplink phase). Within these phases, long transport channel (LCH) cells are also exchanged between entities. This frame structure, along with the centralised organisation of the channel access, leads to the performance and flexibility of H/2.

The flexibility of H/2 is illustrated in direct-link traffic. Here, it is possible for the CC to assign the same time slot to one terminal as a sender, and at the same time, assigns another terminal as a receiver. In this case, the terminals can communicate directly with each other without having to send the data through the CC.

Normally, when transmission is to occur, the downlink traffic is first to be scheduled after the frames' initial administration phase, then the direct-link traffic is scheduled next, and finally, the uplink traffic is scheduled. This schedule order for the first four phases minimises the number of send/receive turnarounds. Attached to the end of a frame as the fifth (and last) phase, is the random access time-interval (the medium access method is slotted ALOHA) in which terminals can compete for channel access. This phase is used to setup associations between the terminals and the CC and other uncommon or unscheduled requests.

Automatic frequency selection, multicast, automatic CC selection, etc, are examples of other capabilities in the H/2 standard apart from the basic mechanisms described above. However, in the present context, the CC's capability to request channel measurements from any terminal, describing the channel characteristics between any two terminals, is important [34].

2.4 Routing Protocols

In this section, several routing protocols for wireless ad hoc networks are described [35]. Currently, there are four routing protocols for wireless MANETs: Destination Sequence Distance Vector (DSDV), Dynamic Source Routing (DSR), Temporally Ordered Routing Algorithm (TORA) and Ad-hoc On-demand Distance Vector (AODV). These routing protocols can be categorised as proactive or reactive routing protocols.

Proactive routing protocols are also called "table driven" routing protocols. In these protocols, the nodes maintain up-to-date routing information of the network topology, where nodes continuously calculate paths to the destinations. Once a route is needed by a source node, it can immediately get a routing path. Updates must happen when the network topology changes, and the network has to notify the change to all nodes in the network. An example of proactive routing protocol is Destination Sequence Distance Vector (DSDV) [36; 35].

On the other hand, in reactive routing protocols, also referred to as "on-demand" routing protocols, nodes only create routes when data traffic need to be sent through the network. There is usually a route determination procedure, which is called by the route discovery operation any time a routing path is needed. The discovery procedure examines all route permutations until it finds a route or terminates when no route is available. In a MANET, node mobility may disconnect some active routes. Therefore, route maintenance is an important operation of reactive routing protocols. Examples of reactive routing protocols are Dynamic Source Routing (DSR) [35; 37] and Ad hoc On-demand Distance Vector (AODV) [35; 38].

Comparing the proactive and the reactive routing protocols, the control overhead is less in reactive routing protocols. Thus, the reactive routing protocol is more scalable than the proactive routing protocol. However, in reactive routing protocols, source nodes may suffer long delays during the search for a route before they can forward their data packets [35].

2.4.1 DSR

The Dynamic Source Routing (DSR) protocol [35; 37] is a reactive routing protocol, and it is based on the source routing algorithm. In a source routing protocol, each data packet contains the complete routing information to reach its destination. Moreover, each node uses caching to maintain the route information that it has acquired.

There are two major phases in the DSR protocol, the route discovery phase and the route maintenance phase [35]. In the route discovery phase, a node which intends to send a data packet to a given destination, checks its route cache. This cache contain the route information that the node has acquired. If the route to the destination is available, the node includes the routing information in the data packet and then sends the data packet. On the other hand, if the route is not found, the node starts a route discovery operation by broadcasting route request packets in the network. These request packets contain the address of the source node, the address of the destination and a unique identification number by which the packets are identified. The requests packets are forwarded from one node to the other, where each node checks the information in the request packet with the information contained in its cache [35].

If a node does not have the routing information for the requested destination, it adds its own address to the route record field of the route request packet and forwards the packet to the next node. The communication overhead of route request packets can be limited by making nodes process all route request packets that they have not seen before, as well as route request packets that contain addresses that are not present in the route record field [35]. This continues until the route request packet reaches its destination or an intermediate node which has the routing information to the destination, and then a route reply packet is generated. The route reply packet that is generated by the destination contains all addresses of the nodes that the route request packet passes through them. In addition, the route reply packet also contains the addresses of nodes that the route request packet traverse concatenated with the route that the intermediate node contained in its route cache [35].

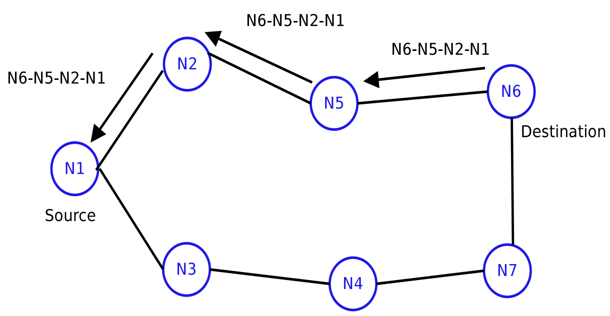

Figure 2.2: Route reply with route record in DSR

Once a destination node receives the route request packet, it uses the collected routing information in the route record field to generate a route reply packet, but in the reverse order as shown in Figure 2.2.

In DSR, when a link disconnection is detected by the data link layer, a ROUTE-ERROR packet is dispatched to the source of every route that uses the failed link. The source node initiates a new route discovery operation after it receives the ROUTE-ERROR packet. In addition, the intermediate nodes remove all routes that contain the failed link from their route caches when the ROUTE-ERROR packet is transmitted to the sources [35].

2.4.2 DSDV

The Destination-Sequenced Distance-Vector (DSDV) Routing Algorithm [35; 36] is a proactive MANET routing protocol. The DSDV Routing Algorithm is based on the Bellman-Ford routing algorithm [39] with certain improvements. Every mobile node has a routing table. This routing table stores the next-hop and number of hops to the destination for all reachable destinations. The DSDV requires that each node periodically broadcasts routing updates. The advantage of DSDV is that it guarantees that the route does not contain a loop.

DSDV guarantees loop-freedom by using sequence numbers to tag each route. The sequence number shows the freshness of a route. Routes with a high sequence number are favoured. A route R' is considered more favourable than the route R if R' has a greater sequence number or, if the routes have the same sequence number but R' has a lower hop-count. The sequence number is increased when a node A detects that a route to a destination D has broken. The next time node A advertises its routes, it will advertise the route to destination D with an infinite hop-count and a sequence number that is larger than before [40].

DSDV is basically a distance vector routing algorithm with small adjustments to make it better suited for ad hoc networks. These adjustments consist of triggered updates that will take care of topology changes in the time between broadcasts. To reduce the amount of information in these packets, two types of update messages are defined: full dump and incremental dump. The full dump carries all available routing information and the incremental dump carries only the information that has changed since the last dump [40].

2.4.3 AODV

The Ad hoc On-demand Distance Vector Routing (AODV) protocol [38; 35] is a reactive routing protocol for MANETs. This protocol is based on the same algorithm as the DSDV algorithm. This protocol maintains only the routing information of the active paths, where AODV does not require nodes to maintain routes to destinations that are not in communication. In AODV, each node has a routing table that contains the routing information. This routing table, called the next-hop routing table, contains information on the destinations to which the node currently has a route.

Unlike in DSDV, the routing table is periodically updated. Moreover, if an entry in the routing table is not used or reactivated for a specified expiration time it expires. In addition, the destination sequence number technique that is used by the DSDV algorithm is also adopted for the AODV protocol in an on-demand way, where this technique guarantees that a route is “fresh" [35].

The process of sending data packets in AODV is similar to that used by the DSR protocol. When packets are to be sent from a node to a destination, the node initiates a route discovery operation if no route is immediately available. Like the route discovery operation in DSR, the source node sends the route request (RREQ) packets through the network (see Figure 2.3). This packet contains the address of the source node, the address of the destination node, the identifier or the broadcast ID, the source node sequence number and the last seen sequence number of the destination. Sequence numbers are needed to ensure that all routes are loop-free and up-to-date. To reduce the flooding overhead, a node removes all RREQs that it has seen before. This is achieved by using the expanding ring search algorithm [41] in the route discovery operation. The TTL (Time-To-Live) value of the first RREQ packet is initialised with a small number. However, the TTL value increases in the following RREQ packet when no route to the destination is found [38; 35].

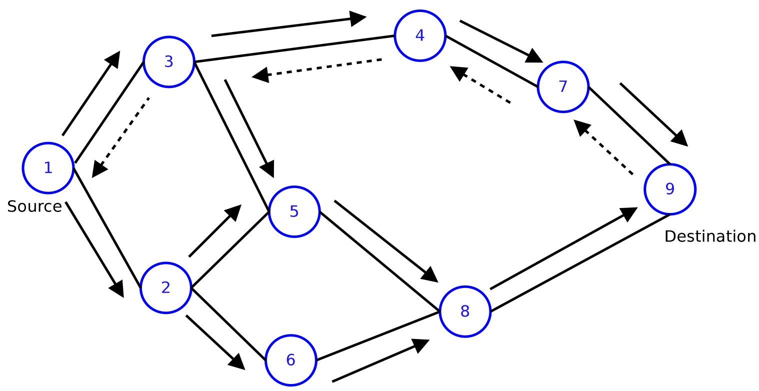

Figure 2.3: Route request packets and the route reply packet in AODV

Every node in AODV has a cache which keeps track of the received request packets, along with the route back to the source of each RREQ. When the request packet arrives at a node which has a route to the destination, or arrives at the destination node itself, the node compares the destination sequence number contained in the packet with the sequence number of the destination it has in its cache. If the destination sequence number in the node's cache is higher or equal to that of the request packet, a route reply (RREP) packet is generated. The route reply packet then follows the same RREQ route but in the reverse direction until it reaches the source node. Nodes along the path which the reply packet arrives at update their next-hop table entries with respect to the destination node as they receive the reply packet. Duplicate reply packets or reply packets with lower destination sequence numbers are dropped [35].

There is also the provision for recovery in AODV when nodes detect a link failure. Nodes broadcast a route error (RERR) packet, which is transferred from the nodes, to the source node so that the source node can re-initiate the route discovery operation if the source node still needs the route to send data packets [35].

2.4.4 TORA

The Temporally Ordered Routing Algorithm (TORA) [35; 42; 43] is a reactive routing algorithm designed to work in a highly dynamic mobile networking environment. It operates based on a highly adaptive loop-free distributed routing algorithm which uses the concept of link reversal. In TORA, the control messages are localised to a small set of nodes around where the changes in topology occur. To do this, each node needs to maintain routing information of adjacent (also called one-hop) nodes. The TORA protocol presents three basic functions: Route creation, route maintenance and route erasure [44].

In the route creation and the route maintenance operations, a node that intends to send packets to a destination does so by using a "height" metric. The purpose of the height metric is to establish a directed acyclic graph (DAG) at the destination. This DAG can be obtained by assigning a logical direction to the links, whether upstream or downstream, based on the relative height metric of the nodes close to the source node (see Figure 2.4). This process of obtaining a DAG is similar to the query/reply process of the Lightweight Mobile Routing (LMR) [44; 45].

The route maintenance operation is necessary for the TORA protocol to reestablish the DAG at the same destination in such cases where a DAG is disconnected due to node mobility. If a node loses its last downstream link, it generates a new reference level which it broadcasts to the neighbours nodes (see Figure 2.5). In this case, nodes that receive the new reference level can update their routing information. Since the "height" metric is dependent on the logical time of a link failure, timing is a very important factor in TORA. After broadcasting the new reference level, the links are reversed to indicate changes in topology and adapt to the new reference level generated. The last operation, route erasure, is carried out by broadcasting a special packet, the clear packet CLR, through the network. This packet erases the invalid routes within the network [44; 35].

In TORA, all the nodes in the network are assumed to have synchronised clocks (which is done typically with an external source such as the Global Positioning System). TORA's metric is a 5-tuple:

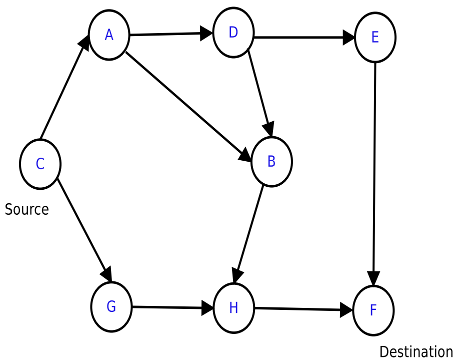

Figure 2.4: Directed acyclic graph of routers defined by the relative height of the routers

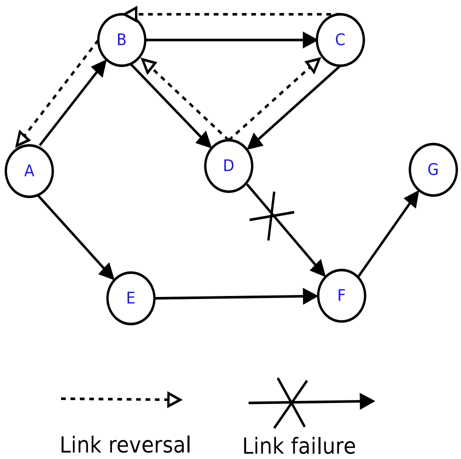

Figure 2.5: Route maintenance in TORA

- the logical time of a link failure
- the unique ID of the node which defines the new reference level
- a reflection indicator bit
- a propagation ordering parameter
- the unique ID of the node.

The reference level is defined by the collection of the first three elements. One of the deficiencies of TORA is the possibility of oscillations within the network. This may occur when different sets of nodes simultaneously continue to detect network partitions, erase routes and create new routes among one another. The instability problem is similar to the "count-to-infinity" in distance-vector routing protocols, except that the oscillations will slowly die out and the routes will converge [44].

2.5 Node Cooperation in Wireless Ad Hoc Networks

A MANET is a wireless multi-hop network formed by a set of mobile nodes in a self-organising way where communication between nodes does not rely on an established infrastructure [46]. Since no fixed infrastructure is used in a MANET, nodes themselves should carry out all networking functions [46]. For instance, if two nodes are out of transmission range, then intermediate nodes are needed to provide a multi-hop transit route from the source to the destination [47; 48]. Thus, cooperation among nodes is an essential requirement in MANETs to provide a multi-hop routes. Cooperation means that the nodes perform networking functions for the benefit of other nodes. A lack of cooperation may have negative effects on network performance. There are several reasons for a node to refrain from forwarding packets on behalf of other nodes. Forwarding packets occupies transmission time that nodes cannot use for transmitting their own packets. Transmitting packets also consumes battery power which is a limited resource on mobile devices. However, with uncooperative nodes, communication over multiple hops becomes impossible. This is because no packets are forwarded and the multi-hop ad hoc network fails. Cooperation is therefore one of the most important factors in wireless ad hoc networks. Nodes can be stimulated to cooperate by punishing non-cooperative behaviour and/or by rewarding cooperative behaviour. In Chapter 3, the issue of stimulating cooperation in self-organising MANETs is addressed.

2.6 Mobility in Mobile Ad Hoc Networks

Nodes in MANETs are potentially mobile and can be connected dynamically in an arbitrary manner [49; 50].

All nodes of these networks are responsible to provide a multi-hop routes and to take part in the discovery and maintenance of routes to other nodes in the network. The mobility of the nodes in wireless ad hoc networks raises two issues. The first issue is how to locate a node in such a network. The second one is how to keep the location information up to date. It is necessary to develop and use mobility models that accurately represent the movements of the mobile nodes in order to simulate a new protocol and/or cooperation in ad hoc networks. A mobility model should mimic the movements of real mobile nodes. This is difficult because changes in speed and direction must occur and they must occur in reasonable time frames. Currently there are two categories of mobility models for representing individual mobile nodes: simple models and collective models. These models are discussed in Chapter 4. The purpose of this thesis is to focus on several useful mobility models to evaluate the performance of cooperation in MANETs.

Chapter 3

Incentives for Collaboration in Mobile Ad Hoc Networks

3.1 Overview of Incentive Mechanisms

Mobile ad hoc networks are an example of mobile wireless communication where communication between nodes does not rely on an underlying static network infrastructure [51; 52]. Nodes in a MANET are mobile and nodes have constrained resources, such as power, bandwidth, computation ability and storage capacity. Since no fixed infrastructure or centralised administration is available, these networks are self-organised and end-to-end communication may require routing via several intermediate nodes. Due to the lack of a fixed infrastructure and the limited transmission range of a node in a MANET, a node has to rely on its neighbours to route its traffic to a destination node [51]. Thus all network functions are based on node cooperation. Without node cooperation, multi-hop routes in a MANET cannot be established. Routing protocols for MANETs, such as the Dynamic Source Routing (DSR) [53] and the Ad hoc On Demand Distance Vector Routing Protocol (AODV) [54] are based on the assumption that all nodes are cooperative.

Sometimes a node does not cooperate in a MANET. A node that does not cooperate is called a misbehaving node. A misbehaving node can be malicious or selfish [55; 1]. These nodes can damage the network and cause routing and forwarding misbehaviours. A malicious node does not cooperate because it deliberately wants to damage the network by dropping packets. A selfish node does not intend to directly damage other nodes, but is unwilling to spend its resources such as battery power, CPU cycles, or available network bandwidth to forward packets, even though it expects other nodes to forward packets on its behalf [1]. To cope with these problems, a self-organising network must contain an incentive for nodes to collaborate, thus avoiding malicious and selfish behaviour. There is a need for mechanisms that encourage nodes to collaborate, allowing the nodes to relay packets for the benefit of other nodes.

Improving the cooperation of nodes in an ad hoc network may also have other advantages. One such advantage is the increase in data flow of the network, since the increased connectivity of the network leads to more possible routes in the network. If more nodes cooperate, the average number of packets that each node has to forward is reduced, which leads to lower energy consumption and improved fairness in the network.

Currently, most of the incentive mechanisms available present an approach that is almost the same as the cooperation problem [1; 56; 57; 58]. These mechanisms are based on a watchdog and a reputation system. The watchdog identifies misbehaving nodes by performing neighbourhood monitoring. This is done by listening to the wireless links and collecting information. According to the collected information, the reputation system maintains a value for each observed node. This value represents the node's reputation. The reputation mechanism can be used to free the network from malicious nodes when it allows the nodes of the network to isolate misbehaving nodes. This can be done by not serving requests from the misbehaving node. Existing incentive mechanisms have advantages and disadvantages. The mechanism presented by S. Marti *et al.* [57] extends the Dynamic Source Routing protocol with a watchdog system for the detection of misbehaving nodes, and a "path-rater" for the avoidance of such nodes in routes. Every node in the network rates and evaluates the performance of other nodes. The path-rater uses the rating information to choose the network path that is most likely to deliver packets. The main drawback of such an approach is that it does not punish selfish nodes that therefore have no incentive to cooperate. There are two main protocols based on the watchdog (WD) and reputation system. These protocols are the CONFIDANT (Cooperation Of Nodes and Fairness In Dynamic Ad-hoc NeTworks) protocol and the CORE (COllaborative REputation) protocol.

The CONFIDANT protocol [1; 56] built on the DSR protocol, is intended to cope with the routing misbehaviour problem. The objective is to find and isolate malicious nodes. Each node observes the behaviour of its one-hop neighbours. This observed information is submitted to a reputation system if a suspicious event is detected. This information is used to maintain a list of ratings reflecting the node's behaviour. The information is given to a path manager if the ratings become "unendurable". The manager can delete all routes containing the misbehaving node from the path cache. The manager can also decide to not serve routing/forwarding requests from a selfish node. Moreover, a trust manager sends an alarm message to alert other nodes of malicious nodes.

The CORE protocol is a collaborative reputation mechanism proposed by Michiardi and Molva [1; 58]. The CORE protocol also has a watchdog component that evaluates the behaviour of the other nodes and detects misbehaving nodes. When a node forwards a packet, the node's watchdog verifies that the next node in the path also forwards the packet. This can be done by listening to the next node's transmissions. The next node is considered as a misbehaving node if it does not forward the packet. In addition, the CORE protocol is complemented by a reputation mechanism that differentiates between subjective reputation (observations), indirect reputation (positive reports by others), and functional reputation (task-specific behaviour) [1]. These reputations are weighted for a combined reputation value. This value is used to make decisions about the cooperation or the isolation of a node. Reputation values are obtained by observing nodes as requesters and providers, and comparing the expected result to the actual result of a request.

The CONFIDANT and CORE protocols have drawbacks. In the presence of collisions and differences in transmission ranges the watchdog weaknesses are not negligible because these characteristics can effect its performance. For example, the watchdog may not able to properly monitor the neighbours and detect misbehaving nodes, and the the watchdog observations can become meaningless. Another drawback is the employment of cooperation in security mechanisms. In the case of the CONFIDANT protocol, malicious nodes may send false alarms about other nodes which are not misbehaving. The impact of wrong accusations on the CONFIDANT reputation system is discussed in [1; 59]. In the CORE mechanism no negative ratings are spread between nodes, but a malicious node can deceive the reputation system by sending a forged Route Reply. Finally, both CONFIDANT and CORE do not take into account network utilisation: by avoiding all routes containing misbehaving nodes, they create a risk of diverting all the traffic to well behaving nodes, with the result of overloading these nodes and the links between them.

Virtual Currency-based Schemes [2] present an incentive mechanism based on the assumption that a price must be paid when nodes send packets to each other, and the reason for this is that mobile nodes in MANETs have limited resources such as battery power. A virtual currency is used to charge/reward the packet forwarding service. The virtual currency system motivates nodes for future cooperation by compensating nodes that cooperate (i.e. act as transit nodes) in the network [2]. The system rewards the cooperating nodes by using a credit or micro payment concept. A node receives a credit for forwarding the packets on behalf of another node, and this credit is deducted from the source or from the destination node. Nuglets and Sprite are two examples of protocols based on the virtual currency concept.

Nuglets: This protocol [56; 2; 60] is used to charge/reward the packet forwarding service. Each node has a credit counter. A node must have a counter value that is at least equal to the route hop count in order to be able to send a packet to the destination. The counter value of a transit node is incremented by one when it forwards a packet on behalf of another node. The counter value is decreased by the hop count when the activated node is a source [2]. There are two models in Nuglets [56; 61]: the Packet Purse Model, where the credit payment is deducted from the source node, and the Packet Trade Model, where the credit payment is deducted from the destination. The problem with this protocol is that it needs tamper-proof hardware to manage the increments and decrements of the credit counter of each node.

Sprite: In this protocol [62; 2], a centralised Credit Clearance Service (CCS) is used to manage the reward and the credit payment operations for each node in the network. A transit node that forwards a packet on behalf of another node is compensated, but the credit that a node receives for its services depends on the success of the forwarding action. Forwarding is considered successful if the next node on the path reports a valid receipt to the CCS [52; 62]. The problem with this approach is that it needs a centralised server to manage the rewards and the credit payment for each node in the network, and this requirement does not meet many practical ad hoc network scenarios.

The use of pricing mechanisms for allocating resources in communication networks has received much attention in recent years. In particular, the work by Kelly *et al.* [6] shows that pricing mechanisms can be used to achieve (in equilibrium) a weighted proportional fair rate allocation. In this chapter incentives for collaboration are introduced into the architecture of ad hoc networks. This leads to the use of pricing mechanisms which have found application in rate control [5; 6; 7] and resource control [8; 9; 63] in wired and wireless networks.

The Crowcroft *et al.* pricing model [3; 4] can be summarised as follows. For each node there is a limit on the bandwidth and power that can be consumed. When a node acts as a source, transit or destination node, it obtains compensation in the form of credits for the congestion costs of the bandwidth and power resources consumed. A node uses its credits to pay for the bandwidth and power congestion costs incurred when it sends its own traffic. New calls are connected on the least cost routes. The bandwidth and power congestion prices are updated at regular intervals, and are meant to reflect the level of congestion at any node along any route.

The dynamics of the system under consideration are illustrated in Chapter 5 using a simulation model to demonstrate the stability of prices at nodes and their credit balances. With regards to performance, the throughput of the system is investigated. Finally, user mobility is considered to determine how it affects their individual throughputs and also how it contributes to the overall system throughput.

3.2 Description of the Pricing Mechanism Model

We model the network as a set $\mathcal{N}$ of mobile nodes that are equipped with directional antennas, with $N = |\mathcal{N}|$ being the number of nodes.

In this section we use the term “node" to denote a topological entity which can be characterised in terms of position, velocity, capacity constraint and routing. The term “user" will refer to a person who desires to send traffic to the other users in the networks, in other words an active node [3].

3.2.1 Traffic Flow on Routes

Amongst the set of nodes $\mathcal{N}$, we define a set $\mathcal{S}$ of sources which originate traffic and a set $\mathcal{D}$ of destinations to which traffic is sent. A set of routes between each source and destination pair must be determined, where a route $r \subset \mathcal{N}$ is a subset of the nodes. These routes can be determined using routing protocols like AODV [54] or DSR [53].

$\mathcal{R}^{\mathcal{S}}(s)$ and $\mathcal{R}^{\mathcal{D}}(d)$ denote the set of routes that originate at source s and the set of routes that terminate at destination d respectively. Let $\mathcal{R}^{\mathcal{T}}(k)$ denote the set of routes that transit through node k.

At a specific point of time, each source s is originating a total traffic flow x_s, which may be split among the routes $r \in \mathcal{R}^{\mathcal{S}}(s)$. Optimisation of the traffic flows from a single source using multiple routes has been considered in [6; 64; 65].

The traffic flow along a particular route r is given by $y_r(t) \geq 0$ and the total traffic flow originating from nodes is

$$x_s = \sum_{r \in \mathcal{R}^{\mathcal{S}}(s)} y_r(t). \tag{3.2.1}$$

3.2.2 The Radio Interference Model

Node i can reach node j when the signal received by node j from node i is strong enough to be successfully decoded [4]. Consider a tagged call in service at node $i \neq D(r)$ on route r, where $D(r)$ is the destination node of route r. The strength of the signal received at node $j = f_r(i)$ from the tagged call is $p_i y_r \ell(z_i - z_j)$ where $f_r(i)$ denotes the node that node i will forward traffic to when using route r. Let p_i denote the power radiated per unit flow by the tagged call at node i, and let y_r denote the flow along route r. The attenuation function is given by $\ell(z_i - z_j) = kd^{-u}$, where $d = \|z_i - z_j\|_2$ is the Euclidean distance between z_i and z_j, and z_i is the (x, y) location of node i, and u is the attenuation factor.

The signal-to-interference ratio β_{ri} [66; 67; 63; 68] is determined through a fixed point equation given by

$$\beta_{ri} = P(\beta_{ri})\hat{\beta}_{ri} \tag{3.2.2}$$

where the packet success probability [63] is

$$P(\beta_{ri}) = (1 - 0.5e^{-\beta_{ri}})^L \tag{3.2.3}$$

with L being the packet size in bits, and

$$\beta_{ri} = \frac{W}{y_r} \frac{p_i y_r \ell(z_i - z_j)}{N_0 + \eta(A + B)} \tag{3.2.4}$$

where W is the chip rate of the spreading code, N_0 the power of the thermal background noise, $0 < \eta \leq 1$ represents the effect of the interference (in terms of the orthogonality of the codes),

$$A = \sum_{k \neq i,j} p_k \ell(z_k - z_j) \sum_{r \in R^S(k)} y_r \tag{3.2.5}$$

is the interfering signal at node j arising from calls originating at the neighbours k of node j, and

$$B = \sum_{k \neq i} p_k \ell(z_k - z_j) \sum_{r \in \mathcal{R}^{\mathcal{T}}(k): k \in r} y_r \tag{3.2.6}$$

is the interfering signal at node j arising from calls transiting the neighbours k of node j.

We describe the relationship between the effective (net) transmission rate y_r on route r, and the actual (gross) transmission rate Y_{ri} between the nodes i and j on route r. If the effective rate is y_r , it requires a gross rate of $Y_{ri} = y_r / P(\beta_{ri})$ where $P(\beta_{ri})$ is the fraction of packets successfully transmitted.

Since the flow $Y_{ri} = y_r / P(\beta_{ri}) \leq W$, and because probabilities are smaller than 1, a lower bound on the value of $P(\beta_{ri})$ can be obtained as:

$$P(\beta_{ri}) \longleftarrow \min(1, \max(y_r/W, P(\beta_{ri}))). \tag{3.2.7}$$

We assume that nodes i and j are within transmission range and can reach each other if the packet success probability is above a certain threshold $P(\beta_{ri}) \geq 0.9$.

3.2.3 The Capacity Constraint

We consider nodes to be restricted to having one transceiver. The capacity constraint can be modelled by calculating the total capacity $c_j(t)$ used at node j at time t

$$c_j(t) = \sum_{r \in \mathcal{R}^{\mathcal{S}}(j)} \frac{y_r(t)}{P(\beta_{rj})} + \sum_{r \in \mathcal{R}^{\mathcal{D}}(j)} y_r(t) + \sum_{r \in \mathcal{R}^{\mathcal{T}}(j)} \left(1 + \frac{1}{P(\beta_{rj})}\right) y_r(t). \tag{3.2.8}$$

Capacity usage is constrained as follows

$$c_j(t) \leq C_j, \tag{3.2.9}$$

where C_j is the total capacity of node j.

3.2.4 The Power Constraint

A key issue in mobile ad hoc networking is energy efficiency, and this can be achieved through traffic management and the optimal routing of traffic flows.

Let $e_{ij}^{(tx)}$ denote the energy consumed per unit flow when transmitting traffic from node i to node j. Let $e^{(rx)}$ denote the energy consumed per unit flow per unit time when receiving data.

We chose $e_{ij}^{(tx)}$ to be a non-zero function in the vicinity of the transmitter, which is given by

$$e_{ij}^{(tx)} = \max(10^{-2},\ 10^{-4}\|z_i - z_j\|_2^2) \tag{3.2.10}$$

Note that if the node j cannot be reached from node i, then $e_{ij}^{(tx)} = \infty$. let $f_r(i)$ denote the node that node i will forward traffic to when using route r.

The power constraint can be modelled by calculating the total power $\gamma_j(t)$ used at time t

$$\gamma_j(t) = \sum_{r\in\mathcal{R}^{\mathcal{S}}(j)} \frac{e_{jf_r(j)}^{(tx)}}{P(\beta_{rj})} y_r(t) + \sum_{r\in\mathcal{R}^{\mathcal{D}}(j)} e^{(rx)} y_r(t) + \sum_{r\in\mathcal{R}^{\mathcal{T}}(j)} \left(e^{rx} + \frac{e_{jf_r(j)}^{(tx)}}{P(\beta_{rj})}\right) y_r(t). \tag{3.2.11}$$

Power usage is constrained as follows

$$\gamma_j(t) \leq \Gamma_j, \tag{3.2.12}$$

where Γ_j is the total power available at node j.

3.2.5 Dual Algorithm

Consider a wireless ad hoc network with a set $\mathcal{N}$ of users accessing the network and a set of links $\mathcal{L}$. The wireless link l between nodes i and j is in $\mathcal{L}$, if nodes i and j are within transmission range of each other. Each link $l \in \mathcal{L}$ has a finite fixed capacity C_l. Each user in $\mathcal{N}$ is associated with a route $r \subset \mathcal{L}$ along which it transmits a traffic flow $x_r(t)$. The route matrix [6] is defined as $A = (A_{jr},\ j \in \mathcal{L}, r \in \mathcal{N})$, where $A_{jr} = 1$ if $j \in r$, so that the path of user r traverses the link j, and $A_{jr} = 0$ otherwise.

Suppose that if a traffic flow $x_r(t)$ is allocated to user r at time t, then this has utility function $U_r(x_r)$ to the user, where $U_r(x_r)$ is an increasing function, strictly concave and continuously differentiable over the range $x_r(t) \geq 0$.

Let $U = (U_r(.),\ r \in \mathcal{N})$ and $C = (C_j,\ j \in \mathcal{L})$, and suppose that the network seeks a rate allocation $x(t) = (x_r(t),\ r \in \mathcal{N})$ which solves the following optimisation problem.

$SYSTEM(U, A, C)$

$$\begin{aligned} &\max \sum_{r \in \mathcal{N}} U_r(x_r(t)) \\ &subject\ \ to\ \ Ax(t) \leqslant C \\ &over\ \ x(t) \geq 0 \end{aligned} \tag{3.2.13}$$

The above maximisation problem cannot be solved directly by the network provider, as it involves utilities U that are unknown by the network. Instead, Kelly *et al.* [6] consider two simpler problems. In the first problem, suppose that user r chooses an amount to pay per unit time $w_r(t)$, and receives in return a traffic flow $x_r(t)$ given by

$$x_r(t) = \frac{w_r(t)}{\lambda_r(t)} \tag{3.2.14}$$

where $\lambda_r(t)$ is a charge per unit flow for user r. Then the utility maximisation problem for user r is

$USER(U_r; r)$:

$$\begin{aligned} &\max U_r\left(\frac{w_r(t)}{\lambda_r(t)}\right) - w_r(t) \\ &over\ \ w_r(t) \geq 0 \end{aligned} \tag{3.2.15}$$

In the second problem, suppose that the network knows the vector $w(t) = (w_r(t),\ r \in \mathcal{N})$, and attempts to maximise the function $\sum_r w_r(t) \log(x_r(t))$. This is known as the network optimisation problem or primal problem [6] which is then defined as

$NETWORK(A, C; w(t))$:

$$\begin{aligned} &\max \sum_{r \in R} w_r(t) \log(x_r(t)) \\ &subject\ \ to\ \ Ax(t) \leqslant C \\ &over\ \ x(t) \geq 0 \end{aligned} \tag{3.2.16}$$

Note that solving the maximisation problem $NETWORK(A, C; w(t))$ does not require the network to know the utility function U.

Kelly *et al.* show that there always exist vectors $\lambda(t) = (\lambda_r(t), r \in \mathcal{N})$, $w(t) = (w_r(t), r \in \mathcal{N})$ and $x(t) = (x_r(t), r \in \mathcal{N})$, satisfying $w_r(t) = \lambda_r(t)x_r(t)$ for $r \in \mathcal{N}$, such that $w_r(t)$ solves $USER(U_r; r)$ for $r \in \mathcal{N}$ and $x(t)$ solves the primal problem $NETWORK(A, C; w(t))$ [69]. Furthermore, the vector $x(t)$ is the unique solution to $SYSTEM(U, A, C)$. This result implies that problems

$NETWORK(A, C; w(t))$ and $USER(U_r; r)$ for $r \in \mathcal{N}$ can be used to obtain the unique solution to $SYSTEM(U, A, C)$.

To solve the primal problem $NETWORK(A, C; w(t))$, we use the method of Lagrange multipliers and the Karush-Kuhn-Tucker (KKT) theorem [70], where the Lagrangian of the above problem is obtained by incorporating the constraints into the maximisation by means of Lagrange multipliers as follows

$$L(x, z, \mu) = \sum_{r \in \mathcal{R}} w_r(t) log(x_r(t)) + \mu^\top (C - Ax(t) - z), \tag{3.2.17}$$

where $z > 0$ is a vector of slack variables and $\mu(t) = (\mu_{jr}(t),\ j \in \mathcal{L})$ is a vector of Lagrange multipliers (or prices). Then

$$\frac{\partial L}{\partial x_r(t)} = \frac{w_r(t)}{x_r(t)} - \sum_{j \in r} \mu_{jr}(t). \tag{3.2.18}$$

Setting equation (3.2.18) equal to zero, the unique optimum to the primal problem
$NETWORK(A, C; w(t))$ is given by

$$x_r(t) = \frac{w_r(t)}{\sum_{j \in r} \mu_{jr}(t)}, \tag{3.2.19}$$

where $(x_r(t),\ r \in \mathcal{N})$ and $(\mu_j(t),\ j \in \mathcal{L})$ solve

$$\mu(t) \geq 0, \qquad Ax(t) \leq C, \qquad \mu^\top(t)(C - Ax(t)) = 0, \tag{3.2.20}$$

and satisfy equation (3.2.19).

To obtain the vector $\mu(t)$ we solve the following dual problem

$$\min_{\mu(t) \geq 0} L(\mu(t)). \tag{3.2.21}$$

After eliminating the terms that do not depend on the prices $\mu(t)$ by using equation (3.2.19), the dual algorithm reduces to the following problem
$DUAL(A, C, w)$:

$$\begin{aligned} &\max \sum_{r \in \mathcal{N}} w_r(t) \log(\sum_{j \in \mathcal{L}} \mu_{jr}(t)) - \sum_{j \in \mathcal{L}} \mu_{jr}(t) C_j \\ &\mu(t) > 0. \end{aligned} \tag{3.2.22}$$

Though the problem $DUAL(A, C; w(t))$ is tractable, it would be difficult to implement a solution in a centralised manner. Instead Kelly *et al.* propose the use of a decentralised algorithm, also known as dual algorithm, that computes the optimal solution.

Consider the following system that represents the dual algorithm

$$\frac{d}{dt}\mu_{jr}(t) = \kappa\left(\sum_{r:j\in r} x_r(t) - q_j(\mu_{jr}(t))\right), \tag{3.2.23}$$

where

$$x_r(t) = \frac{w_r(t)}{\sum_{j\in r}\mu_{jr}(t)}. \tag{3.2.24}$$

The dual algorithm can be motivated in several ways. For example, suppose that $q_j(\eta)$ is the flow through link j which generates a price η at link j. Then, the right hand side of (3.2.23) could be described as the vector of excess demand at prices $(\mu_j(t), j \in \mathcal{L})$, and we can recognise (3.2.23)-(3.2.24) as a tâtonnement process which describes the prices adjusted according to supply and demand [71].

Consider the following function

$$\mathcal{V}(\mu) = \sum_{r\in\mathcal{N}} w_r(t)log(\sum_{j\in r}\mu_{jr}(t)) - \sum_{j\in\mathcal{L}}\int_0^{\mu_{jr}(t)} q_j(\eta)d\eta. \tag{3.2.25}$$

We use the function $\mathcal{V}(\mu)$ defined by (3.2.25) to investigate the stability of the dual algorithm (3.2.23)-(3.2.24). Consider the function $\mathcal{V}(\mu)$, where $w_r(t) > 0$, $r \in \mathcal{N}$, and suppose that for $j \in \mathcal{L}$ we have $q_j(0) = 0$, and $q_j(\eta)$, $\eta > 0$ is a continuous, strictly increasing function of η.

Theorem: The strictly concave function $\mathcal{V}(\mu)$ is a Lyapunov function for the system of differential equations (3.2.23)-(3.2.24), and the unique value $\mu(t)$ maximising $\mathcal{V}(\mu)$ is a stable point of the system, to which all trajectories converge.

Proof: The assumptions on $w_r(t) > 0$, $r \in \mathcal{N}$, and on $q_j(\eta)$, $j \in \mathcal{L}$, ensure that $\mathcal{V}(\mu)$ is strictly concave on $\mu(t) \geq 0$ with an interior maximum. The maximising value of $\mu(t)$ is thus unique, and is determined by setting the derivatives

$$\frac{\partial}{\partial\mu_{jr}}\mathcal{V}(\mu) = \sum_{r:j\in r}\frac{w_r(t)}{\sum_{k\in r}\mu_{kr}(t)} - q_j(\mu_{jr}(t)) \tag{3.2.26}$$

to zero. Now consider

$$\frac{d}{dt}\mathcal{V}(\mu) = \sum_{j\in\mathcal{N}}\frac{\partial\mathcal{V}(\mu)}{\partial\mu_{jr}}.\frac{d}{dt}\mu_{jr}(t). \tag{3.2.27}$$

Inserting (3.2.23) and (3.2.26) into (3.2.27), we get

$$\frac{d}{dt}\mathcal{V}(\mu) = \kappa \sum_{j\in\mathcal{N}} \left(\sum_{r:j\in r} \frac{w_r(t)}{\sum_{k\in r}\mu_{kr}(t)} - q_j(\mu_{jr}(t)) \right)^2, \tag{3.2.28}$$

establishing that $\mathcal{V}(\mu)$ is strictly increasing with t, unless $\mu(t) = \mu$, the unique value μ maximising $\mathcal{V}(\mu)$. The function $\mathcal{V}(\mu)$ is thus a Lyapunov function for the system (3.2.23)-(3.2.24).

The vector μ maximising $\mathcal{V}(\mu)$ is a stable point of the system, to which all trajectories converge. Furthermore, with an appropriate choice of the functions $q_j(\eta)$, $j \in \mathcal{L}$, the maximisation of the function $\mathcal{V}(\mu)$ can arbitrarily approximate the problem $DUAL(A, C; w)$.

The maximisation of the Lyapunov function $\mathcal{V}(\mu)$ becomes the dual problem if, for $j \in \mathcal{L}, \eta > 0, q_j(\eta) = C_j$. These functions violate the assumption that $q_j(\eta)$ is continuous at $\eta = 0$, but they may be arbitrarily closely approximated.

3.2.6 Flow Allocation and Route Prices

According to equation (3.2.19), the total flow generated by node s at time t in the case where each node originates one call at a time is

$$x_s(t) = \sum_{r\in R^S(s)} y_r(t) = \frac{w_s(t)}{\min_{r\in R^S(s)} \sum_{j\in r}\mu_{jr}(t)}, \tag{3.2.29}$$

where each source node s chooses the route r^* with lowest cost

$$r^* = \min_{r\in R^S(s)} \sum_{j\in r} \mu_{jr}(t), \tag{3.2.30}$$

and where $y_r(t) > 0$ only on those routes r that attain a minimum in equation (3.2.30) with the variable $\mu_{jr}(t)$ being the price that node j charges for forwarding a unit of flow to the next node $k = f_r(j)$ along route r given by

$$\mu_{jr}(t) = \begin{cases} e^{(tx)}_{jk}\mu^P_j(t) + \mu^B_j(t) & j \text{ is the source node on route } r \\ (e^{(tx)}_{jk} + e^{(rx)})\mu^P_j(t) + 2\mu^B_j(t) & j \text{ is a transit node on route } r \\ e^{(rx)}\mu^P_j(t) + \mu^B_j(t) & j \text{ is the destination node on route } r \end{cases} \tag{3.2.31}$$

where $\mu_j^P(t)$ denotes the power congestion price which satisfies the differential equation (DE)

$$\frac{d}{dt}\mu_j^P(t) = \frac{\kappa \mu_j^P(t)}{\Gamma_j}(\gamma_j(t) - \Gamma_j), \tag{3.2.32}$$

with initial value $\mu_j^P(0) = 1$, where κ is a constant of dimension s^{-1}. Likewise, the bandwidth congestion price satisfies the differential equation

$$\frac{d}{dt}\mu_j^B(t) = \frac{\kappa \mu_j^B(t)}{C_j}(c_j(t) - C_j), \tag{3.2.33}$$

with initial value $\mu_j^B(0) = 1$. The differential equation for the bandwidth congestion price can be approximately evaluated through

$$\mu_j^B(t+\Delta) = \mu_j^B(t)\left(1 + \kappa\Delta\left(1 - \frac{c_j(t)}{C_j}\right)\right), \tag{3.2.34}$$

for some suitable value of Δ, with a similar expression for $\mu_j^P(t+\Delta)$. The congestion prices are thus constant when the resource is fully utilized, and increase/decrease when the resource is over/under utilized. The congestion prices are adjusted every Δ seconds, so that the resources at each node are utilized as fully as possible.

The global stability of the system (3.2.29)-(3.2.32) can be established by the construction of an appropriate Lyapunov function [6; 70], in the case where the network structure is static. We investigate here a model where both the network structure and the set of sources is varying over time.

3.2.7 The Willingness-To-Pay

Each node s determines its resource usage according to its willingness-to-pay $w_s(t)$ at time t for the congestion costs incurred in sending its traffic which is given by

$$w_s(t) = \alpha_s b_s(t), \tag{3.2.35}$$

where $\alpha_s > 0$.

3.2.8 The Credit Balance

The nodes are provided with an incentive to provide resources for forwarding transit traffic and receiving traffic. Each user s maintains a credit balance $b_s(t)$ initially set to b. The credit balance of node s is adjusted as follows.

A node expends credits $\sum_{r\in R^S(s)} y_r(t)\mu_r(t)$ for the congestion costs (bandwidth, power) incurred in transmitting its own traffic through the source, destination and transit nodes on its outbound routes, where $\mu_r(t) = \sum_{j\in r} \mu_{rj}(t)$.

A node receives credits $\sum_{r:s\in r} y_r(t)\mu_{rs}(t)$ for the congestion costs (bandwidth, power) incurred in acting as a source, transit node, or as a destination node.

A credit balance that differs from b is discounted using a factor $\beta = 0.01$, so that over one second, under-provisioned nodes that possess a credit balance of less than b receive 1% of the credits that they lack, and over-provisioned nodes that possess a credit balance larger than b surrender 1% of that part of their balance that exceeds b. The credit balance $b_s(t)$ satisfies the differential equation

$$\frac{d}{dt}b_s(t) = -\beta\left(b_s(t) - 1\right) + \Omega_s(t), \tag{3.2.36}$$

where without loss of generality we set $b = 1$ and the "cash flow" $\Omega_s(t)$ is given by

$$\Omega_s(t) = \sum_{r:s\in r} y_r(t)\mu_{rs}(t) - \sum_{r\in R^S(s)} y_r(t)\mu_r(t). \tag{3.2.37}$$

This differential equation can be approximately evaluated through

$$b_s(t+\Delta) = b_s(t) - \beta\Delta\left(b_s(t) - 1\right) + \Delta\Omega_s(t).$$

If the credits earned are equal to the credits spent, $\sum_s \Omega_s(t) = 0$, the total credit balance is equal to the number of nodes N. This can be proved by induction on t.

Recall that $b_s(0) = 1$ for all s, so that $\sum_s b_s(0) = N$. Next we assume that $\sum_s b_s(t) = N$ at time t, and we proceed to proof $\sum_s b_s(t+\Delta) = N$ at time $t+\Delta$. Observe that

$$\sum_s b_s(t+\Delta) = \sum_s b_s(t) - \beta\Delta\sum_s\left(b_s(t) - 1\right) + \Delta\sum_s \Omega_s(t),$$

where $\sum_s \Omega_s(t+\Delta) = 0$ and $\sum_s\left(b_s(t) - 1\right) = \sum_s b_s(t) - \sum_s 1 = N - N = 0$. Then

$$\sum_s b_s(t+\Delta) = N - \beta\Delta\left(0\right) + \Delta(0) = N \tag{3.2.38}$$

so that $\sum_s b_s(t+\Delta) = N$, thereby concluding the proof.

The equations described in Section 3.2 above are used to design a simulator which computes the route flows in a MANET. The simulation proceeds as a sequence of steps. In each step, for those nodes which currently originate calls, the simulator computes the node prices, which determine the route prices; the credit balances are updated and the willingness-to-spend is computed; the new flow allocations are computed; the resources in use are computed, and the next simulation step begins. Additional updates take place when calls enter or leave the simulated network.

Chapter 4

Mobility Models in Mobile Ad Hoc Networks

4.1 Overview

A MANET is a collection of mobile nodes with no pre-established infrastructure forming a temporary network. All communication in a MANET occurs through a wireless medium. Realistic mobility models are needed in simulations in order to evaluate system and protocol performance. For example, to simulate a new protocol, it is necessary to develop and use mobility models that accurately represent the movement of the mobile nodes that will eventually use the given protocol. It is then possible to determine whether or not the proposed protocol will be useful when implemented. It is therefore imperative that accurate mobility models are chosen [72].

Currently, two types of mobility models have been used to simulate networks: traces and synthetic models [73]. Traces are mobility patterns that are observed in real life systems. These models provide accurate information, especially when they involve a large number of nodes and an appropriately long observation period. However, new network environments such as ad hoc networks are not easily modelled if traces have not yet been created. In this situation it is necessary to use synthetic models. Synthetic models attempt to represent the behaviours of nodes without the use of traces. In this chapter, several synthetic mobility models that have been proposed for (or used in) the performance evaluation of ad hoc network protocols are presented. These mobility models are then used to simulate the effect of cooperation incentives in MANETs.

Since mobile nodes in ad hoc wireless networks can move in many different ways, to choose an appropriate mobility model to simulate the performance of a MANET is not simple. A mobility model should attempt to mimic the movements of real mobile nodes. Changes in speed and direction must occur and they must occur in reasonable time frames. Moreover the mobility models not only attempt to describe individual motion behaviours such as changes in direction and speed, but also consider the collective motion of all the nodes over time.

This chapter presents several mobility models. A survey of some individual mobility models in ad hoc networks is given in Section 4.2. The models presented are the random waypoint mobility model [74], the random Gauss-Markov model [75] and the boundless simulation area mobility model [76]. Section 4.3 focuses on group mobility models, where the reference point group mobility model [77] is presented, and a biological mobility model [78] and the adaptive group behaviour mobility model [10] are introduced.

4.2 Individual Mobility Models

Individual mobility models represent the movement pattern of a mobile node independent of other mobile nodes in its neighbourhood, and are the most used models in the performance evaluation of MANETs [50].

The random walk mobility model [79] is one of the most used mobility models in MANET simulation. In this model, the movement direction and speed at time $t + \Delta t$ has no relationship with the direction and speed at time t. This characteristic makes the mobility model memoryless, and generates an unrealistic movement for each mobile node, presenting sharp turns, sudden stops, and accelerations. Other models based on the random walk mobility model have also been proposed [80; 81]. The random waypoint mobility model [74] is based on the random walk mobility model. This model includes pause times between changes in destination and speed. The boundless simulation area mobility model [76] is also an individual mobility model. In this model a relationship exists between the previous and the new direction of travel and velocity of mobile node. Finally, the Gauss-Markov mobility model that was originally proposed for the simulation of a personal communication system (PCS) [75] is described. This model has been used for the simulation of an ad hoc network [82]. In brief, the boundless simulation area and Gauss-Markov mobility models are enhancements of the random waypoint model. These two models introduce the concept of memory, where the speed/direction (Boundless) and direction of a movement (Gauss-Markov) are relative to the previous state of the corresponding node.

4.2.1 The Random Waypoint Mobility Model

Johnson and Maltz describe the random waypoint (RWP) model in [74]. In this model, a mobile node remains in one location for a certain period of time (the pause time). Once this time expires, the mobile node selects a random destination, uniformly distributed over a predefined region, and moves to that destination at a random speed, that is also uniformly distributed between a predefined minimum and maximum speed. At the new destination the node experiences another delay before starting the process again. A typical trajectory of a node moving in the random waypoint model is shown in Figure 4.1.

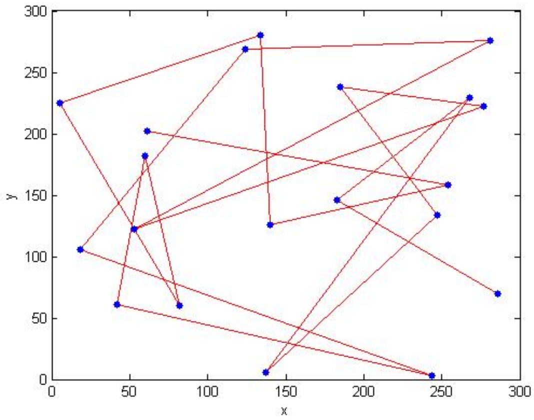

Figure 4.1: Travelling pattern of a mobile node using the random waypoint mobility model

4.2.2 The Boundless Simulation Area Mobility Model

Haas describes the boundless simulation area mobility model in [76]. In this model, the relationship between the previous direction and velocity of a mobile node with its current direction and velocity is described as

$$\begin{aligned} v(t+\Delta t) &= \min\left(\max\left(v(t)+\Delta v, V_{min}\right), V_{max}\right) \\ \theta(t+\Delta t) &= \theta(t)+\Delta\theta \end{aligned} \tag{4.2.1}$$

where $v(t)$ and $\theta(t)$ are the velocity and the direction of the mobile node at time t. For each time interval Δt the direction and the velocity are updated according the above equations. V_{max} and V_{min} are the maximum and minimum velocity respectively, Δv is the change in the velocity which is uniformly distributed between $[-A_{max}, A_{max}]$, $\Delta\theta$ is the change in the direction which is uniformly distributed between $[-\alpha, \alpha]$ where A_{max} is the unit acceleration/deceleration and α is the maximal angular change.

The mobile node updates its location according to

$$\begin{aligned} x(t+\Delta t) &= x(t)+v(t)\cos\left(\theta(t)\right)\Delta t \\ y(t+\Delta t) &= y(t)+v(t)\sin\left(\theta(t)\right)\Delta t. \end{aligned} \tag{4.2.2}$$

The boundless simulation area mobility model ensures that mobile nodes that reach one side of the simulation area (edge of the network) reappear on the opposite side of the simulation area.

To make the model more practical for our simulation, we assume that the direction of the mobile node is bounded between θ_{min} and θ_{max}, and the equations (4.2.1) are rewritten as

$$\begin{aligned} v(t + \Delta t) &= \min\left(\max\left(v(t) + \Delta v, V_{min}\right), V_{max}\right) \\ \theta(t + \Delta t) &= \min\left(\max\left(\theta(t) + \Delta\theta(t), \theta_{min}\right), \theta_{max}\right). \end{aligned} \tag{4.2.3}$$

This creates a torus-shaped simulation area allowing mobile nodes to travel in an unobstructed manner. Figure 4.2 illustrates an example path of a mobile node using the boundless simulation area Mobility Model.

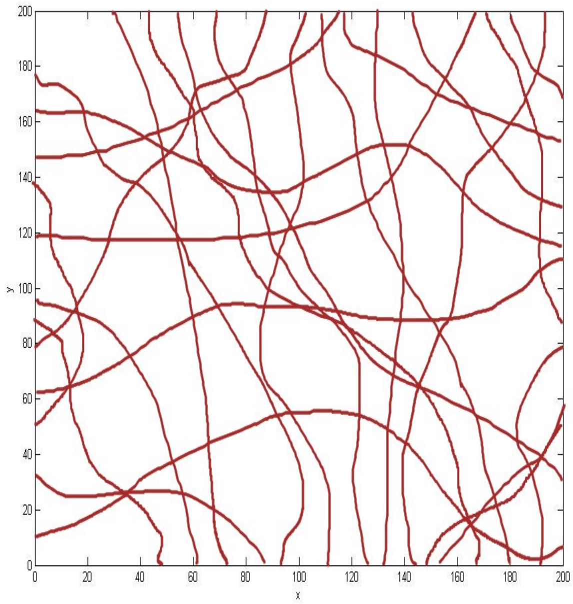

Figure 4.2: Travelling pattern of a mobile node using the boundless simulation area mobility model.

4.2.3 The Gauss-Markov Mobility Model

The Gauss-Markov mobility model was developed by Liang and Haas [75], and was described by Sanchez [83]. The motion of the nodes is computed at discrete time intervals t. At the beginning of each time interval, a node updates its velocity direction and direction as

$$
\begin{aligned}
s_t =& \alpha s_{t-1} + (1-\alpha)\overline{s} + \sqrt{1-\alpha^2} s_{x_{t-1}} \\
d_t =& \alpha d_{t-1} + (1-\alpha)\overline{d} + \sqrt{1-\alpha^2} d_{x_{t-1}}
\end{aligned}
\tag{4.2.4}
$$

where s_t and d_t are the new velocity and direction of the mobile node at time t. The parameter α used to vary the randomness, where $0 \leq \alpha \leq 1$; $\overline{s}$ and $\overline{d}$ are constants, representing the mean value of the velocity and direction as $t \to \infty$. The random variables $s_{x_{t-1}}$ and $d_{x_{t-1}}$ are sampled from a standard normal distribution with standard deviation 1 and mean 0.

At each time interval, the next location of the node is given by

$$
\begin{aligned}
x_t =& x_{t-1} + s_{t-1} \cos(d_{t-1}) \Delta t \\
y_t =& y_{t-1} + s_{t-1} \sin(d_{t-1}) \Delta t
\end{aligned}
\tag{4.2.5}
$$

where (x_t, y_t) and (x_{t-1}, y_{t-1}) are the x and y coordinates of the mobile node's position at the t^{th} and $(t-1)^{st}$ time intervals, respectively and s_{t-1} and d_{t-1} are the speed and direction of the mobile node respectively at the $(t-1)^{st}$ time interval.

To ensure that the mobile node does not remain near to the edge of the network for a long period of time, the mobile nodes are forced to move away from the edge of the network by changing the mean of the direction of the nodes. Figure 4.3 illustrates the change of the mean direction when a node is near the edge of the network.

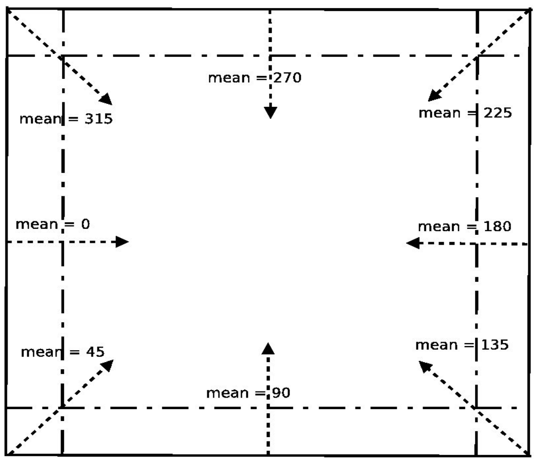

Figure 4.3: Change of mean angle near the edges (in degrees)

Figure 4.4 illustrates an example travelling pattern of a mobile node using the Gauss-Markov mobility model. The mobile node begins its movement at position $(70, 70)$ and moves for 5000 seconds. In Figure 4.4, Δt is 0.1 second, α is 0.6, $s_{x_{t-1}}$ and $d_{x_{t-1}}$ are chosen from a standard normal distribution. The value of s is fixed at $0.01m/s$; the value of d is initially $\pi/3$ radians but changes over time according to the edge proximity of the node.

As shown in Figure 4.4, the Gauss-Markov mobility model eliminates the sudden stops and sharp turns encountered in the random walk mobility model by allowing past velocities (and directions) to influence future velocities (and directions).

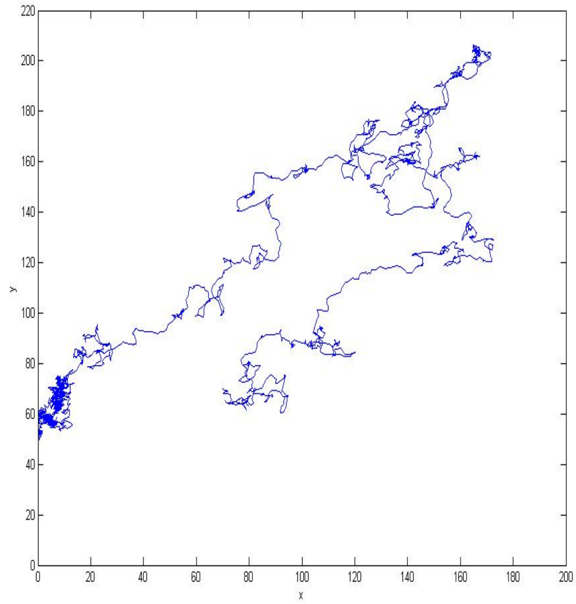

Figure 4.4: Travelling pattern of a mobile node using the Gauss-Markov mobility model

4.3 Group Mobility Models

Group mobility models are used to represent the movement of a group of mobile nodes. These models have been used to predict the partitioning of MANETs, which is defined as a wide-scale topology change caused by the group movement behaviour of the mobile nodes [84]. In this section, the reference point group mobility (RPGM) model is presented. This model was developed by Hong *et al.* [77], where for each mobile node there is an associated reference point which defines the group movement.

Next a biological mobility model [78] is presented. In this model each node attempts to maintain a minimum distance between itself and all the other nodes at all times. Finally, the adaptive group behaviour mobility model [10] is presented. This mobility model presents several basis behaviours as general building blocks for synthesising artificial group behaviour in multi-agent systems. These basis behaviours are applied to analyse the mobility of mobile nodes in a MANET.

4.3.1 Reference Point Group Mobility

In the reference point group mobility (RPGM) model [77], each group of nodes has a logical centre, which defines the characteristics of the group's motion such as location, speed and direction. The trajectory of a group is thus determined by the trajectory of its logical centre.

In addition to the logical centre, the RPGM model defines a reference point and a random motion vector for each node in the group. A reference point is a point about which a node moves at random with respect to the logical centre. The random motion vector represents the random deviation of a node from the reference point.

The random motion vector is updated periodically and its magnitude and direction are uniformly distributed over the intervals $[0\ ,\ \ RM_{max}]$ and $[0\ ,\ \ 2\pi]$ respectively. Let $n(t_0)$ be the location vector of a node of the RPGM model at $t = t_0$, then

$$n(t_0) = c(t_0) + \overrightarrow{RP} + \overrightarrow{RM}(t_0), \tag{4.3.1}$$

Where $c(t_0)$ denotes the location vector of the logical centre of the group at time t_0, $\overrightarrow{RP}$ is a vector from the logical centre to the reference point, and $\overrightarrow{RM}(t_0)$ is the random motion vector. Then at $t = t_0 + \tau$

$$n(t_0 + \tau) = c(t_0 + \tau) + \overrightarrow{RP} + \overrightarrow{RM}(t_0 + \tau), \tag{4.3.2}$$

For $t_0 \leq t \leq t_0 + \tau,\ n(t)$ is given by

$$n(t) = \frac{(t_0 + \tau - t)n(t_0) + (t - t_0)n(t_0 + \tau)}{\tau}, \tag{4.3.3}$$

Figure 4.5 depicts the movement of the RPGM model for a group of three nodes.

At times t_0 and $t_0 + \tau$ the trajectory of the group is illustrated by superimposing the positions of the nodes, their associated reference points and the group's logical centre, over time, on the same diagram.

For the purpose of clarity, only the vectors associated with node 1, $\overrightarrow{RM}$ and $\overrightarrow{RP}$, have been labelled. It is useful at this point to recall that the $\overrightarrow{RP}$ for a particular node remains constant throughout time.

4.3.2 The Biological Mobility Model

Many animal groups such as fish schools and bird flocks display collective behaviour. Couzin *et al.* [78] presented a self-organising model of group for-

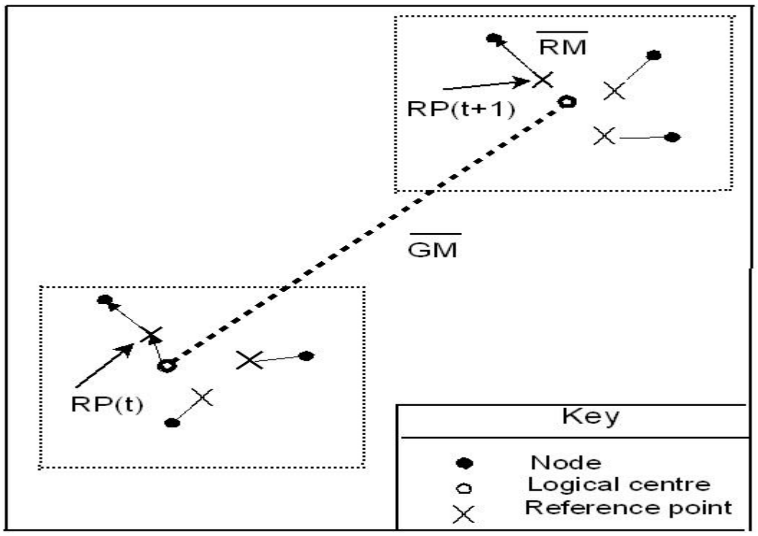

Figure 4.5: Description of the RPGM model.

mation in three-dimensional space, and used it to investigate the spatial dynamics of animal groups. In this section we use the same model in [78] with modifications to make it more practical in MANETs.

In this model each node attempts to maintain a minimum distance between itself and all other mobile nodes at all times. The principal advantage of using this type of model is that collisions are avoided [78].

The model consists of N individuals ($i = 1, \ldots, N$), with vectors c_i representing the position of node i and unit direction vectors v_i. To simplify our model, we make our simulation in two-dimensional space; time is discrete, with a time step τ. At each time step, individuals evaluate the position or orientation or both, of the $N-1$ neighbours with respect to the three behavioural zones described in Figure 4.6. The actions that a particular individual takes will depend on the occupancies of the behavioural zones.

Consider an individual i surrounded by three concentric zones

- the zone of repulsion (ZOR)
- the zone of orientation (ZOO)
- the zone of attraction (ZOA).

Each individual attempts to maintain a minimum distance and avoid collisions with other individuals within **a zone of repulsion (ZOR)**, which is modelled as a circular area with radius r_r. If N_r neighbours are present in this zone (determined by the condition $0 \leq |c_j(t) - c_i(t)| \leq r_r$ where $c_j(t)$ is the position of the j^{th} neighbour individual , $j = 1, ..., N_r, j \neq i$) at time t, individual i responds by moving away from the neighbours within this zone. The direction of the individual i within the zone of repulsion is given by

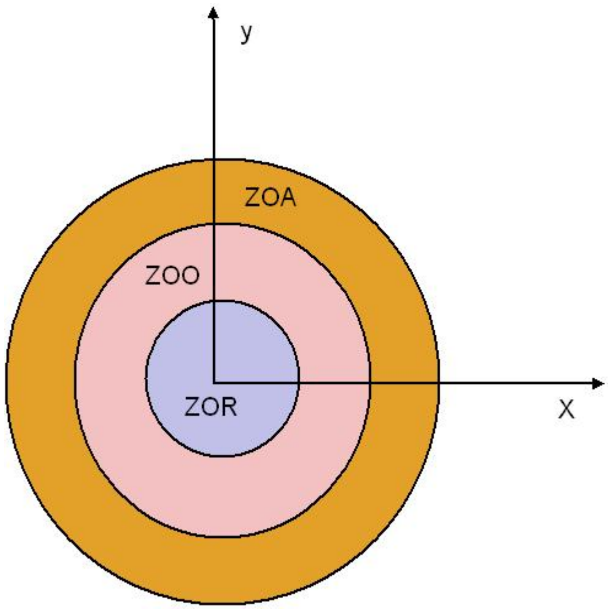

Figure 4.6: The three behavioural zones: ZOR= zone of repulsion, ZOO= zone of orientation, ZOA= zone of attraction.

$$d_r(t+\tau) = -\frac{\sum_{j\neq i}^{N_r} r_{ij}(t)}{|\sum_{j\neq i}^{N_r} r_{ij}(t)|} \tag{4.3.4}$$

$$r_{ij}(t) = \frac{c_j(t) - c_i(t)}{|c_j(t) - c_i(t)|}, \tag{4.3.5}$$

where $r_{ij}(t)$ is a vector pointing from individual i in the direction of neighbour j . When $N_r > 0$, the movement direction of individual i is

$$d_i(t+\tau) = d_r(t+\tau) \tag{4.3.6}$$

If there are no neighbours present within the zone of repulsion (ZOR) ($N_r = 0$) the individual i responds to neighbours within the **zone of orientation** and the **zone of attraction**. These zones are circular with radii r_o and r_a, respectively.

The zone of orientation (ZOO) contains N_o neighbours governed by the condition $r_r \leq |c_j(t) - c_i(t)| \leq r_o$. Likewise, there are N_a neighbours detectable in the zone of attraction (ZOA) such that $r_o \leq |c_j(t) - c_i(t)| \leq r_a$ is satisfied.

We define $\Delta r_o = r_o - r_r$ and $\Delta r_o = r_a - r_o$ to be the widths of these zones. $v_i(t)$ denotes the unit direction vector at time t.

The directions of the individuals within the zones of orientation and attraction are given respectively by

$$d_o(t+\tau) = \sum_{j=1}^{N_o} \frac{v_j(t)}{|v_j(t)|} \tag{4.3.7}$$

$$d_a(t+\tau) = \frac{\sum_{j\neq i}^{N_a} r_{ij}(t)}{|\sum_{j\neq i}^{N_a} r_{ij}(t)|} \tag{4.3.8}$$

If neighbours are only found in the zone of orientation (ZOO) ($N = N_o$), then

$$d_i(t+\tau) = d_o(t+\tau). \tag{4.3.9}$$

Likewise, if all neighbours are found in the zone of attraction (ZOA),

$$d_i(t+\tau) = d_a(t+\tau). \tag{4.3.10}$$

If neighbours are found in both zones,

$$d_i(t+\tau) = \frac{1}{2}\left(d_o(t+\tau) + d_a(t+\tau) \right). \tag{4.3.11}$$

In the case when the directions forces cancel one another out and give a zero vector, or if no neighbours are detected, then

$$d_i(t+\tau) = d_i(t). \tag{4.3.12}$$

To simplify the model we assume that each individual moves at a constant speed s, and at time t individual i at position $c_i(t)$ travels with speed s in the direction $d_i(t+\tau)$. Between t and $t+\tau$ the individual moves a distance $\Delta = \tau s_i$, updating the position at time $t+\tau$:

$$c_i(t+\tau) = c_i(t) + d_i(t+\tau)\Delta \tag{4.3.13}$$

In some MANET applications including battlefield communication and disaster relief, collaboration among nodes exists and the nodes follow guide nodes or leaders. The biological mobility model is adapted to represent collective motion, where the nodes follow guide nodes to establish an optimal coverage in an area of interest.

A guide node moves to a specified location. The guide node must encourage a collective motion among its neighbouring nodes so that these nodes and their neighbours follow the guide node to the vicinity of the specified location and establish maximal coverage in this vicinity. If a guide node is within radio transmission rage of node i, then node i moves towards the guide node. If several guide nodes are presented, the node i moves toward the nearest guide. In order to ensure that nodes are included in the movement of the group so that the nodes can follow the guide nodes, the velocity of the nodes must be greater than the velocity of guide nodes.

The motion rules of this model are represented by the following algorithm:

Algorithm 1 The motion rules for the biological mobility model

```
Biological model:
if guide nodes are present in any zone then
  Node i moves towards the nearest guide node
end if
if nodes are present in the ZOR then
  Node i moves away from the nodes in the ZOR
else
  if nodes are present in the ZOO then
    node i does not move
  else
    if nodes are in the ZOA then
      node i moves towards the nodes in the ZOA
    else
      node i does not move
    end if
  end if
end if
```

4.3.3 Adaptive Group Behaviour

This section presents the concept of basis behaviour that was proposed by Matrić [10]. The mobility model presented by Matrić uses basis behaviours as general purpose building blocks for synthesising artificial group behaviour in multi-agent systems. The model presents a self-organising group formation in two-dimensional space, and uses it to investigate the spatial dynamics of a flock of nodes. The model is used to show how differences among individuals influence the group structure, and how individuals employing simple, local rules can change their spatial position within a group (e.g. to move to the centre, the front, or the periphery) in the absence of information on their current position within the group as a whole, or to improve their utilities. These results are considered in the context of the evolution of the topology of an ad-hoc network.

This model (referred to as the "flocking behaviour" or "collective model") is based on simple rules of avoidance, which yields motion without collisions, i.e. safe-wandering. Avoidance in groups can be achieved by dispersion, a behaviour that reduces local interference. In contrast to various goals that minimise interaction by decreasing physical proximity, other goals may involve the exchange of resources through proximity, which is achieved through aggregation. Aggregating with other nodes or moving to a specific location or region involves some form of homing. Any collective movement of a group requires coordinated motion in order to minimise interference. Following and flocking are two common forms of such structured group motions.

In this section the following set of basis behaviours is presented:

- safe-wandering: minimises collisions between nodes and between nodes and obstacles
- following: allows nodes to follow guide nodes
- aggregation: gathers the nodes in order to establish a maximum distance between them
- dispersion: spreads out the nodes over an area in order to establish a minimum distance between them
- homing: allows nodes to reach a goal region or location.

We use these basis behaviours to build a flocking behaviour model by combining the outputs of safe-wandering, dispersion, aggregation, and homing. To do this, the strategies used to implement each of the basis behaviours in the collective motion are presented in the form of algorithms. Their formal definitions can be found in [10].

4.3.3.1 Safe-Wandering

Inspired by animal navigation routines [85], safe-wandering is a combination of two rules: one rule prevents a node from colliding with obstacles, and another rule keeps the node turning randomly without moving. The avoidance component consists of two complementary behaviours, one for avoiding kin and another for avoiding everything else. The Avoid-Kin behaviour takes advantage of group homogeneity; since all nodes execute the same strategy, the algorithm can take advantage of the resulting spatial symmetry. The Avoid-Everything-Else behaviour prevents the nodes from remaining near to obstacles such as barriers and bounds for a long period of time.

The safe-wandering algorithm is given by Algorithm 2, where node i attempts to avoid collision with node j when j is within a distance *d-avoid* of node i.

Algorithm 2 The Safe-Wandering algorithm

Avoid-Kin:
if node j is within *d-avoid* of node i **then**
  if node j is on the left **then**
    node i turns right and moves forward by $V\Delta t$
  else
    node i turns left and moves forward by $V\Delta t$.
  end if
end if
Avoid-Everything-Else:
if an obstacle is within *d-avoid* of node i **then**
  if the obstacle is on the left **then**
    node i turns right and moves forward by $V\Delta t$
  else if the obstacle is on the right **then**
    node i turns left and moves forward by $V\Delta t$
  else
    node i backs up and turns randomly.
  end if
end if
Random-Turn: node i turns randomly without moving.

4.3.3.2 Following

Following is achieved by a simple rule that steers the nodes towards the position of the guide nodes or leaders. A guide node is instructed to move to a specified location, and the nodes follow the guide node. If the guide node is present within a distance `d-follow` of node i, then node i moves toward the guide node. If many guides present within a distance `d-follow` of node i, then node i moves toward the nearest guide. The velocity of the guide nodes must be less than the velocity of nodes. This condition ensures that nodes follow the guide nodes.

Algorithm 3 The Following algorithm

if one or more guide nodes are within *d-follow* of node i **then**
  node i moves towards the nearest guide node by $V\Delta t$.
end if

4.3.3.3 Dispersion

Robust dispersion behaviour can be designed as an extension of safe-wandering. While avoidance in safe-wandering reacts to the presence of a single node, dispersion uses the local distribution of all of the nearby nodes (nodes within a distance `d-disperse` of node i) in order to decide in which direction to move. The algorithm computes the local centroid, `Centroid-disperse`, to determine the density distribution of the nearby nodes, and moves away from the area of highest density.

Dispersion maintains a desired distance between the nodes. The dispersion algorithm is given by Algorithm 4, where node i attempts to maintain a minimum distance between itself and the nearby nodes.

Algorithm 4 The Dispersion algorithm

if one or more nodes are within *d-disperse* of node i **then**
  compute the local centroid *centroid-disperse* of the nearby nodes of node i;
  node i moves away from *centroid-disperse* by $V\Delta t$.
end if

4.3.3.4 Aggregation

Aggregation is the inverse of dispersion, where the goal of aggregation is to achieve and maintain a maximum distance between nodes. The aggregation algorithm computes the local centroid, `Centroid-aggregate`, to determine the density distribution of nearby nodes (nodes within a distance `d-aggregate` of node i). Nodes use this `Centroid-aggregate` to decide in which direction to move. If one or more nodes are within `d-aggregate` of node i, node i moves towards the local `Centroid-aggregate`.

The aggregation algorithm is given by Algorithm 5

Algorithm 5 The Aggregation algorithm

if one or more nodes are within *d-aggregate* of node i **then**
  compute the local centroid *centroid-aggregate* of the nearby nodes of node i; node i moves towards the local *centroid-aggregate* by $V\Delta t$.
end if

4.3.3.5 Homing

The goal of homing behaviour is to move the nodes toward a specified location called “`home`". Homing behaviour can be implemented by a simple pursuit strategy, where the home location is predefined and known by the nodes. Matrić [10] found that the trajectories of homing behaviour are far from optimal, where homing is effective as long as the density of the nodes is low. Matrić proved that homing becomes increasingly inefficient as the group size grows.

The homing algorithm is given by Algorithm 6, where node i attempt to reach its goal location “`home`".

Algorithm 6 The Homing algorithm

if node i is at home **then**
  node i stops moving
else
  node i moves towards the location of home by $V\Delta t$.
end if

4.3.4 Flocking Behaviour

In the spatial domain, the outputs of all the basis behaviours are in the form of direction and velocity vectors, so the sums of such vectors produce coherent higher-level behaviours. To illustrate this method we implement a **flocking behaviour model** by combining the outputs of safe-wandering, aggregation, dispersion and homing. Intuitively, aggregation keeps the nodes from getting too far from each other, dispersion keeps the nodes from getting too close, homing moves the flock of nodes toward some location and safe-wandering prevents nodes from collisions.

The choice of the distances `d-avoid`, `d-disperse` and `d-aggregation` depends on the nodes' characteristics such as communication ranges. In our flocking model, the constituent basis behaviours are complementary, i.e. their conditions do not interfere, and these distances satisfy the following condition

$$\texttt{d-avoid} < \texttt{d-disperse} < \texttt{d-aggregate}$$

The local centroid, for both dispersion and aggregation, is computed as follows

$$C_i(t) = \frac{\sum_{j=1}^{N} p_j(t)}{N}, \tag{4.3.14}$$

where N is the number of nodes that are present within a distance `d-aggregate` of node i and $p_j(t) = (x_j, y_j)$ is the position of node j at time t.

A few adjustments were made to the original flocking behaviour algorithm to present a more realistic model of motion in a MANET. First, a zone of orientation was added to the model where the ZoO stabilises the node positions. `d-orientation` satisfies the following condition

$$\texttt{d-avoid} < \texttt{d-disperse} < \texttt{d-orientation} < \texttt{d-aggregate}.$$

The safe-wandering behaviour is changed so that if j is within `d-avoid` of node i, node i moves away from node j.

In addition, the following behaviour was used instead of the homing behaviour in order to simplify the motion when nodes follow the guide nodes. If a guide node k is present in any zone of node i, then the direction of node i is given by

$$d_i(t+\Delta) = \frac{\lambda_i v_i(t+\Delta) + \lambda_g v_i^g(t+\Delta)}{\lambda_i + \lambda_g},$$

where $v_i(t+\Delta)$ denotes the movement direction derived from the avoidance, dispersion or aggregation rules and Δ is a time step. The movement direction of the nodes within the zone of avoidance is

$$v_i(t) = -\frac{p_k(t) - p_i(t)}{|p_k(t) - p_i(t)|},$$

where $p_i(t)$ is the position of node i at time t.

For the dispersion and the aggregation zones, the movement direction is given by

$$v_i(t) = M\frac{C_k(t) - p_i(t)}{|C_k(t) - p_i(t)|},$$

where $C_k(t)$ is the position of the local centroid k at time t. $M = 1$ for the aggregation rule and $M = -1$ for the dispersion rule.

$v_i^g(t+\Delta)$ denotes the movement direction of node i that makes it move towards the nearest guide node K, $\lambda_i = 9$ and $\lambda_g = 1$.

To simplify to the model, we assume that each node moves at a constant speed V, and at time t node i at position $p_i(t)$ travels with speed V in the direction $d_i(t+\Delta)$. Between t and $t+\Delta$ the node i moves a distance $X = \Delta V$, updating the position at time $t+\Delta$:

$$p_i(t+\Delta) = p_i(t) + d_i(t+\Delta)X. \tag{4.3.15}$$

The Flocking behaviour algorithm is given by Algorithm 7. Flocking is defined as a collective motion that requires that all the nodes stay within a flocking range. Unlike aggregation, flocking not only requires the nodes to stay together, but also to move toward a goal location “`home`".

Flocking is more efficient than individual homing as the number of nodes increases. Matrić [10] showed that the performance of flocking is dependent on the size of the flock where small flocks are less stable than larger flocks.

In the next Chapter we will apply the simulation model which was developed in Section 3 to analyze the effect of the incentive model on resource prices, and how these prices in turn influence the credit balance and the data flows in a static and in a dynamic MANET. Finally, we will use the simulator to evaluate the utility of the Adaptive Group Behaviour model in obtaining an optimal area coverage.

Algorithm 7 The Flocking algorithm

```
if node j is within d-avoid of node i then
  node i computes the direction vector v_i(t) to move away from node j.
end if
if no nodes are within d-avoid of node i then
  if one or more nodes are within d-disperse of node i then
    compute the local centroid centroid-disperse of the nearby nodes of
    node i; node i moves away from centroid-disperse in the direction v_i(t)
  else
    if one or more nodes are within d-orientate of node i then
      node i does not move (v_i(t) = 0)
    else
      if one or more nodes are within d-aggregate of node i then
        compute the local centroid centroid-aggregate of the nearby nodes
        of node i; node i moves towards centroid-aggregate in the direction
        v_i(t)
      else
        node i does not move.
      end if
    end if
  end if
end if
if guide nodes are present in any zone of node i then
  node i computes the direction d_i(t + Δ), and updates the position at time
  t + Δ
else
  node i uses the direction v_i(t + Δ), and updates the position at time t + Δ.
end if
```

Chapter 5

Simulation

The dynamics of the system described in Chapter 3 are illustrated using a simulation model. This simulation uses the same parameters that were used by Crowcroft *et al.* [3; 4]. The simulation studies was done using the DESMO-J (Discrete-Event Simulation Modelling in Java) simulator [86]. Certain characteristics of the system discussed in Chapter 3, such as power and bandwidth prices are illustrated, where the stability of prices at the nodes and the credit balances are demonstrated in the case of a static network. In both static and dynamic networks the throughput of the system is also investigated. In addition, the mobility of the nodes is investigated, where the simulation shows how the mobility of the users in the network affects their individual throughputs and also how it contributes to the overall system throughput.

Assume that a node in MANET can move and make observations within a circular area centred on its own location. The coverage of the network is defined as the total area observed by the mobile nodes. In this chapter, a collective mobility model, the adaptive group behaviour mobility model [10], is used to model area coverage in a MANET. This collective model is based on the concept of basis behaviour introduced by Matrić [10]. In this model, nodes move autonomously in order to maximise the coverage of the network. In addition, the mobile nodes ensure that they do not move so far from each other, that they disconnect from each other. Guide nodes are instructed to move to specified locations. These guide nodes induce a correlated movement of groups of nodes that follow the guide nodes and establish maximal coverage in the specified vicinities. Simulation results demonstrate the coverage achieved by a group of 100 nodes when moving on an unbounded plane.

5.1 Simulating Incentives for Collaboration

Consider a MANET consisting of 10 nodes located randomly according to a uniform distribution within a geographical area of $100m \times 100m$. The network is shown in Figure 5.1. The network topology represents a set of nodes with diverse geographical locations and topological relationships. The features include the clustering of nodes towards the top-right corner and nodes closely situated within the geographical centre of the network (nodes $N0$ and $N8$). Nodes with higher geographical isolation (particularly nodes $N1$ and $N2$) are also included.

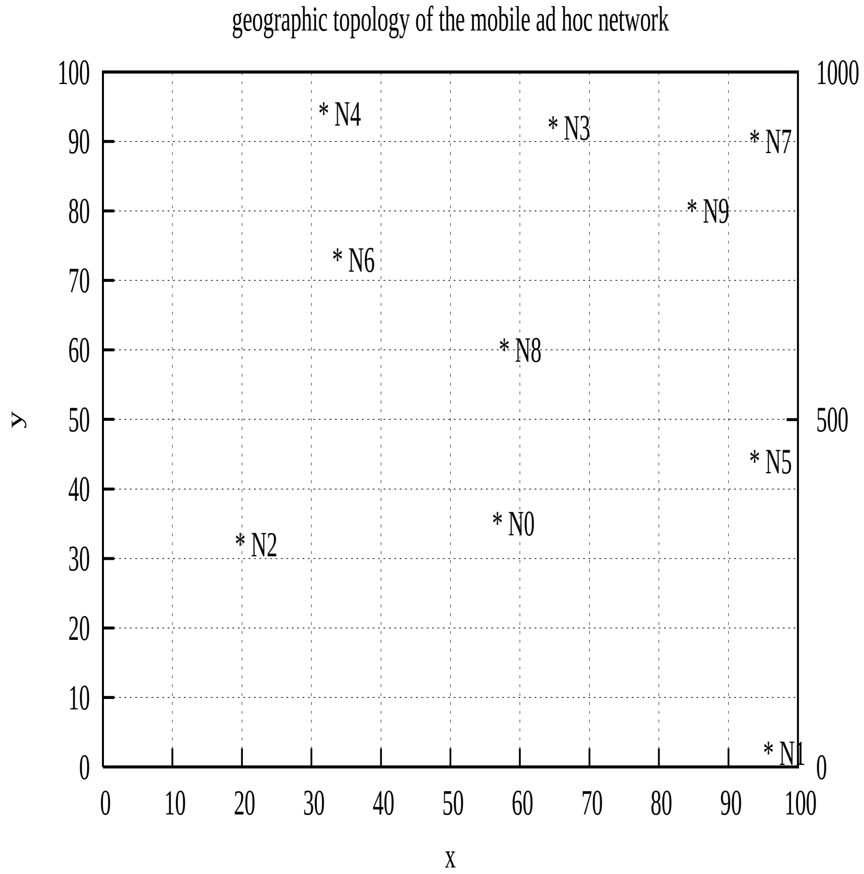

Figure 5.1: Topology of the MANET.

Each node is equipped with a single transceiver with a range of 56 metres. This defines its neighbours within the network. Wireless interference between mobile nodes is not considered during the simulation. Nodes in the centre of the network have a large set of neighbours and have a large number of routes from which to choose in order to send traffic to a particular destination. On the other hand, isolated nodes such as $N1$ and $N2$ have only a few neighbours. These nodes can only select routes from a smaller set of possible paths. The traffic model assumes that a particular user establishes a connection with a randomly selected destination. The duration of this connection is exponentially distributed. Once the connection with a destination node terminates, the user remains idle for an exponentially distributed period of time before randomly selecting another destination. Thus each user will communicate with a number of different users during the course of the simulation [3].

When a user initiates a connection with another node, it first determines the least cost route and then uses that route for the duration of the connection. This is a departure from the model described in Chapter 3 where the users monitor all available routes to the recipient and route traffic through the route with minimum cost [3]. However, our departure from the model is a realistic one, because it is desirable to minimise the cost of the amount of routing information that has to be distributed within the network. When using one of the ad hoc routing protocols, such as AODV [38] or DSR [87], it is reasonable to assume that the integrity of a route will need to be checked before routing a stream of packets along a particular path. Nevertheless, it is unlikely that nodes will continuously monitor all paths at the granularity level of transmitting each packet. The consequence of this departure from the model is that the system will not achieve optimal performance, but there is a trade-off between optimality and the overhead involved in continuously monitoring the costs of routes to the destination. An advantage of this approach is that route-flap is avoided, which may occur if the price of another route drops below the route currently used, and then a user begins to frequently swap traffic between these two routes.

5.1.1 A Static Network

The static network topology is simulated for $10000s$. The mean duration of a connection between nodes is $0.5s$, and a user is idle for a mean period of $0.5s$ after completing a connection. The users update their prices every $0.01s$. The system parameters are based on these used by Crowcroft *et al.* [3; 4]. These parameters are set as $\alpha_s = 0.3$, $\beta = 0.01$ and $\kappa = 0.05$. The bandwidth capacity is set to $C = 10$ for all nodes in the network, while the maximum power is $\Gamma = 0.5$. The energy parameters associated with transmitting and receiving traffic are given by $e_{ij}^{(tx)} = 10^{-4} |z_i - z_j\|_2^{1/2}$ and $e^{(rx)} = 10^{-3}$, with z_i and z_j being the geographical position of nodes i and j respectively.

The power prices and the bandwidth prices of four representative nodes (nodes $N1$, $N7$, $N8$ and $N9$) in the network are shown in Figure 5.3 and Figure 5.2 respectively. Node $N1$ has been selected, as it is on the edge of the network. Node $N7$ is also on the edge of the network but with nodes $N3$ and $N9$ in close proximity. The prices of node $N8$ nearest to the centre of the network is also plotted. Node $N9$ is also plotted because it is frequently used as a transit node.

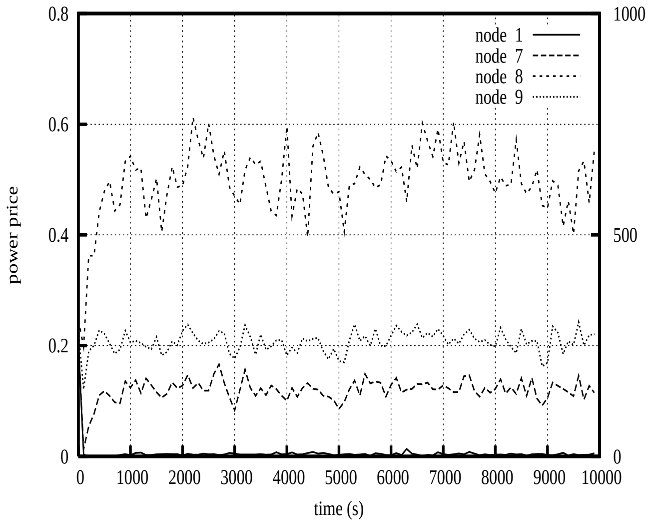

Figure 5.2: Power prices

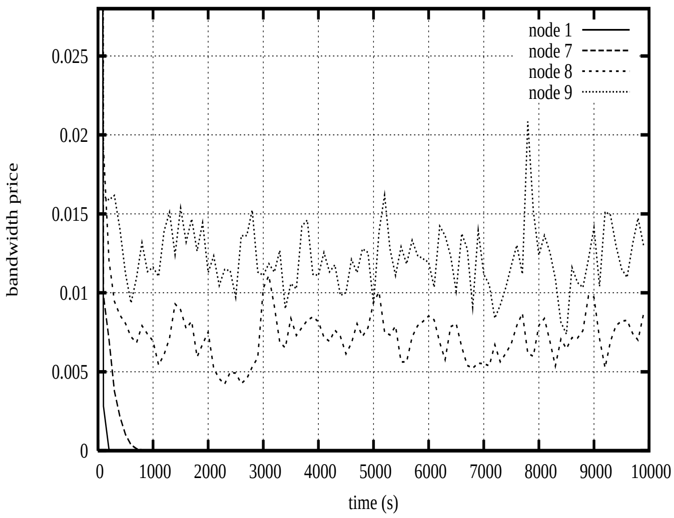

Figure 5.3: Bandwidth prices

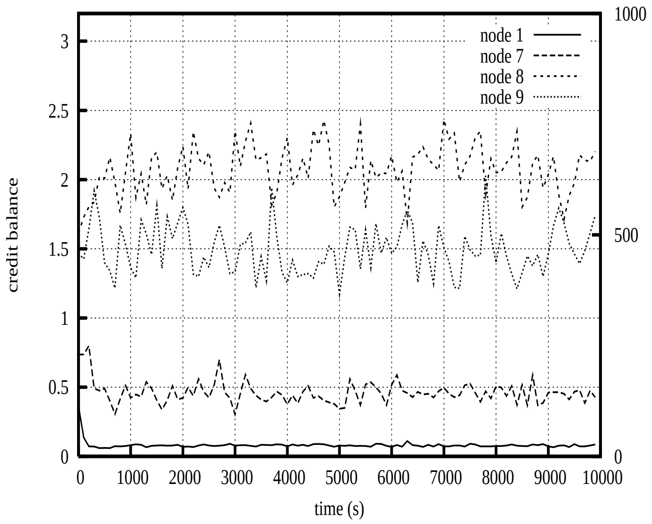

Figure 5.4: Credit balance

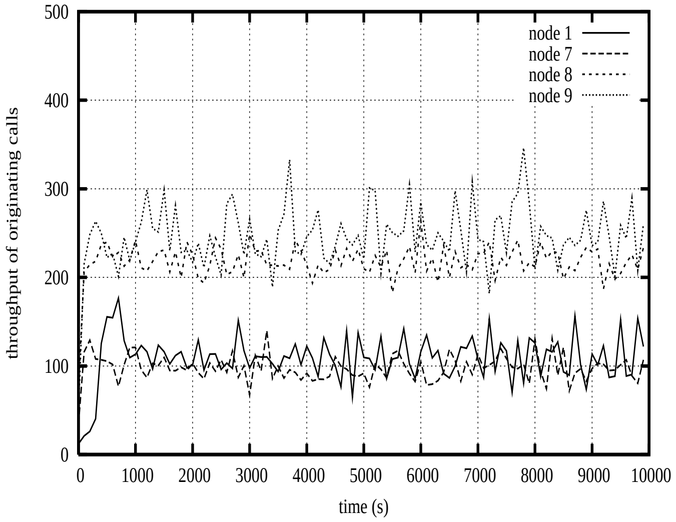

Figure 5.5: Throughput

Figure 5.2 and Figure 5.3 show that each price stabilises about a mean value. These results suggest that the system described in Chapter 3 is stable. A second observation that can be made is about the prices of node $N1$. The plots show that the $N1$ prices are small and decay rapidly to zero. This is because $N1$ is on the edge of the network with a higher geographical isolation compared to the other nodes. Hence no routes use $N1$ as a transit node. This means that the only traffic flows that can consume bandwidth and power resources at this node are those originating or terminating at this node. The resources at this node are not heavily in demand and so the resource prices are low. On the other hand, $N8$ prices are relatively high. The reason for this is that node $N8$ is the nearest node to the centre of the network. Thus, the traffic flows that consume bandwidth and power resources at this node are those flows originating or terminating at this node including a large amount of transit traffic that $N8$ will carry for the rest of network nodes.

Despite the differences between the positions of $N8$ and $N9$ in the network, it is interesting to compare the prices of nodes $N8$ and $N9$. The bandwidth price is the highest for $N9$, while $N8$ has the highest power price. The reason for this is that the distances between $N8$ and its neighbouring nodes are all relatively high. In addition, node $N8$ is closest to the centre of the network. Thus the power consumed by $N8$ in transmitting to other nodes is bigger than other nodes. In comparison, $N9$ is not near to the centre of the network. However, it is close to nodes $N3$ and $N7$. In this case $N9$ will carry a larger amount of traffic for these nodes, $N3$ and $N7$, and for other nodes that route traffic around this cluster of nodes (see Figure 5.5). Hence, its capacity usage will be high, as reflected by its bandwidth price.

The credit balances and the throughputs are plotted in Figure 5.4 and Figure 5.5 respectively. These quantities stabilise around their mean value. The mean value for each node's credit balance is dependent on its geographical location within the network. As expected, node $N8$ maintains the highest credit balance, as it is the closest to the centre of the network. This means that this node carries a large amount of transit traffic as in Figure 5.5. In addition, $N8$ will be charging high power prices for doing so, and thus accruing significant credit in the process. As the location of a node gets closer to the edge of the network, its credit balance is seen to decrease.

The total credit balance and the total throughput are shown in Figure 5.6. Since the initial credit balance for each node in the network is 1, the total credit balance is 10 (the number of the nodes in the network) which is the case.

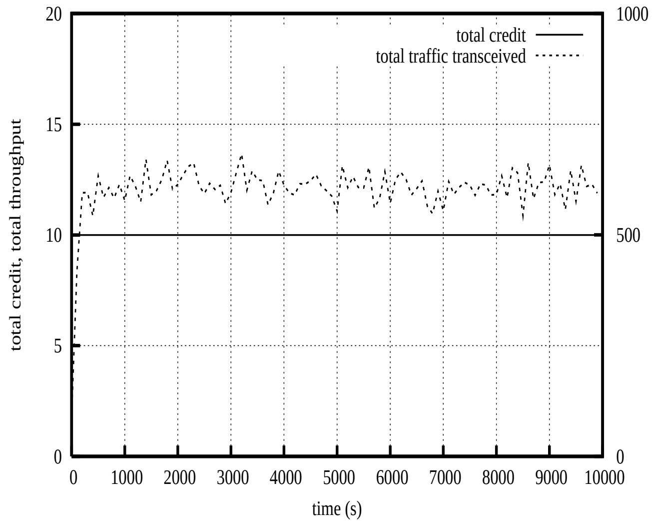

Figure 5.6: Total credit and total throughput

5.1.2 A Dynamic Network

The objective of this thesis is to study the effect of node mobility on the performance of an ad hoc network. This is done in the context of the incentive mechanism discussed in Chapter 3. Consider the original topology represented in Figure 5.1.

The movement of node $N1$ node is shown in Figure 5.7. The performance of the system is observed as $N1$ moves across the network passing through the centre of the network and reaching the other edge of the network by the end of the simulation. The simulation runs for $10.000s$. The velocity of $N1$ is set to $(0.0074,\ \ 0.0126)m/s$ so that N1 reaches the opposite edge of the network at the end of the simulation. The remaining of the system parameters are given in Table 5.1.

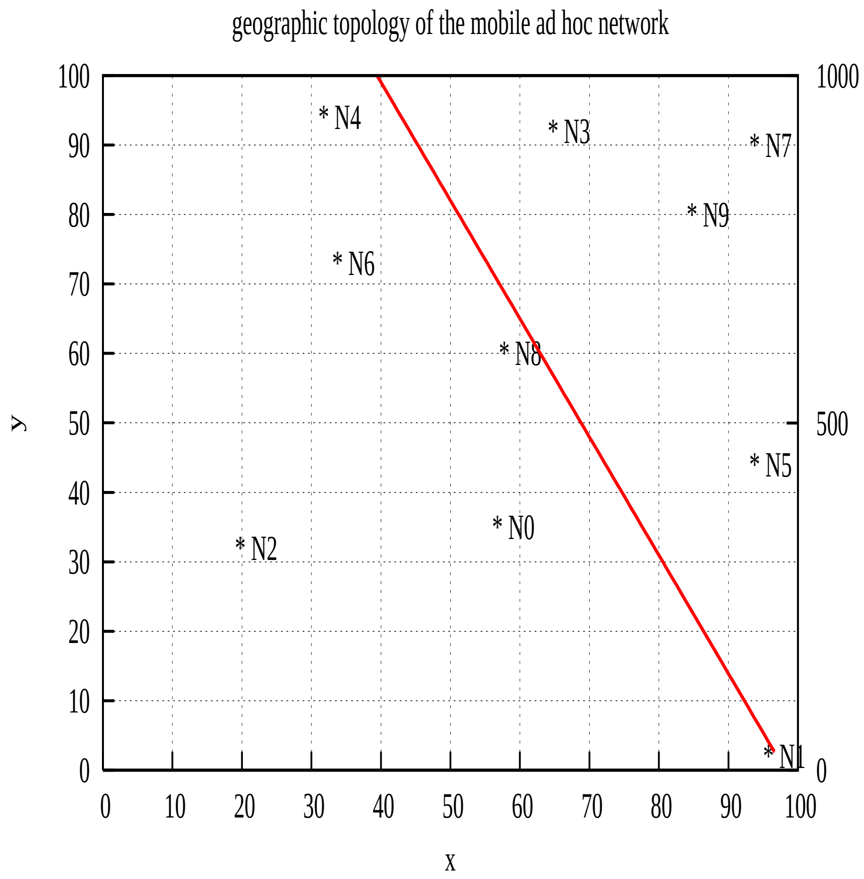

Figure 5.7: Topology of the network when node 1 moves across the network.

When node $N1$ approaches the centre of the network, it will be used as a transit node to carry traffic between other nodes. This can be observed in Figure 5.8 which shows that when node $N1$ reaches the centre of the network it can transmit to and receive from the entire network. The increase in the number of $N1$ neighbours is reflected in both the bandwidth and power prices. Figures 5.9 and 5.10 show that the prices of bandwidth and power at node $N1$ increase. The other nodes now have a choice of sending traffic through $N8$ or $N1$. Hence the power price of $N8$ is reduced as $N1$ approaches the centre of the network. A second observation is that node $N2$ prices are small and decay rapidly to zero. This is because $N2$ is the only node on the edge of the network with a high geographical isolation.

Both the bandwidth and power price associated with node $N1$ decrease as node $N1$ moves away from the centre of the network. This can be seen in Figures 5.9 and 5.10. Since the prices and the traffic load associated with node $N1$ increase when $N1$ is near to the centre, the credit balance of node $N1$ also grows (seen Figure 5.11). This increases the ability of node $N1$ to generate its own traffic because its willingness-to-pay is related to its credit balance.

call holding time	$0.5s$
user idle time	$0.5s$
update time	$0.01s$
α_s	0.3
β	0.01
κ	0.05
C	10
Γ	0.5
$e_{ij}^{(tx)}$	$10^{-4}\,\|z_i - z_j\|_2^{1/2}$
$e^{(rx)}$	10^{-3}

Table 5.1: The system parameters.

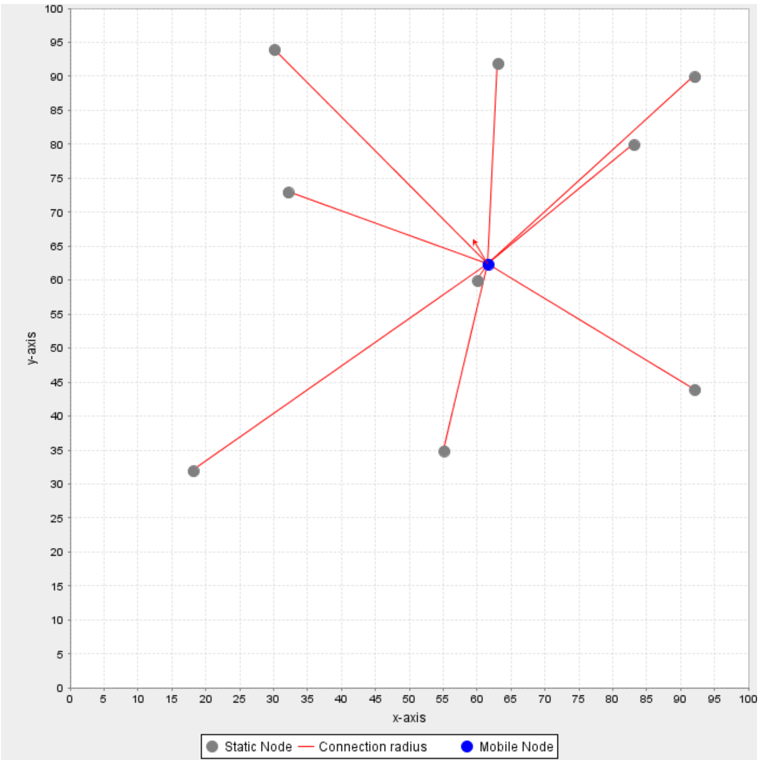

Figure 5.8: Representation of node 1 in the centre of the network.

Figure 5.11 shows that the credit balance of node $N8$ decreases slightly when $N1$ is near to the centre because of the competition between $N1$ and $N8$ to relay transit traffic. This is principally due to the fact that $N1$ is close to $N8$, and then the cost of sending traffic to $N1$ becomes substantially less. In this case the nodes in the network have a choice for sending traffic either through $N1$ or through $N8$.

When $N1$ is near to the centre, close to $N8$, the bandwidth price of node

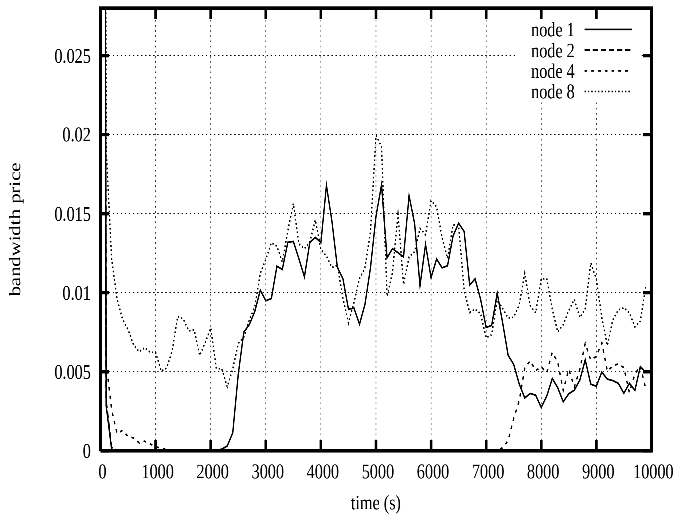

Figure 5.9: Bandwidth prices.

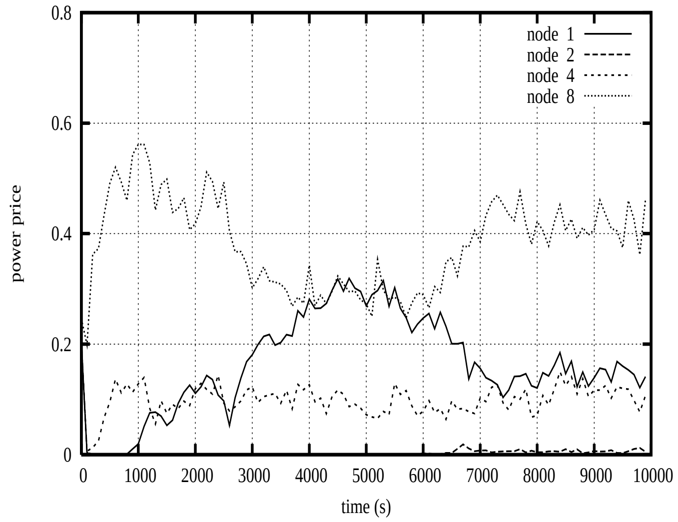

Figure 5.10: Power prices.

$N8$ increases. This is because of the increase in the traffic between $N1$ and $N8$. When node $N1$ moves away from the centre of the network and approaches node $N4$ the increase of the bandwidth price happens again and this can be observed in Figure 5.9.

Figure 5.13 represents the total credit balance and the total throughput of the network. As expected, the total credit balance is 10 (the number of the nodes in the network) which is a good test of the correctness of the simulator implementation.

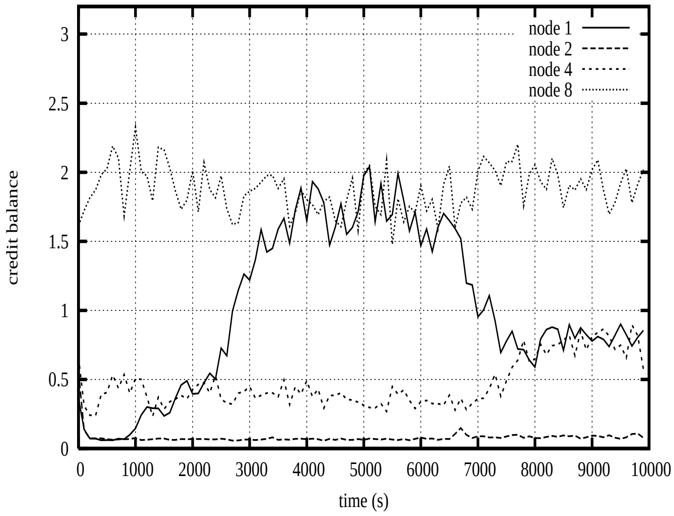

Figure 5.11: Credit balances.

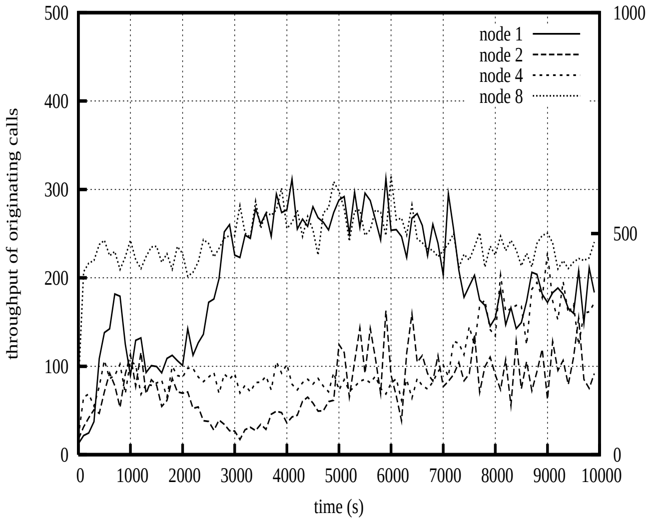

Figure 5.12: Throughput.

5.2 Maximising Area Coverage on a 2D Surface

The previous simulation focused on the effect of node mobility on the performance of an ad hoc network. The mobility studied in that simulation was a simple movement, where only one node moved to a predefined location. In this section, a collective mobility model is introduced and studied which maximises the area coverage on a 2D surface.

Group mobility models, or collective mobility models, are generally used in MANETs to predict the partitioning of MANETs. This mobility is defined as a wide-scale topology change, caused mainly by the group movement behaviour of the mobile nodes [72]. These mobility movements are often used to

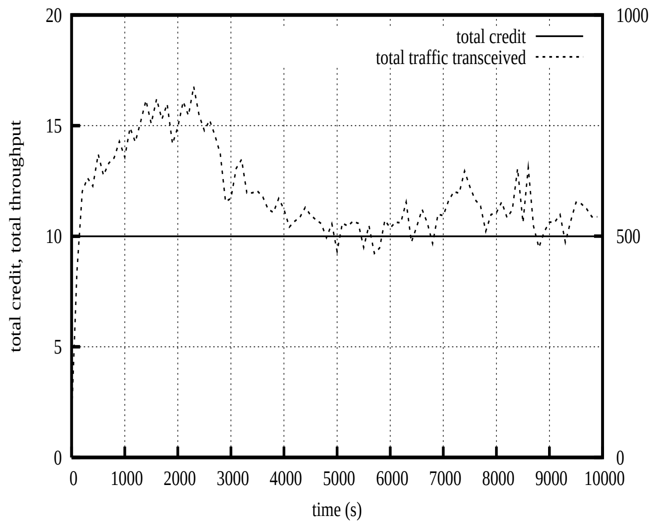

Figure 5.13: Total credit and total throughput.

coordinate clusters of nodes' movements in order to achieve particular goals.

In this thesis an adaptive mobility model is investigated. This model is based on the concept of basis behaviour proposed by Matrić [10] and discussed in Chapter 4. The adaptive mobility model enables nodes in an ad hoc network to spatially distribute themselves in order to maximise their area coverage, which is defined as the total area observed by the nodes [88].

The adaptive model is represented by the application of three basis behaviours derived from Matrić [10]. These basis behaviours are Safe-Wandering, Dispersion and Aggregation. The ZoO, derived from the Biological Mobility Model, is also included in this model where it is used to stabilise the movements of nodes.

The first experiment investigates the spatial distribution of the nodes where nodes are free to move away from each other in Safe-Wandering and Dispersion zones. In a safe-wandering zone a node reacts to the presence of a single node and moves away from it. However, in a Dispersion zone node i uses the local distribution of all of the nearby nodes (nodes within a distance `d-disperse` of node i) in order to decide in which direction to move. The simulation is run for up to $20,000s$. The node movements are updated every $0.1s$. The simulation parameters are given in Table 5.2.

To mimic the reality of nodes' movements, an error must be added to the distance between nodes. The distance $r_n(t) - r_i(t) = (x,\ y)$ between nodes n and i at time t is computed as follows

$$\begin{aligned} x &= x + E(0.05x)\cos(\theta) \\ y &= y + E(0.05y)\sin(\theta), \end{aligned} \tag{5.2.1}$$

where $E(z)$ is a random variable sampled from an exponential distribu-

N	100	The number of nodes
`d-avoid`	$9m$	The radius of the zone of Safe-Wandering
`d-disperse`	$12m$	The radius of the zone of Dispersion
`d-orientation`	$15m$	The radius of the zone of Orientation
`d-aggregate`	$17m$	The radius of the zone pf Aggregation
r_d	$56m$	The radius of node-to-node radio transmission
V	$0.05m/s$	The speed of each node

Table 5.2: Simulation parameters.

tion with parameter z, and θ is a random variable sampled from a uniform distribution in the range $[-\pi, \pi]$.

Figure 5.14 shows the final spatial distribution of 100 nodes. The nodes are initially located in a $10m \times 10m$ area at the centre of a $300m \times 300m$ plane. The boundaries of the plane are sufficiently far away to ensure that nodes will not reach the edge of the network during the simulation. Most of the nodes locate themselves approximately $12.5m$ apart at the vertices of a hexagonal lattice.

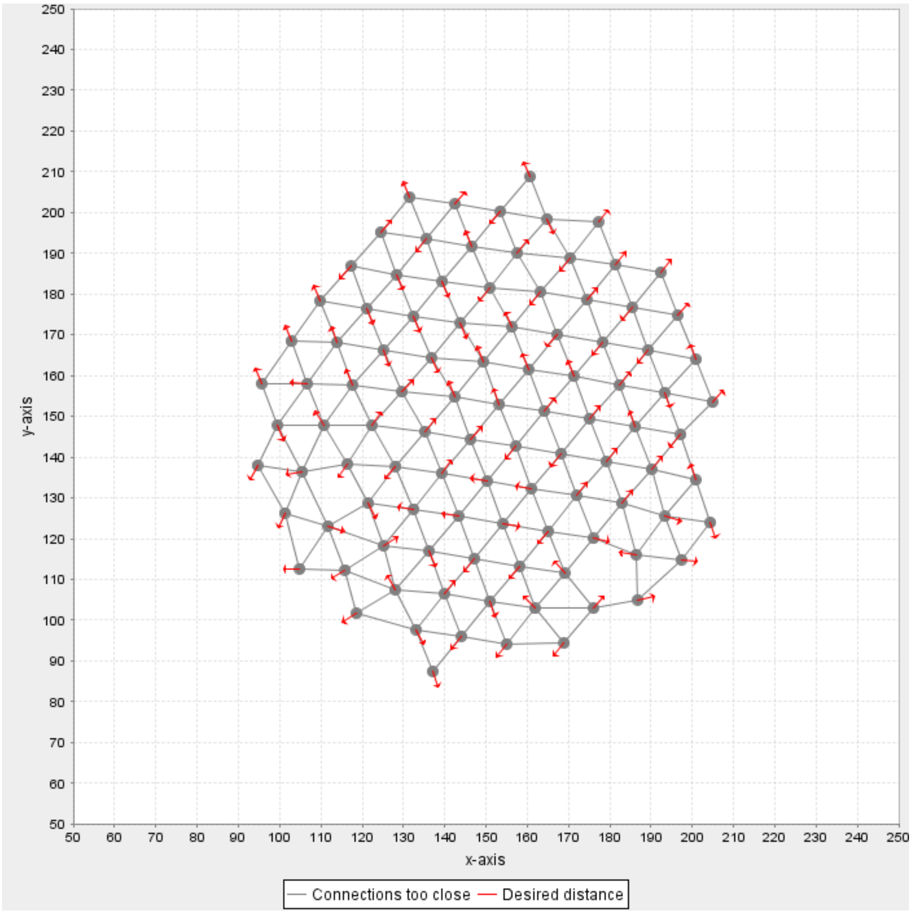

Figure 5.14: The coverage achieved when 100 nodes are originally located in the central $10m \times 10m$ of a $300m \times 300m$ plane.

5.3 Maintaining Cluster Connectivity

In some MANET applications, including battlefield communication and disaster relief, collaboration among nodes exists and the nodes follow guide nodes or leaders. The adaptive group mobility model is modified to represent a collective motion. A guide node moves to a specified location. In this case the guide node must induce a collective motion among its neighbouring nodes so that the nodes follow the guide node to the vicinity of the specified location and establish maximal coverage in this vicinity.

In the case of more than one guide node, nodes may split up into different clusters. Each cluster may follow a different guide node. However, the clusters may lose radio connection between themselves when they move too far away from each other. In order to keep radio connectivity between these clusters some nodes leave their clusters and act as transit nodes to connect these clusters.

In order to prevent disconnection between clusters, the distance between these transit nodes must be less than r_d, the radius of node-to-node radio transmission. In addition, transit nodes should not be too close to each other in which case too many nodes will act as relays between the clusters and spend their resources far away from the vicinity of the guide nodes where observations have to be made. For this reason, a node calculates its new movement step without executing it unless it verifies the following: if the movement step is executed without losing the connection, there are one or more nodes N within a radius r_d. Node K executes its movement step. If the node K loses the connection with node N when it executes this movement step, then node N is located at a distance further than r_d. In this case node K must verify whether another node R can be used as a relay between node K and node N. Such a node R must be no more than r_d distance from nodes k and N. If such a relay node R cannot be found, then node K is immobilised, the movement step of node K is denied, and connectivity with node N is preserved [88].

Figure 5.15 shows the final spatial distribution of the nodes when the nodes are initially uniformly located in a $10m \times 10m$ area at the centre of a $500m \times 500m$ plane. There are four guide nodes. The first guide node, initially located at the centre (249, 250), moves at $2cm/s$ unit until it reaches $(90, 250)$ where it stops. A second guide node, located at $(251, 250)$, moves at $2cm/s$ unit until it reaches $(410, 250)$ where it stops. Another two guide nodes are located at (250, 251) and (250, 249) respectively and move at $2cm/s$ unit until they reach (250, 410) and (250, 90) respectively where they stop.

The nodes follow the guide nodes and eventually split up into 4 clusters. Connectivity between the four clusters is maintained by immobilising nodes at the edges of their respective clusters. This is done when the current movement step would disconnect the clusters from each other. The immobilised nodes maintain connectivity between the four clusters and form a ring in the middle of the network. When the guide nodes reach their targets they stop moving. In this case the nodes apply the standard roles, safe-wandering, dispersion, orientation and aggregation zones, to reach their maximum area coverage. This can be observed in Figure 5.15 where nodes surround the guide nodes in approximately hexagonal lattices.

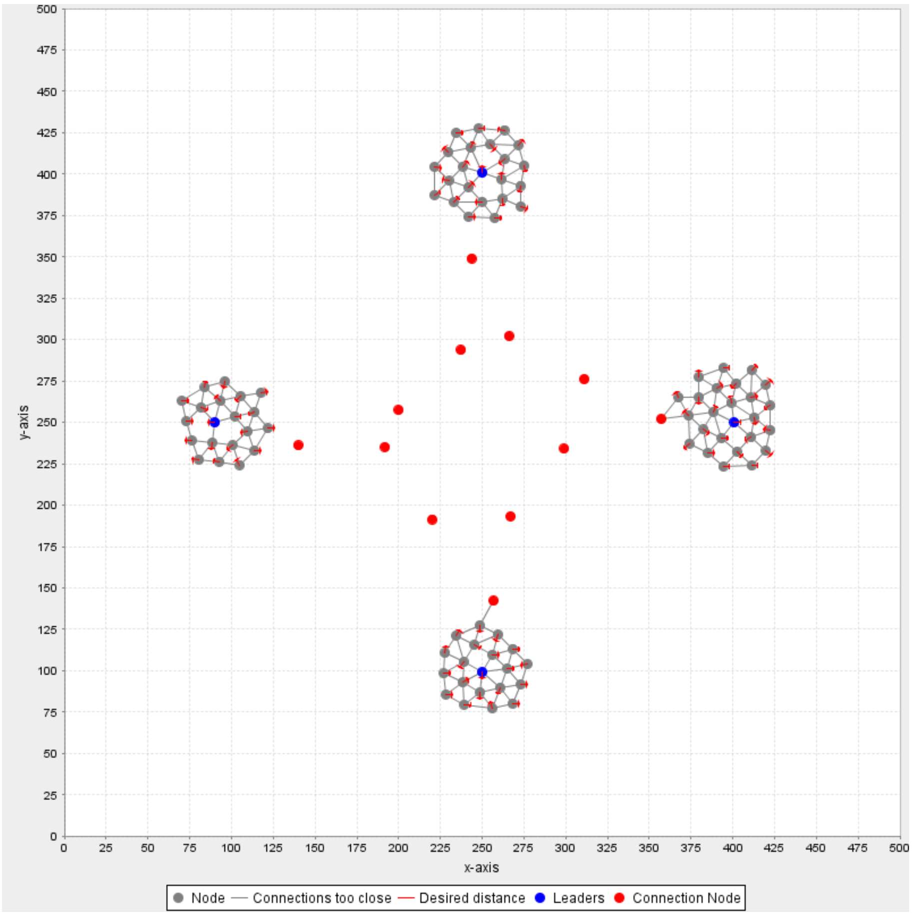

Figure 5.15: The coverage achieved when 100 nodes are originally located in the central $10m \times 10m$ of a $500m \times 500m$ plane: four guide nodes move north, south, east and west respectively.

Chapter 6

Conclusion

In this thesis, a model of a mobile ad hoc network is presented where nodes are given incentives to collaborate. The model is described by Crowcroft *et al.* in [3; 4]. In this model, each node has a credit balance that determines how much the node can spend on transmission resources in the next time interval. For each node there are two resources: bandwidth and power, each with its own price. Credits are spent when a node acts as a source node and sends traffic through the network. Credits are earned when a node acts as a transit or a destination node. Routes for connections from a source node to a destination are chosen in such a way that the route price is minimal.

A static network was studied through a simulation. This simulation demonstrates that the node bandwidth prices, power prices and credit balance are all stabilised about a mean value, which provides evidence that the system is stable. The simulation also shows the advantages of a node being near the centre of the network, as this allows the node to act as a transit node and earn credits.

The mobility of nodes is also investigated. Chapter 4 presents several mobility models that can be used to simulate a mobile ad hoc network. In this thesis a simple movement model is utilised to investigate the effect of the node movement on the incentive mechanism: a single node is allowed to move through the centre of the network. This motion shows that the overall performance of the network varies with the current geographical location of the users. The motion of a mobile node can affect not just its own performance, but also the overall performance of the network.

A collective mobility model, the adaptive group mobility model, is also investigated where the nodes move autonomously in order to maximise the area coverage of the network. At the same time, these nodes ensure that they do not move so far away from each other that they disconnect themselves. The adaptive mobility model is used to maximise the area coverage. The model studied shows that nodes are able to locate themselves at the vertices of a hexagonal lattice.

The adaptive group mobility model is also investigated in the presence of guide nodes. A guide node moves to a specific vicinity where the observation must happen. The rest of nodes follow the guide node. In the case of more than one guide node, the nodes may split up into different clusters following the guide nodes causing the clusters to disconnect from each other. In this event, some nodes leave their clusters and act as transit nodes to connect these clusters. The simulation shows that at the end of the simulation each cluster of nodes surrounds its guide node and the transit nodes formed a ring in the middle of the network.

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