CONTINUOUS FLOW ROUTING (CFR): A WIRELESS AD HOC NETWORK ROUTING PROTOCOL FOR SUPPORTING MULTIMEDIA FLOWS

A THESIS

SUBMITTED TO THE DEPARTMENT OF COMPUTER ENGINEERING

AND THE INSTITUTE OF ENGINEERING AND SCIENCE

OF BILKENT UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

By

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July, 2006

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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July, 2006

Multimedia flows require special routing layer support in ad hoc networks due their unique characteristics and certain requirements on packet delay, jitter, loss rate and bandwidth. In this thesis we propose a wireless ad hoc routing protocol (called CFR) with route discovery and maintenance mechanisms, that is specifically designed for better supporting multimedia flows in wireless ad hoc networks. Since multimedia flows are long durational, it is important to route them through stable routes in order to minimize route failures and disturbance on the flows. We propose to improve the stability by considering the energy drain rates and estimated remaining lifetimes of nodes while selecting the best routes. Additionally we provide a maintenance scheme that acts pro-actively and re-routes the traffic if a node starts getting very low energy. For this we define two thresholds on remaining lifetime of a node. After the first threshold is reached, the node re-routes some of its flows so that the traffic load on the node is reduced. This helps to an even distribution of traffic to nodes of an ad hoc network. After the second threshold is reached, the node has very few energy and therefore redirects all its traffic to some other routes so that the flows are not disturbed by the route failure when the node depletes all of its energy and can not route anymore. We implemented the protocol as part of an ns2-based simulator and proved that it works correctly. Additionally, we compared the protocol against some other similar protocols. The results show that CFR can indeed help supporting multimedia flows better.

Keywords: Ad-Hoc Networking, Route Maintanence, Multimedia Streaming.

ÖZET

SÜREKLİ AKIŞ YÖNLENDİRMESİ (SAY): TASARSIZ AĞLARDA ÇOKLU ORTAM SUNULARINI DESTEKLEMEK İÇİN YÖNLENDİRME YÖNTEMİ

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Çoklu ortam sunuları; sahip oldukları özel nitelikler ve paketlerdeki gecikme, gecikme miktarındaki dalgalanma ve paket kaybı oranı gibi özel ihtiyaçları nedeniyle, tasarsız ağlarda yönlendirme seviyesinden desteğe ihtiyaç duymaktadırlar. Bu tez içerisinde, tasarsız ağlarda çoklu ortam sunularının başarımını artırmak amacıyla gerçeklenmiş, yönlendirme keşif ve bakım mekanizmalarından oluşan, SAY yöntemini sunmaktayız. Çoklu ortam sunuları uzun ömürlerinden dolayı hatalardan uzak dayanıklı yönlendirmelere ihtiyaç duyulmaktadır. Yönlendirmelerin dayanıklılığını artırmak için enerji seviyesindeki azalma oranı ve bileşenlerin kalan ömürlerini hesaba katarak en iyi yönlendirme seçilmektedir. Ayrıca sunduğumuz bakım sistemi sayesinde bir bileşenin enerjisinin çok azaldığı durumlarda, daha bir hata ortaya çıkmadan yönlendirmeler değiştirilerek tehlikeli bileşen dışarıda bırakılmaktadır. Bileşenlerin kalan ömürlerine bağlı iki eşik değeri tanımlanmıştır. İlk eşik değerine erişildiğinde bileşenler üzerlerindeki akışların bir kısmını bakıma alarak üzerlerindeki yükü azaltmaktadırlar. Bu sayede ağ üzerindeki yükün tüm bileşenlere mümkün olduğunca eşit dağıtılması da sağlanmaktadır. Bileşenin çok az ömrü kaldığında ikinci eşik değerine erişilir ve bileşenin üzerindeki tüm akışlar bakıma alınarak herhangi bir akışın kesintiye uğraması engellenir. Yöntemimizi ns2 tabanlı simülatör üzerinde gerçekleyerek yöntemin doğruluğunu kanıtladık. Ayrıca diğer yöntemler ile kıyaslayarak yöntemimizin başarısını ölçtük. Elde ettiğimiz sonuçlara göre SAY, çoklu ortam sunularının başarımını artırmaya destek sağlamaktadır.

Anahtar sözcükler: Tasarsız Ağlar, Yönlendirme Bakımı, Çoklu Ortam Sunuları.

To my mother, Birsen KARA...

Acknowledgement

I would like to express my gratitude to my supervisor Assist. Prof. Dr. İbrahim Körpeoğlu for his realistic, encouraging and constructive approach throughout my masters study and his efforts and patience during supervision of the thesis.

I would like to express my since appreciation to the jury members, Assist. Prof. Dr. İlyas Çiçekli, and Assoc. Prof. Dr. Ezhan Karaşan for reviewing and evaluating my thesis.

I thank to the members of Networking and Systems Group at Bilkent University during the years 2003 to 2006 for their comments on my studies and for the sparks they caused.

I also thank to the Scientific and Technical Research Council of Turkey (TÜBİTAK) for its support to the project with grant number 104E028.

I would like to express my appreciation to TÜBİTAK UEKAE / ILTAREN for the understanding and support during my academic studies. I also want to thank to people I work with for the joy they bring to my life making my business life together with academic life a pleasureful experience.

I thank to my wife, who became the light of life with her patience and morale support during my studies.

Finally, I would like to express my thanks to my parents, making me who I am now with their love, trust, freedom understanding and every kind of support throughout my life.

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Chapter 1

Introduction

Wireless technologies have changed the way people think about networks by offering users freedom from the constraints of physical wires. Over the last decade, wireless communication has experienced significant growth and wireless communication became widely available. Mobile Ad Hoc Networks (MANET) [16] were introduced upon these technological enhancements and are becoming an important type of networks for the future.

MANETs are wireless networks that do not have a fixed infrastructure. Nodes in a MANET can communicate with each other by using routes that pass through their neighbors and through some other intermediate nodes. There is no central coordination. Lack of a central coordination and the dynamic environment that MANETs have, however, makes the route construction a difficult process. Different routing protocols [28] are proposed for MANETs so far that try to find the best route to a destination according to some objectives. Some of these protocols aim for shortest paths, some aim for minimum cost in terms of overhead incurred on the network, and some aim for energy efficiency and prolonging the network lifetime. The objectives are not limited with these.

A data transmission between any two nodes in a MANET first requires the MANET routing protocol to discover a path between these two nodes. Once the path is discovered, i.e. a route is constructed, the source node can continuously transmit packets with the help of its neighbors and other intermediate nodes towards the destination node. Hence, the transmission of packets from the source to the destination depends on the availability of some intermediate nodes with enough energy if the source and destination nodes are not with direct reach of each other. If one of the nodes on the discovered path becomes no longer available to carry the traffic between the source and destination, the flow of traffic gets disturbed and another path, if any, has to carry the traffic. There can be two main reasons for a node on the routing path to become unavailable for routing:

- **Mobility** : The node might have moved. Ad hoc networks usually consist of portable devices like laptops or pocket PCs and therefore mobility is an expected behaviour. This may disturb and break the discovered routes.
- **Lack of Energy** : Nodes in a MANET are usually battery-powered devices in order to be portable. Hence they have limited energy which can deplete with time. Therefore, if the node on the routing path between the source and destination depletes all of its energy, it can no longer forward the packets. Hence, lack of energy can be another reason for a route break.

Ad hoc routing protocols are optimized for handling topology and condition changes due to these two main factors which affect the lifetime of routes. There are many routing solutions proposed that considers node mobility [1,3,6,11,13] and energy efficiency [19,29,31,32].

In this thesis we focus on ad hoc network routing schemes that considers energy efficiency. Several optimized protocols are proposed to efficiently use the nodes' energies and increase the network lifetime, but many of them do not consider efficiently maintaining the routes as well. Hence many of the proposed routing protocols lack efficient maintenance algorithms. In ad hoc networks, however, this is a very important issue, since the network topology may change quite frequently and if routes are not adapted to those changes in an efficient and fast manner, they may get broken and flows can get disturbed.

A common approach to deal with the topology changes in MANETs as far as routing is concerned is updating the routes periodically so that routes are derived from the latest state of the network. But trying to update and maintain routes periodically is an expensive process in terms of messaging overhead imposed on the bandwidth-scarce wireless links and processing overhead imposed on the energy-scarce nodes. Another problem is finding an appropriate update period to update the route information. Therefore, even periodic updates may not be sufficient sometimes to protect route failures and to prevent the disruption of the traffic flowing in the network.

A type of traffic that can be affected most from route breaks and slow maintenance of routes is multimedia/real-time traffic. Multimedia traffic and the traffic of most real-time applications flow as a stream of packets from a source to a destination. The delay and jitter the packets encounter, and available end-to-end bandwidth are important parameters for multimedia traffic. Since a broken route can increase the delay, jitter and packet loss rate, and decrease the available bandwidth, multimedia applications and real-time applications are not so tolerant to broken routes that happen in the middle of flows. Continuous flow of traffic is an important issue for these types of applications.

There are some studies on how to support multimedia and real-time traffic in ad hoc networks, and some route discovery and maintenance algorithms are already proposed [3, 13, 22, 30]. But many of these maintenance algorithms start recovering from a route failure after the route gets broken, acting in a reactive manner, or they have limited patching capabilities. There are also some studies that applies some pre-emptive strategies. The Pre-Emptive Routing scheme [13] informs the source of a flow about a likely route failure and lets the source choose another route. In this case the source constructs another route, which is an expensive process. The ARMP [3] algorithm implements a patching algorithm on threat; but it can only use a single neighbor node if available.

In this thesis we developed and studied a MANET routing protocol including discovery part and maintenance part, whose objective is to support multimedia flows in a better manner. Our protocol tries to minimize the effect of route breaks on the multimedia flows. We concentrate especially on route failures due to lack of energy, but the protocol can easily be extended to support route breaks due to mobility. As mentioned, route failures/breaks cause increase in *end to end delay*, *delay jitter* and *packet loss rate* which is not desirable for multimedia flows.

We call our proposed routing protocol as *Continuous Flow Routing* (CFR). It is based on tracking the expected lifetime of MANET nodes using their remaining energy levels and current loads, and it aims to keep routes that carry multimedia flows alive as long as possible. The protocol consists of three main parts: *Lifetime Prediction*, *Route Construction* and *Route Maintenance*.

The remaining lifetime of a node can be predicted by looking to its remaining battery energy. But the remaining energy level itself is not sufficient for an accurate prediction. In a highly loaded network, the traffic load on nodes may not be distributed evenly and a node may carry the traffic of many flows established between pairs of nodes of the network. Hence the energy dissipation rate of the node depends also on the amount of traffic carried (generated, consumed, or forwarded) by the node. Therefore we should also include the expected traffic load of the node as well while predicting the expected lifetime of the node. A node with a heavy traffic load will deplete its energy sooner than a node with a lighter traffic load, assuming their initial energies are the same. On the other hand, predicting the expected traffic load in the future may not be easy. But it may be related to the current load; and the current load affects the current energy drain rate for the node. Hence the energy drain rate of a node and its traffic load are closely related if we assume most of the energy of a node is spent for communication. Therefore we use the energy drain rate of nodes as our additional metric for predicting the lifetime of nodes. This is similar to what MDR (Minimum Drain Rate) protocol proposes [19].

The MDR protocol [19] provides a MANET route finding and maintenance algorithm based on the energy drain rate of MANET nodes. While finding an initial route between a source and a destination, it tries to select a path going over nodes that have maximum remaining lifetimes. Since we follow a similar approach, we adapt MDR's route discovery scheme as our base route discovery algorithm. On top of that we propose our own route maintenance algorithm.

Having a route maintenance algorithm is important for a routing protocol, but we have to be careful about the cost of maintenance. Each maintenance operation will have an associated processing and communication cost; therefore, maintenance should not be triggered too frequently. For this reason, it is important to have the routes to be stable as long as possible. A scheme that will provide stable routes is highly valuable for networks that will carry multimedia traffic.

The MDR protocol [19] uses a generic approach for route finding, and enables any of the base route discovery mechanisms to be used as the underneath supporting protocol. For example, in MDR paper, DSR protocol (Dynamic Source Routing) is used as the route discovery mechanism. DSR [17] uses source routing and does not maintain route tables to forward packets at intermediate nodes. But we prefer to use AODV (Ad Hoc On-Demand Distance Vector) [26] protocol as the basis for our route discovery and maintenance mechanisms. Since AODV is table driven protocol, it stores the route information on nodes in a distributed manner, and this facilitates easy local modification of routes when they get broken. In AODV, route information is kept partially in each node, and each node contributes for finding of routes.

The route maintenance mechanism of CFR depends on tracking the remaining lifetime of nodes. A node, which has a traffic load exceeding its capacity or gets close to end of its lifetime, triggers the CFR route maintenance mechanism. There are two thresholds defined for triggering route maintenance. An alternative route is searched when the remaining lifetime of a node drops below one of these two pre-defined thresholds. These thresholds are: *Reduce Load* threshold, and *Rescue Node* threshold. Although there are two different thresholds, the algorithm to find the backup route works similar.

When the first threshold value, *reduce load* threshold, is reached at a node, the node instructs its previous nodes on each route to find an alternative backup route that excludes this node from their paths. But the nodes that get this instruction and the range of backup route search mechanism are limited to reduce the overhead on the network. If an alternative route can be found, routes going

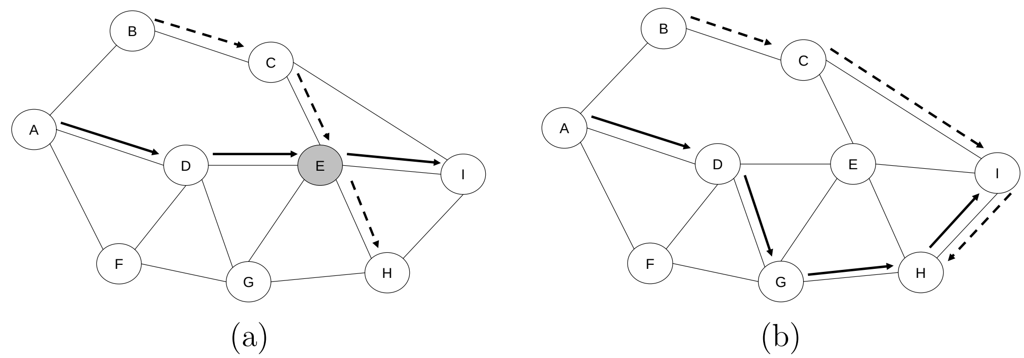


Figure 1.1: An application of route maintenance: (a) Node E requests a maintenance, (b) Routes are updated and node E is excluded

over this node are modified to exclude this node and to include the alternative sub-paths. The backup routes are started to be used, and in this way the traffic load on the node is decreased. If there is no alternative route found, transmission of traffic is continued using the existing route that is going over this node.

Later on, the node will reach to the very end of its life, and will not be able to continue to take part in any further transmission. This time *Rescue Node* threshold is reached. In this case, all the previous nodes for flows going over this node are instructed to find alternative routes with *unlimited* search range. If an alternative route exists, it will be found and used before the node totally gets drained out of its energy. But if backup route discovery fails, there is nothing that can be done and the flows that are going over this node will be disturbed.

We also evaluated our proposed protocol. We used simulation as our evaluation methodology. We implemented our protocol as part of the *ns2* network simulator [8] and compared its performance against some other related proposals. Simulating our protocol as part of ns2 verifies that our protocol works correctly and is feasible to be implemented as part of an ad hoc network.

We can summarize the contributions of the thesis as follows:

- We propose a routing protocol for ad hoc networks to support multimedia flows so that the disturbance of flows due to lack of energy is reduced. The proposed algorithm has both a route discovery part and route maintenance part.

- We adapt the MDR's route discovery to run over AODV protocol. MDR is implemented with DSR.
- We proposed a new route maintenance scheme that either reduces the load on a node with small amount of remaining energy, or redirects all the flows on a node, that is very close to die, to some other nodes around
- We implemented the proposed protocol as part of ns2 and it is corrected and verified.
- The protocol is evaluated and compared to some other similar protocols.

The remaining part of the thesis is organized as follows. In the next chapter, we provide some background information to introduce the reader on wireless networks, multimedia applications, and ad hoc network routing algorithms. In Chapter 3, we describe some studies that are related to our study. Then in Chapter 4, we give a detailed description of our proposed solution, the Continuous Flow Routing (CFR) protocol. And in Chapter 5 we evaluate our solution and provide some results. Finally, we provide our conclusions and discuss some future work issues in Chapter 6.

Chapter 2

Background

This thesis is about supporting real-time and multimedia traffic in wireless ad hoc networks at the routing layer. Therefore, before describing our solution and some related work, we will first give some background information about the topic and some related fields.

2.1 Wireless Computer Networks

Wireless networking and computing has been evolved very rapidly over the last years. Wireless communication and networking technologies provide the users connectivity without wires, and this makes communication more flexible, easy to configure and use. Wireless technology also enables mobility. Additionally, lots of new networking applications and network usage scenarios have been possible with the advent of wireless technologies. For example, use of wireless local area network (wireless LAN) technologies is expanding rapidly in applications of computer systems, in inventory management systems in warehouses, in highly mobile user environments like hospitals and universities. Additionally, wireless LANs are replacing wired LANs in some places like museums [21].

Users of wireless networks expect the same services and capabilities that they have in wired networks. However, to meet these objectives, wireless community has some challenges and constraints that are not in practice with wired networks [5]:

- **Frequency allocation**: A wireless network may require that all users operate on a common frequency band.
- **Interference and reliability**: Simultaneous transmission by two or more sources and sharing the same frequency band causes interference which makes communication impossible.
- **Security**: In wired networks, access to the transmission medium can be physically secured, which is not possible in wireless networks.
- **Power consumption**: Wireless devices meant to be portable and/or mobile, and are typically battery powered. Therefore, devices and software must be designed to be energy-efficient, resulting in implementation of special solutions like our proposal in this thesis.
- **Human safety**: Research is ongoing to determine whether radio transmissions are linked to human illness. Networks should be designed to minimize radio transmissions.
- **Mobility**: One of the primary advantages of wireless networks is that nodes can be mobile. This brings forth some issues and challenges that have to be considered by network and protocol designers. This is not an issue in wireline networks.
- **Throughput**: Capacity of wireless networks is expected to approach their wired counterparts. However, due to physical limitations and limited available bandwidth, wireless channels usually support much less data rates currently.

There are now lots of different wireless communication and networking technologies. There are cellular/wide-area wireless networks, satellite wireless networks, wireless MANs, wireless LANs, and wireless PANs. There are different standards for these different technologies. The standardization activities are still on going. There are sometimes more than one standard supporting a certain type of wireless network. For example, there are two main standards for wireless LANs: the IEEE 802.11 standard [5, 15] and the HiperLAN [18] standard.

Wireless networks can usually provide the same capabilities and services that their wired counterparts can provide. But since the characteristics of wireless and wired networks are different, there is also difference in the performance they provide to the higher layer network protocols and to the applications. The routing layer, or the transport layer protocols are affected by the properties of the physical links.

Just to give an example, TCP's congestion control mechanism assume that packet losses are caused by network congestion, which is not always the case in wireless networks. In TCP, when a packet is not acknowledged by the receiver within a certain duration, called the retransmit timeout interval (RTO), the sender retransmits the packet and doubles the RTO. This process is repeated until an acknowledgement is received. This exponential back-off of the RTO works well in wired networks, but in wireless networks it hurts the TCP performance. Therefore some solutions for this problem have been proposed [2].

The effect is not only on the transport layer; the routing layer is also affected by the existence of wireless links and mobile devices. Therefore there is also work on routing layer for coming up with routing solutions to better support applications executing over wireless and mobile networks. For example, in [7], a fixed RTO solution is proposed and it increases the performance of pro-active routing algorithms significantly.

Wireless networks can be classified according to their range, bandwidth, etc. But there is also another important classification criteria: does the network require an infrastructure, or no infrastructure. Therefore, we can say that there are currently two types of wireless networks whose design differs from each other quite significantly [28]:

- **Infrastructure-based wireless networks**: They require the existence of fixed and wired gateways that form the backbone of the network. Those gateways act in some sense as the bridge between the wired and wireless links. They also work as base stations. An end-user terminal (a cell phone, a PDA, or a computer) usually connect to a base station over a single wireless link (Figure 2.1).

- **Ad hoc wireless networks**: They have no fixed base stations (or routers). All nodes in an ad hoc wireless network is capable of being mobile, and they can be connected to each other dynamically in an arbitrary manner (Figure 2.2). The configuration and maintenance of the topology should be automatic and self-organizing. A connection from one node to anther node may go over one or more wireless links. An intermediate node on such a path will act as a router even though it can be just an ordinary user terminal/computer. Hence, each end-user node in the network can be both a source/destination of traffic and a forwarder/router of traffic.

Figure 2.1: Infrastructure-based wireless network

2.2 Wireless Ad Hoc Networks

The principle behind ad hoc networking is *multi-hop relaying*, which traces its roots back to 500 B.C. Darius I, the king of Persia, implemented a communication system for sending messages and news from his capital to remote provinces in the empire, by using a line of shout men placed on towers. This system was more than 25 times faster than normal messengers [25, p. 191].

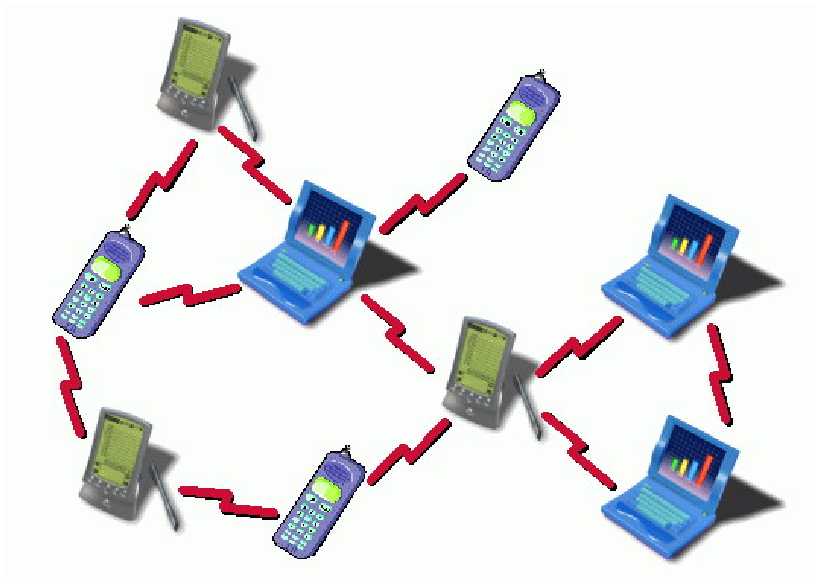


Figure 2.2: Ad Hoc network

Ad hoc networks are formed by mobile nodes without using any other extra infrastructure (Figure 2.2). The nodes constituting the network function as routers besides functioning as user terminals. They can discover other nodes and routes to each other. The discovered routes can be maintained and repaired when they break down for some reason.

There are many application areas of ad hoc networks [25, p. 197 - 204]:

- **Military applications**: Establishing communication among a group of soldiers will be much simpler with ad hoc networks. There will not be any need for setting up an infrastructure.

- **Collaborative and distributed computing**: Setting up a quick network for information sharing can be done with ad hoc networks.

- **Emergency operations**: Ad hoc networks will be easily set up when all communication infrastructure becomes unavailable, or quick operation in a rescue area is required.

- **Wireless mesh networks**: A communication network can be set up by using ad hoc devices without doing any planning.

- **Wireless sensor networks**: Sensor nodes deployed as part of a specific application domain can communicate to their base station by using ad hoc network algorithms.

Nodes in an ad hoc network communicate with each other by using their neighbours in between. This type of multi-hop communication requires a routing algorithm to be used. In the next section we will discuss some routing protocols proposed for ad hoc networks.

2.3 Ad Hoc Routing Protocols

The absence of any central coordinator or base station makes the routing a complex problem in wireless ad hoc networks compared to the routing problem in infrastructure-based wireless networks. The major requirements of a routing protocol for wireless ad hoc networks are the following [25, p. 207 - 208]:

- **Minimum route acquistion delay**: Time spent for finding a route to a destination should be as small as possible.
- **Quick route reconfiguration**: Routes should be quickly reconfigured whenever some network conditions change and break the routes.
- **Loop-free routing**: Like any other routing protocol, an ad hoc network routing protocol should find paths that do not contain cycles.
- **Distributed routing approach**: Since there is no central authority in ad hoc networks, routing protocols should be totally decentralized and distributed.
- **Minimum control overhead**: The control packets sent by routing algorithms should be as low as possible.
- **Scalability**: A routing protocol should not fail when the number of nodes in the network increases.

- **Support for QoS**: The routing algorithm should support provisioning of quality of service in the network for QoS-demanding applications.
- **Support for time-sensitive traffic**: The routing protocol should try to minimize the average and maximum delay that packets can encounter.
- **Security and privacy**: Ad hoc networks should be resilient to threats and vulnerabilities. Therefore routing protocols should not have security holes.

We can classify the routing algorithms for ad hoc networks into two major categories [28]:

- **Table-driven routing protocols**: These routing protocols attempt to maintain consistent up-to-date routing information from each node to every other node in the network; so they require one or more tables stored on nodes for routing information. They respond to changes in network topology by propagating updates throughout the network. Samples of these algorithms are DSDV, CSR, WRP [28].
- **Source-initiated on-demand routing protocols**: This type of protocols create routes only when desired by the source node. When a node requires a route to a destination, it initiates a route discovery process to find the route. This route is maintained by a route maintenance protocol until the destination becomes unavailable or the route is no longer desired. Samples of these protocols are AODV [26], DSR [17], TORA [28].

We will briefly explain DSR and AODV protocols in the following sections as they are protocols that are closely related to our solution in this thesis.

2.3.1 DSR

The Dynamic Source Routing (DSR) [17] protocol is based on route caches maintained by nodes that store full path information to destinations. Route discovery is initiated by broadcasting a *route request* packet. This route request packet contains the address of the destination, along with the source node's address and a unique identification number. Each node receiving the packet, checks whether it knows of a route to the destination. If it does not, it adds its own address to the *route record* of the packet and broadcasts it to neighbors of the node. To reduce number of route request packets, each node handle only one packet of a discovery (by the help of a unique identifier and checking the route record).

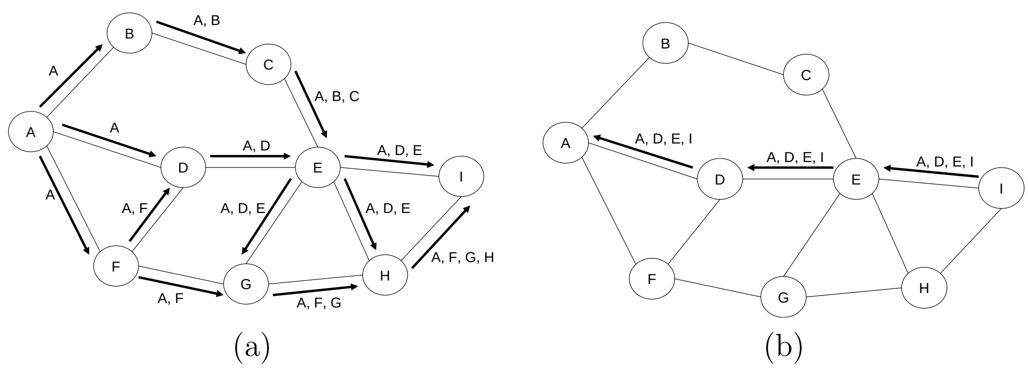


Figure 2.3: DSR Route Discovery Process: (a) Route request packets are flooding over network, (b) Route reply packets are going to the source node

When the request packet reaches to the destination or an intermediate node with a cache entry to the destination, a *route reply* packet is generated and sent to the source node. The route record is completed to the destination and embedded into the route reply packet. This route record data is used in the reverse path while sending the packet to the source node. If symmetric links are not supported, another route discovery is initiated with the route record data embedded. The route discovery process is illustrated in Figure 2.3.

All packets sent from the source node include their own route records to be used by intermediate nodes while intermediate nodes forward them to destinations.

2.3.2 AODV

The Ad Hoc On Demand Distance Vector (AODV) routing protocol [26] is based on local routing tables stored in nodes. When a source node needs a path to a destination, it invokes a path discovery process by broadcasting its route request packet to its neighbors. Each node receiving the route request packet creates a routing table entry for the source node and broadcasts the packet again. If the destination or an intermediate node with fresh enough routing table entry to the destination receives the packet, it replies back with a route reply packet. Each node receiving the route reply packet creates a route table entry to the destination and forwards the packet towards the source node.

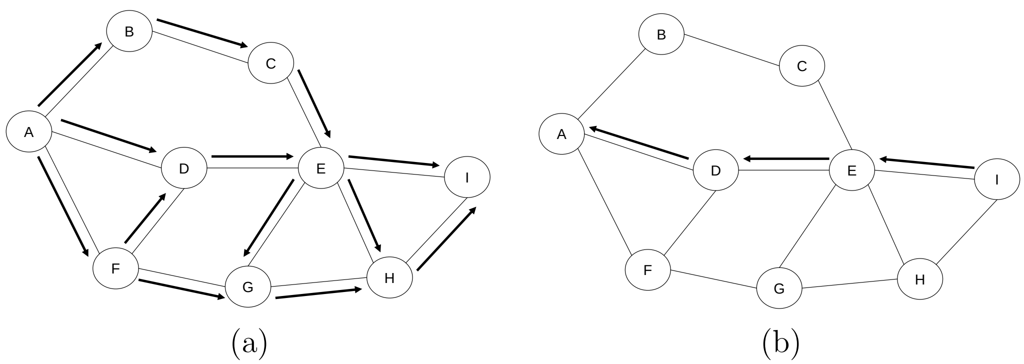


Figure 2.4: AODV Route Discovery Process: (a) Route request packets are flooding over network, (b) Route reply packets are going to the source node

At last all nodes on the path to the destination will have routing table entries for both source and destination nodes. All packets sent from the source node are then forwarded by the intermediate nodes using the routing table entries created earlier. The AODV route discovery process is illustrated in Figure 2.4, and a sample routing table is shown in Table 2.1.

Destination	**Next Hop**
I	E
H	E
B	A

Table 2.1: Sample AODV Routing Table of node D

2.4 Multimedia Communication

In the last few years, the development and deployment of networked applications that transmit and receive audio and video content over the Internet have grown tremendously. New multimedia networking applications such as entertainment video, IP telephony, Internet radio, teleconferencing and much more are announced every day.

The service requirements of these multimedia applications differ from the requirements of the traditional data-oriented applications, such as web access, email, file transfer, etc. In particular, the multimedia applications are highly sensitive to end-to-end delay and delay variation (jitter), however, they can tolerate occasional packet losses [20, p. 483 - 484].

2.4.1 Examples of Multimedia Applications

Multimedia applications that can be run on computer networks can be categorized in three broad classes: [20, p. 484 - 487]

- **Stored Audio and Video**: Clients request media files (audio/video) stored on servers. Example stored audio/video content may include lectures of a professor, archives of famous radio broadcasts, etc.
- **Live Audio and Video**: This is similar to traditional radio and television broadcast, except that the transmission takes place over a computer network, like Internet or an ad hoc network. If Internet is used, users can receive the live audio and video content from any point on the world.
- **Real-Time Interactive Audio and Video**: In these applications, users can communicate with each other using audio/video over a network like Internet. Internet Phone, for example, is an example application that can be used to transfer interactive audio between two users.

2.4.2 Networking Related Problems for Multimedia Applications

Today, most computer networks and Internet are based on best-effort service for all data packets carried, no matter whether they belong to multimedia applications. In other words, such a network makes its best effort to move each data packet from a sender to a receiver as quickly and as reliably as possible. However, there is no guarantee that the packet will reach to the destination within some certain time interval. There is no guarantee on the jitter and bandwidth either. Packet delay, loss rate, jitter, and bandwidth, however, are important parameters for multimedia applications [20, p. 501 - 503]. Below we briefly describe these parameters.

- **Packet Loss**: Multimedia applications often use UDP as the transport layer protocol to reduce end-to-end delay as much as possible. But the UDP protocol does not offer a reliable transmission. However, multimedia applications can tolerate packet losses to some extend. Packet loss rates between 1% and 20% can be tolerated by using special encoding schemes. On the other hand, if packet loss rate exceeds 10-20%, there is nothing that can be done and the quality of communication drops below acceptable ranges.

- **End-to-End Delay**: Accumulation of all processing and transmission delays on the route between a multimedia server and client forms the end-to-end delay. For stored and live multimedia streams, delays up to tens of seconds between the request and arrival of data can be tolerated. However, for interactive audio applications, such as Internet telephony, delays less than 150 milliseconds are not perceived by a human listener, delays between 150 and 400 milliseconds can be acceptable, and delays exceeding 400 milliseconds can result in frustrating conversations. Thus packets that are delayed by more than this threshold are effectively lost.

- **Delay Jitter**: End-to-end delay is the result of many changing factors on the route between the source and destination, and therefore its value is somewhat random around an average value. It depends on the load on the network nodes, the link bandwidths, the path length, and many other things like the MAC protocol behaviour. This random components contributing to the end-to-end delay causes the end-to-end delay to change from packet to packet. The amount of variation in delay is called *jitter*. If the receiver ignores the presence of jitter and plays out the arriving data packets as soon as they arrive, the quality of multimedia presentation becomes unacceptable for the receiver. Therefore jitter has to be removed by using a playout buffer, sequence numbers, timestamps, and playout delay.

The values of these parameters have to take some certain values, or have to be below a maximum value, or in some range. This can be achieved if the network has support for this. This support is called Quality of Service (QoS) support. Supporting QoS in a network is a complicated task and requires the involvement of many different protocols and components. Selecting routes based on the required QoS, reserving channel and bandwidth, performing call admission control, and fair share scheduling are some of them.

2.4.3 Running Multimedia Applications over Ad Hoc Networks

Ad hoc networks have some special characteristics that effect how QoS is provided in the network to support multimedia applications [25, p. 508 - 509]. Below we list those characteristics and some related issues.

- **Dynamically varying network topology**: Nodes in an ad hoc network can move, can get disconnected, can get shut down, or their batteries can deplete their energy. These events may cause links to be broken and topology to change. Hence we have a time varying topology that can change at arbitrary time instances.

- **Imprecise state information**: Any state information regarding a node (for example its links and neighbors) can become obsolete after a short amount of time.

- **Lack of central coordination**: Unlike wireless networks that rely on an infrastructure, wireless ad hoc networks do not have special nodes that can act as central coordinators.

- **Error-prone shared radio channel**: The radio channel is a broadcast medium, and therefore suffers from several impairments such as attenuation, multi-path propagation, and interference.

- **Hidden terminal problem**: Two nodes that would like to send packets to another node in the middle may not be aware of each other due to their limited range, and therefore can send packets simultaneously. This causes collisions.

- **Limited resource availability**: Resources such as bandwidth, battery energy, storage space, and processing capacity are much more limited in nodes constituting a wireless ad hoc network compared to devices in other type of networks, like Ethernet, WLAN, or Internet.

- **Insecure medium**: Communication through a wireless channel is highly insecure due to the broadcast nature of the channel.

Chapter 3

Related Work

In this chapter we will briefly describe some related work on routing in ad hoc networks and support of multimedia traffic in ad hoc networks.

3.1 Energy-Aware Routing

In ad hoc networks, nodes are generally mobile and have limited battery capacity. A routing protocol for ad hoc networks should be aware of this limitation and select the paths accordingly.

There are different solutions proposed for energy aware routing in ad hoc networks. Some of these solutions try to increase the lifetime of the whole network, and some try to have paths with maximum lifetime. We will describe these solutions briefly.

Minimum Total Transmission Power Routing (MTPR) protocol [29] is based on finding paths that consume less energy compared to other alternatives. Assume we have a route $r_d = n_0, n_1, ...n_d$, and let's $T(n_i, n_j)$ denote the energy consumed while transmitting from a node n_i to a node n_j. Then the total energy consumption on the route can be calculated as $P(r_d) = \sum_{i=0}^{d-1} T(n_i, n_{i+1})$. The MTPR protocol tries to find the route r_O that satisfies $P(r_O) = \min_{r_j \in r_*} P(r_j)$

for all possible routes r_*.

MTPR tries to reduce the total power consumption on a path, but it does not care about the battery capacities (remaining energy levels) of nodes on the path. Nodes may have variable battery capacities and this can affect the lifetime of paths that are selected. The Min-Max Battery Cost Routing Protocol (MM-BCR) [31] tries to find the path that consist of nodes with maximum battery capacities. Let $c_i(t)$ denote the battery capacity of a node n_i at time t. The MMBCR defines the cost function as $f_i(t) = 1/c_i(t)$. A node with less capacity (energy) should be more reluctant to forward packets; therefore the cost function of a route r_j can be defined as $R(r_j) = \max_{\forall n_i \in r_j} f_i(t)$, and the route r_O is selected by $R(r_O) = \min_{r_j \in r_*} R(r_j)$.

Using only the remaining battery energy in a cost function may not be the most efficient way of finding a route with maximum lifetime. The MMBCR-like routing algorithms will always prefer nodes with high energy in their paths, and these nodes will suffer from high traffic load and will consume their energy much faster. The Minimum Drain Rate protocol (MDR) [19] is a successor of other energy-aware routing algorithms, which uses the drain rate rather than the energy level of batteries as a factor in determining routing paths. MDR uses the battery drain rate and the remaining battery energy of a node to estimate the remaining lifetime of the node. MDR route selection scheme then depends on this lifetime estimation and tries to select a route with maximum lifetime. We will talk more about this protocol in Section 4.3, since our route construction scheme is an adapted version of MDR.

3.2 Route Maintenance Solutions

There is no central coordination in ad hoc networks and the nodes can be mobile. Additionally, the state of the nodes in terms of remaining battery energy and the amount of traffic carried may change over time. All these can cause quite frequent topology changes and route failures. Routing protocols for ad hoc networks have to adapt to these changes and route failures so that the adverse effects on the applications are reduced as much as possible.

One approach for dealing with route failures is predicting the time that a route failure will happen and then trying to find an alternative route before the current route totally fails. For example, in Pre-Emptive Routing protocol [13], every node on a route keeps track of its links' signal stabilities. If the signal stability for a neighbor on a route drops below a threshold, then the node sends a packet to the source of the route to inform it about the up-coming failure. The source then tries to re-establish another route before the current route becomes invalid.

The Pre-Emptive routing protocol measures the signal stability with a simple ping-pong message exchange. A node that receives a packet with low power sends a ping message to the adjacent node. Then the adjacent node replies with a pong message. This exchange is repeated for a while and the signal stability is measured by the ratio of corrupted packets. If this ratio exceeds a certain threshold, a warning signal is generated and sent back to the source of the route, which initiates a route discovery to replace the current route.

Both the route recovery process and the signal stability detection scheme of Pre-Emptive Routing have some flaws. The Active Route Maintenance Protocol (ARMP) [3] implements a better solution. In that, a route maintenance protocol is proposed to prevent the paths from getting broken. The protocol tracks the distances between nodes on a route depending on the signal strength information, and finds out the weak connections. A weak connection is an unreliable link between two nodes on a route. That link is loosing its signal strength and may cause a route break in the near future. The active node on the weak connection is the node whose migration causes the link instability. ARMP tries to find an alternative of the active node, and if found, modifies the current route to use the alternative node. Sometimes there is no active node. In this case, the protocol finds a new node between two nodes at each side of the weak connection so that the route is preserved.

The ARMP protocol uses SSA [6] for route establishment and uses its signal strength measurement while detecting an active node. The SSA protocol is based on finding the route that has the most stable signal strengths by measuring signal strengths periodically and getting their weighted average (Equation 3.1).

$$SS_{cumulative} = \alpha \times SS_{cumulative} + (1 - \alpha) \times SS \tag{3.1}$$

The ARMP protocol does route maintenance with a single node in the neighbourhood of the critical link. Sometimes an alternative node can not be found in the close vicinity of the critical link, but a wider backup route search can be useful to protect the link. In CFR we use wider backup route search around the critical link to find an alternative sub-route and protect the ongoing flows.

3.3 Multimedia on Ad Hoc Networks

Supporting multimedia applications on ad hoc networks is a difficult problem due to strong requirements of multimedia traffic and highly dynamic and unpredictable environment that wireless ad hoc networks provide.

There are many proposals for supporting multimedia traffic on wireless ad hoc networks. The proposals usually interest one or more layers of networking stack. Cross-layer approach, which involves a design or modification of more than one layer for a specific purpose, is also a popular approach for supporting multimedia and improving performance in wireless networks. For example, application layer and network layer and lower layers can interact with each other to support multimedia.

In Dynamic Adjustment Packet Control [12], with a special feedback mechanism between the network layer and the application layer, the network layer can inform the application about a link failure and hop-count. Then the multimedia application can adjust the its bit-rate and other parameters to adapt to the changing situation.

Another approach is use of a special multimedia encoding system that transports multimedia data over multiple paths. The protocol is called multi-stream coding with multi-path transport [24]. The protocol uses a special encoding algorithm that divides the multimedia data into multiple streams and sends them over multiple distinct paths.

A more general approach to support multimedia applications on wireless ad hoc networks is integrating QoS provisioning capability into the design of the network and its protocols; in other words, implementing a QoS architecture. Currently QoS algorithms that can reduce delay and that can provide some guarantees on delay are based on frequency or bandwidth allocations in the network [10]. However, this may not be possible for all environments.

Chapter 4

Continuous Flow Routing Protocol

In this chapter we describe in detail our proposed routing protocol for ad hoc networks and supporting multimedia flows. We will first give an overview of the algorithm and then will describe our solution in more detail.

4.1 Protocol Overview

Multimedia streams have some special characteristics and requirements that are different than the best effort transmissions, and therefore there is a need for special handling of this type of traffic in network nodes (Section 2.4.2). The requirements of multimedia traffic from a carrier network include: low and bounded end-to-end delay, low and bounded jitter, low packet losses, and a certain amount of end-to-end available bandwidth.

In ad hoc networks, routes are constructed dynamically by all nodes in the network before or after a connection request arrives, and route construction has an associated cost, i.e. it takes time and incurs overhead on the network. Hence it may introduce delays on the packets during their transmission in the network.

For source-initiated routing protocols (Section 2.3), this cost is always in effect for the initialization of the route. But for all protocols, a change in the state of a node (its location or its energy level) may break down an established route(s) going over this node, and this increases the delay and jitter for packets belonging to flows following this route. Although the increase is temporary until the construction of the new route, it is still disturbing for multimedia applications. Additionally, temporary route outage may cause packet losses due to buffer overflows and this again reduces the quality of multimedia streams.

A node may cause a route failure due to several reasons (as also described in Section 2.4.3):

- Nodes are mobile: A node can change its location so that it gets out of the transmission range of the previous node on the route.
- Nodes are not centrally managed: User of a node (device) can shutdown his/her device without waiting the on-going flows to terminate.
- Nodes may run out of energy: Nodes in an ad hoc network are generally battery powered and therefore have limited initial energy.

Our Continuous Flow Routing (CFR) algorithm is designed to improve the performance of ad hoc networks for better support of multimedia traffic in terms of lower delay, lower jitter and lower packet losses by trying to prevent route failures for on-going flows due to lack of energy.

Our solution basically consists of three main procedures:

- Lifetime Prediction
- Route Construction
- Route Maintenance

CFR uses the lifetime prediction technique presented in MDR [19] to construct and maintain routes. This technique uses *instant energy consumption rate*

($DrainRate_i$) and *remaining battery power* (RBP_i) to calculate the estimated remaining lifetime of a node n_i. The remaining battery lifetime is simply found by dividing these two quantities:

Estimated remaining lifetime for a node $n_i = \frac{RBP_i}{DrainRate_i}$.

CFR adapts the route construction algorithm of MDR [19]. MDR is a general algorithm that can be applied on several base routing algorithms and MDR paper implements its drain rate based route selection mechanism on DSR [17]. In this paper we selected AODV instead of DSR because of its suitability for manipulation of routes after their construction, which is needed for route maintenance.

Route maintenance of CFR is based on *keeping track of the remaining lifetimes* of nodes in the ad hoc network. When a node's estimated remaining lifetime drops below a certain *threshold*, the node invokes the backup route finding procedure with *limited range* and tries to reduce its traffic load so that the remaining lifetime of the node is extended. Even though the load is reduced, the node will still continue to carry some traffic and therefore will continue to deplete its energy. After some time later its remaining energy will be so low and close to finish. This is a critical energy level, which we identify as another threshold, after which the backup route finding procedure is invoked again, but this time *without a limit* on the range (i.e. the number of hops the backup route request packets can travel). With the backup route finding procedure, all of the flows going over this node will be tried to be routed over paths excluding this node. Of course, we may not succeed this always for every flow. The flows that can not be re-directed will be disturbed and broken when the node runs out of energy.

4.2 Lifetime Prediction

The "shortest path seeking" routing protocols may not always lead to stable routes. They consider the hop count; not the energy levels or other metrics related with stability. With stability we mean long durational routes, i.e. routes that are not required to be changed quite frequently. Routing protocols should consider some metrics that are more directly related with stability in order to better support multimedia flows, because multimedia flows are long durational. As mentioned earlier, stability can be disturbed at least due to mobility or lack of energy. For better stability, we can, for example, use the remaining energy levels of nodes on the paths while selecting routes. The route selection can select a path that will have the longest lifetime, i.e. is most stable.

How can we estimate the lifetime of a routing path is an issue. Several different parameters can be used for this. There are already proposed lifetime-based routing algorithms which use different metrics indicating stability, such as signal-strength [1, 3, 6], statistical data [11] and battery power [29, 31, 32].

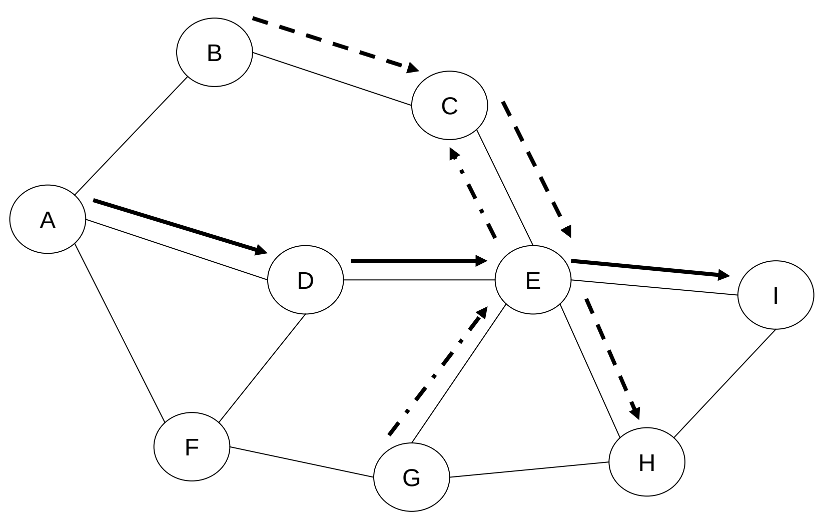


Figure 4.1: A node with high battery power may get higher load, node E transmits packets of three different flows

Our lifetime prediction procedure depends on the *energy state* of nodes. Many energy-aware routing algorithms [29, 31, 32] use remaining battery power (RBP) for selecting best routes, however RBP is not the only factor that affects the lifetime of nodes and routes. For example we can have the following scenerio. A node that has the highest remaining energy may be selected by many routes in the network (Figure 4.1) and therefore may carry lots of traffic. This will cause the node to consume its energy much faster than other nodes and therefore die sooner.

CFR uses the lifetime prediction technique of MDR [19] in its route construction and maintenance schemes. In MDR, each node n_i monitors its energy consumption and computes (samples) the energy drain rate for every T seconds. Lets denote the last calculated value with DR_{sample}. Then the new energy drain rate DR_i for the node n_i is calculated via exponential averaging (Equation 4.1) by using the last sample value and the previous value for drain rate (DR_{old}).

$$DR_i = \alpha \times DR_{old} + (1 - \alpha) \times DR_{sample} \tag{4.1}$$

How to calculate the DR_{sample} is explained in [19] in detail. It is based on the work by Feeney and Nilson [9] that defines energy consumption by using a linear equation: $E = m \times p + n$, where p is the packet size in bytes and m and n are statistically derived constants. MDR uses this function with values calculated by Network Interface Card (NIC) driver, depending on each sent/received packet and its length.

Like MDR, we used 0.3 as the value of α to better reflect the current energy consumption of nodes. Although MDR uses 6 seconds as the value of T, we use *one* second to quickly react with route update when the remaining lifetime of a node drops below a threshold.

By using the current battery drain rate (DR_i) and the remaining battery energy (RBP_i), we can estimate the remaining lifetime of a node n_i by dividing these two numbers. Lets C_i denote the remaining lifetime of node n_i. Then:

$$C_i = \frac{RBP_i}{DR_i} \tag{4.2}$$

4.3 Route Construction

CFR adapts the route construction scheme of MDR. Like MDR, route maintenance is tried to be avoided by using more stable routes, since maintenance in

MDR and in CFR can be done upon a route failure which causes extra delay, jitter and packet loss. Therefore, our routing algorithm tries to find a route that has the longest expected lifetime.

The expected lifetime (L_p) of a path r_p, is determined by the node that has the smallest remaining lifetime, i.e. the node that has the smallest C_i value (4.2):

$$L_p = \min_{\forall n_i \in r_p} C_i \tag{4.3}$$

Like in MDR, CFR route construction between a source and destination is based on selecting a path between the source and destination that has the maximum lifetime. Lets denote the selected path with r_M, which is the route to be used. Lets r_* denote all possible paths between the given source and destination, and lets r_i denote any one of these paths. Then we can define the selected path as follows:

$$r_M = \max_{\forall r_i \in r_*} L_i \tag{4.4}$$

In [19], MDR is implemented with DSR [17]. However, in CFR, we selected the AODV algorithm (Ad hoc on-demand distance vector routing)) [26] as the underlying route discovery protocol. The reason behind selecting AODV for CFR is its better suitability for maintenance algorithms. In AODV, packets are forwarded at intermediate nodes via the help of *local routing tables* which can easily be updated without dealing with other nodes in the network. A route maintenance protocol can use these local routing tables to implement its local recovery procedure to find and use alternative routes.

For adapting MDR to run using AODV, we had to modify the route selection process. DSR does route selection with the knowledge of all alternative paths. In DSR, all paths from the source to the destination are known by the source node together with the C_i (Equation 4.2) values (i.e. remaining lifetimes) of the nodes on the paths. Then, the source node selects the path that has the largest minimum C_i value (max-min selection). But in AODV, there is no full path information available on any node. All of the path structure is distributed over the nodes on the path, and route selection has to be done by the collaborative efforts of the intermediate nodes on the paths.

For implementing route selection on AODV, we have done the following modifications on the base AODV and MDR protocols.

- We added a C_i field to routing control packets, as in MDR with DSR. This field is used in route selection.
- We added support for multiple ROUTE REQUEST packets. In base AODV, every ROUTE REQUEST packet has a BROADCAST ID, and for each BROADCAST ID, nodes only respond to the first ROUTE REQUEST packet, and ignore others (Figure 2.4). However, in CFR, nodes may respond to ROUTE REQUESTs arriving from a source node multiple times.
- We removed the *route cache* mechanism proposed by MDR so that we have routes with latest energy consumption rates.
- We changed the route replacement procedure that prefers *shortest paths.* Our route replacement procedure prefers highest C_i values (largest remaining energy).
- Base AODV constructs *reverse routes* while searching for routes to destinations. But the reverse routes have smaller lifetimes than the forward routes. In CFR, we set the reverse route lifetime equal to forward route lifetime, so that we can use reverse routes during the execution of the CFR maintenance procedure.

You can easily see main modifications on AODV route discovery protocol by comparing Algorithm 4.1 with Algorithm 4.2.

In CFR, a source node that would like to find a route to a destination first generates and broadcasts a ROUTE REUQEST packet. Each neighbor receiving

```
for all ROUTE REQUEST packet P do
    if [P_src, P_bcast_id] exists in Broadcast ID cache then
        Drop the packet
        Continue for the next packet
    end if
    Add [P_src, P_bcast_id] into Broadcast ID cache
    if P_seqno is newer or P_hopcount is better than reverse route then
        Update reverse route with P
    end if
    if Node is P_dst then
        Send route reply
    else if Node have a cache entry for P_dst then
        Send route reply with cache
    else
        Increment P_hopcount
        Broadcast P
    end if
end for
```

Algorithm 4.1: Route Discovery of AODV

```
for all ROUTE REQUEST packet P do
    if [P_src, P_bcast_id] exists in Broadcast ID cache then
        if P_Ci is worse than reverse route then
            Drop the packet
            Continue for the next packet
        end if
    end if
    Add [P_src, P_bcast_id] into Broadcast ID cache
    if P_seqno is newer or P_Ci is better than reverse route then
        Update reverse route with P
    end if
    if Node is P_dst then
        Send route reply {Don't use route caches}
    else
        Increment P_hopcount
        Broadcast P
    end if
end for
```

Algorithm 4.2: Route Discovery of CFR the packet also broadcasts it further. In this way, the ROUTE REQUEST packets arrive to the destination node.

Each node that receives a ROUTE REQUEST packet first reads the C_i information in the packet, and replaces the value if the node has a smaller C_i value. Then node also stores the reverse route information (towards the source node), together with this C_i value. If the node receives a ROUTE REQUEST packet with the same BROADCAST ID again, it compares the C_i value stored in the packet with the C_i of the reverse route established earlier (and stored in the route cache/table). If the packet has a larger C_i value, then the node updates the reverse route stored in the route cache and broadcasts another ROUTE REQUEST.

ROUTE REQUEST packets arrive to the destination with minimum C_i values on their paths. Destination node replies to the first ROUTE REQUEST packet with a ROUTE REPLY packet and stores the reverse route (towards the source node) information together with this C_i value in its route cache/table. If another ROUTE REQUEST packet with the same BROADCAST ID arrives to the destination node, the destination node compares the C_i value of the packet with the C_i value of the reverse route entry stored earlier, and resends a ROUTE REPLY packet if the new request have a larger value. In a ROUTE REPLY packet, the destination node puts its own C_i value into the packet header. This value is updated at each node towards the source so that when the ROUTE REPLY packet arrives to the source, the packet contains the minimum C_i value on the path. Using this information, the source node can select the best path.

Each intermediate node receiving a ROUTE REPLY packet updates its route table entry for the destination node so that the entry includes the C_i value that is largest among all other reply packets received from the same destination.

Finally the source node will receive a ROUTE REPLY packet. Upon receiving the packet, the source updates its route table/cache so that it now has a route table entry for the destination node showing the next node towards that destination. At that time, the source can immediately start the transmission of the packets towards that destination without waiting for the best path information to become available. Meanwhile, if another ROUTE REPLY packet arrives to the source node, the source node compares the C_i value in the packet and in the respective route table entry. If the packet has a larger C_i value, the source node updates the route table entry with the new C_i value and next-node information. This indicates the availability of a better route from the source to the destination. Then the packets are sent from source using the better route. If another ROUTE REPLY is received regarding the same destination, the same procedure is applied again.

4.4 Route Maintenance

There are many route maintenance algorithms with different approaches that try to avoid a route failure or recover from a route failure so that the transmission of packets are not disturbed much. Some route maintenance schemes are described in Section 3.2.

In CFR, route maintenance is triggered when a node on some routing path starts having a low energy level. The maintenance is initiated by that node, which may cause route failure if maintenance is not executed since it has low energy remaining which can be exhausted quite soon. Therefore something has to be done pro-actively if we want the ongoing flows not to be disturbed.

A node that will initiate route maintenance may have reached to its low energy limits; which may be a reason for starting maintenance. Another reason for starting maintenance can be high traffic load on the node. The node may have too much traffic going over itself which causes a high battery drain rate (Equation 4.1) for the node. This situation is signaling an uneven distribution of traffic.

More speficically, nodes in CFR keep track of their C_i (Equation 4.2) values for every T seconds. C_i values indicate the estimated remaining lifetime of the nodes. If the C_i value of a node drops below a certain threshold, the node initiates the route maintenance procedure, which we also call as Backup Route Mechanism.

Backup Route Mechanism is based on modifying the existing routing paths going over the node triggering the mechanism (the critical node), so that all or some of the routing paths will exclude the critical node and will go over alternative paths. The Backup Route Mechanism consists of three main procedures:

- **Flow tracking**: Each node in CFR monitors the packets that it forwards, and builds a flow cache that defines the transmissions going over the node.
- **Flow marking**: When a node needs to start the Backup Route Mechanism, it first informs the nodes residing on the paths of the flows going over this node about the backup process that will be initiated soon.
- **Node exclusion**: The node exclusion procedure tries to find an alternative route that excludes the critical node, without disturbing the ongoing transmission.

Two different thresholds are defined in CFR that are used to decide when to start the Backup Route Mechanism:

- **Reduce Load Threshold**: In CFR a node with high traffic load, or reaching to the end of its lifetime, may invoke a *limited* but less costly maintenance procedure which involves reducing the traffic load on the node. When this threshold is reached, not all flows but only some of them are redirected. This threshold is useful to distribute the load more evenly to nodes in the network.
- **Rescue Node Threshold**: Even we distribute the load of a node after the first threshold is reached, the node will still have some flows going over it, and therefore will still consume energy. Its energy level will continue to decrease, and when it becomes too low (the node is dying), there is need to redirect the remaining on-going flows so that they will not be disturbed when the node dies. We call this threshold that causes the node to transfer all its flows to some other possible nodes as the Rescue Node threshold. In fact, we are not rescuing the node, but its flows. When this threshold is

reached, the CFR route maintenance is executed without any limitations. All nodes in the network may contribute to finding alternative routes for the flows of this node. If alternative route(s) can be found, *all* the flows will start using these routes. In this way, the flows will not get affected from the failure of the dying node.

The limitation on the maintenance protocol for Reduce Load threshold is done by decreasing the maximum hop-count of BACKUP REQUEST packets and selecting only some of the flows for re-routing over some other nodes. The flows are selected for re-routing according to their time of creation. The newer flows are re-routed, whereas the older flows remain to flow over the critical node. Since the critical node has still some significant amount of energy left after the Reduce Load threshold is reached, there is no need to re-route all its flows. Otherwise the node will not be utilized well and will become a free rider. Therefore only some of the flows are re-routed. This reduces the overhead imposed on the network due to the control traffic of the route maintenance mechanism. In our implementation, we define the maximum hop-count as 3, and select half of the flows of the critical node for re-routing. But some other methods can be applied as well.

In some cases the maintenance protocol will not be able to find an alternative route within its limitations, so it will have to continue to carry the flows and transmit packets. But sooner or later it will reach the Rescue Node threshold which has no limitations on searching for alternative routes, and hopefully alternative routes will be found and the flows will be re-routed over these paths and saved.

Next, the main procedures of the Backup Route Mechanism will be described in more detail.

4.4.1 Flow Tracking

For its maintenance procedure, CFR requires information to be maintained about the flows that go over a node. In this way, each node will know which flows exist in

Misc fields	Source IP Address	Destination IP Address	Data

Table 4.1: Key Fields of an IP Datagram

itself to be re-routed during the execution of the maintenance procedure. To keep track of the flows, a node monitors the packets forwarded by itself and examines their IP header information which reveals the source and destination of each packet. Each different source-destination pair can be considered as a different flow. The extracted flow information is stored in a flow database (cache). Each entry in the cache stores information about a different flow, its source node, destination node, the start time, etc. In this way, a node knows which source-destination pairs are using this node for their communication.

Flow tracking mechanism is based on examining the IP packet headers [20, p. 311] (Table 4.1). The IP header of a packet has a source IP address field, and a destination IP address field. These identify the source node the packet has originated from and the destination node the packet is targeted for. After reading the IP header information, the node can identify which pairs communicate with each other through this node, consider it as a flow, and store the respective information in a flow database. (Algorithm 4.3).

for all Forwarding Packets P **do**
  $header \leftarrow Header_{IP}(P)$
  $src \leftarrow header_{source}$
  $dst \leftarrow header_{destination}$
  if Flow Database does not have an entry for $[src, dst]$ **then**
    $entry \leftarrow$ Create New Database Entry for $[src, dst]$
  else
    $entry \leftarrow$ Get Database Entry for $[src, dst]$
  end if
  $entry_{expire} \leftarrow CurrentTime + FlowCacheTimeout$
end for

Algorithm 4.3: Flow Tracking

To have an up to date flow database (to remove flows that no longer sends packets), a timer runs in a node periodically that expires after $FlowCacheTimeout$ seconds. When the timer expires, the flows (entries) that have $ExpireTime$ smaller than the $CurrentTime$ are removed from the cache.

Source	**Destination**	**Creation**	**Expiration**
0	5	1.123	23.623
8	23	12.345	25.345

Table 4.2: A Sample Flow Database

4.4.2 Flow Marking

Before finding an alternative route, CFR first marks the other nodes the flows go through besides the critical node. This is required for node exclusion procedure. Marking is done by sending a packet, called PREP BACKUP, from the critical node to the sources and destinations of the flows.

Field Name	**Description**
type	Type of the Routing Packet (PREP BACKUP)
reserved	Reserved Bytes of AODV
src	Initiator of backup mechanism (Critical Node)
back_dst	Main destination of the flow
bcast_id	Broadcast ID of this request
isSourceSide	Marking Type
min_cI	Minimum required C_i value on the new route

Table 4.3: PREP BACKUP Packet

When a node tries to invoke Backup Route Mechanism, depending on the threshold type, it selects some of the flows going over the node to be re-touted. Then, for each flow, the node sends two PREP BACKUP packets in each direction: one packet towards the source of the flow, another packet towards the destination of the flow (Table 4.3). The *isSourceSide* field of a PREP BACKUP packet is set depending on the direction of the packet. The field is set to TRUE if the packet is sent towards the source, otherwise it is set to FALSE.

Each node receiving a PREP BACKUP packet runs the Algorithm 4.4.

4.4.3 Node Exclusion

As explained in Algorithm 4.4, the node exclusion procedure is invoked by the nodes between the critical node and the source node for each flow going over the

```
for all received PREP BACKUP packet P do
    if P_isSourceSide is True then
        Mark the node as REQUESTER for [P_src, P_bcast_id]
        if Node's C_i value is greater than P_cI then
            Invoke Node Exclusion Procedure with the remaining TTL
        end if
    else
        Mark the node as REPLIER for [P_src, P_bcast_id]
    end if
    Forward the packet to its destination
end for
```

Algorithm 4.4: PREP BACKUP Handling

critical node. Lets call each such node as a *REQUESTER* node. To invoke node exclusion and find an alternate route, a *REQUESTER* node broadcasts a packet called BACKUP REQUEST (Table 4.4). Handling of BACKUP REQUEST packets is described in Algorithm 4.5.

Field Name	**Description**
type	Type of the Routing Packet (BACKUP REQUEST)
reserved	Reserved Bytes of AODV
src	Initiator of Backup Request
src_seqno	Source Sequence Number
back_src	Critical Node
bcast_id	Broadcast ID of this request
back_dst	Main destination of the flow
cI	C_i value of this route request
min_cI	Minimum required C_i value on the new route
hop_count	Hop Count

Table 4.4: BACKUP REQUEST Packet

While trying to re-route a flow to a destination, each node receiving the BACKUP REQUEST packet broadcasts it further so that the packet can reach either to the destination, or to a node between the critical node and the destination that was on the previous routing path. That node should have received the PREP BACKUP packet and therefore can reply to the BACKUP REQUEST packet indicating the availability of a route to the destination.

Nodes can implement a limitation on broadcasting of PREP BACKUP and

BACKUP REQUEST packets using the TTL field of the IP header. This field can initially be set to a certain value (3 in our case) when the PREP BACKUP packet is initiated. Then each node receiving the packet will decrement the field value by one before forwarding (broadcasting) it further. Finally, the TTL value will reach to zero and the packet will be dropped at that node and will not be forwarded anymore. When a node receiving PREP BACKUP packet broadcasts a BACKUP REQUEST, it transfers the the remaining TTL value and range of BACKUP REQUEST packet is limited on the nodes far away from the critical node. This limits the reach of BACKUP REQUEST broadcast packets and can help in reducing the overhead that Backup Route Mechanism imposes over the network.

A BACKUP REQUEST packet has a special field called min_cI. This field is used to guarantee that all of the nodes on the new backup path (re-routing path) will have C_i values that are greater than the C_i value of the critical node. This way backup paths will always be better than the current path that we want to change. Otherwise there is no meaning in changing the path.

for all received BACKUP REQUEST packet P **do**
    if C_i of node is greater than P_{min_cI} **then**
        if Node is not marked for $[P_{src}, P_{bcast\_id}]$ **then**
            Mark the node as $INTHEMIDDLE$ for $[P_{src}, P_{bcast\_id}]$
            Update P_{cI} according to node's C_i value
            Broadcast P again {Search again}
        else if Node is marked as $REPLIER$ for $[P_{src}, P_{bcast\_id}]$ **then**
            Send a BACKUP REPLY packet to P_{src} {Backup route is found}
        end if
    end if
end for

Algorithm 4.5: BACKUP REQUEST Handling

In node exclusion procedure, nodes construct routes to node P_{back_dst} (main destination of the flow), but send replies to node P_{src} (the initiator of BACKUP REQUEST) instead of the main source of the flow, so that newly constructed routes modify the whole path between main source and destination, but only deal with small portion of nodes.

Handling of a BACKUP REPLY (Table 4.5) packet is similar in some aspects to handling of standard CFR ROUTE REPLY packets. A node receiving a BACKUP REPLY packet, first updates the P_{c_I} field and then forwards the packet towards the destination (which is the initiator of the corresponding BACKUP REQUEST packet). When the initiator of the BACKUP REQUEST packet receives the corresponding BACKUP REPLY packet, it can continue transmission of the packets belonging to the re-routed flow by using the new route.

Field Name	**Description**
type	Type of the Routing Packet (BACKUP REPLY)
reserved	Reserved Bytes of AODV
src	Initiator of Backup Reply
dst	Initiator of Backup Request
back_src	Critical Node
back_dst	Main destination of the flow
bcast_id	Broadcast ID of this request
hop_count	Hop Count
cI	C_i value of this route reply

Table 4.5: BACKUP REPLY Packet

4.4.4 Sample Maintenance

In this section we will describe our route maintenance algorithm with an example (Figure 4.2).

- (a): Node F reaches to the rescue node threshold.
- (b): Node F sends PREP BACKUP packets to source and destination. But marks the *isSourceSide* field to `true` for packets sent to the source, and `false` for packets sent to the destination.
- (c): Nodes that receive PREP BACKUP packet, marked as source side (A, C, D), broadcast BACKUP REQUEST packets (some packets are omitted).
- (d): A node that receive a PREP BACKUP packet, but not marked as source side, replies the BACKUP REQUEST and sends BACKUP REPLY packet (H, K).

- (e): Route is modified and the node F is excluded from the path.

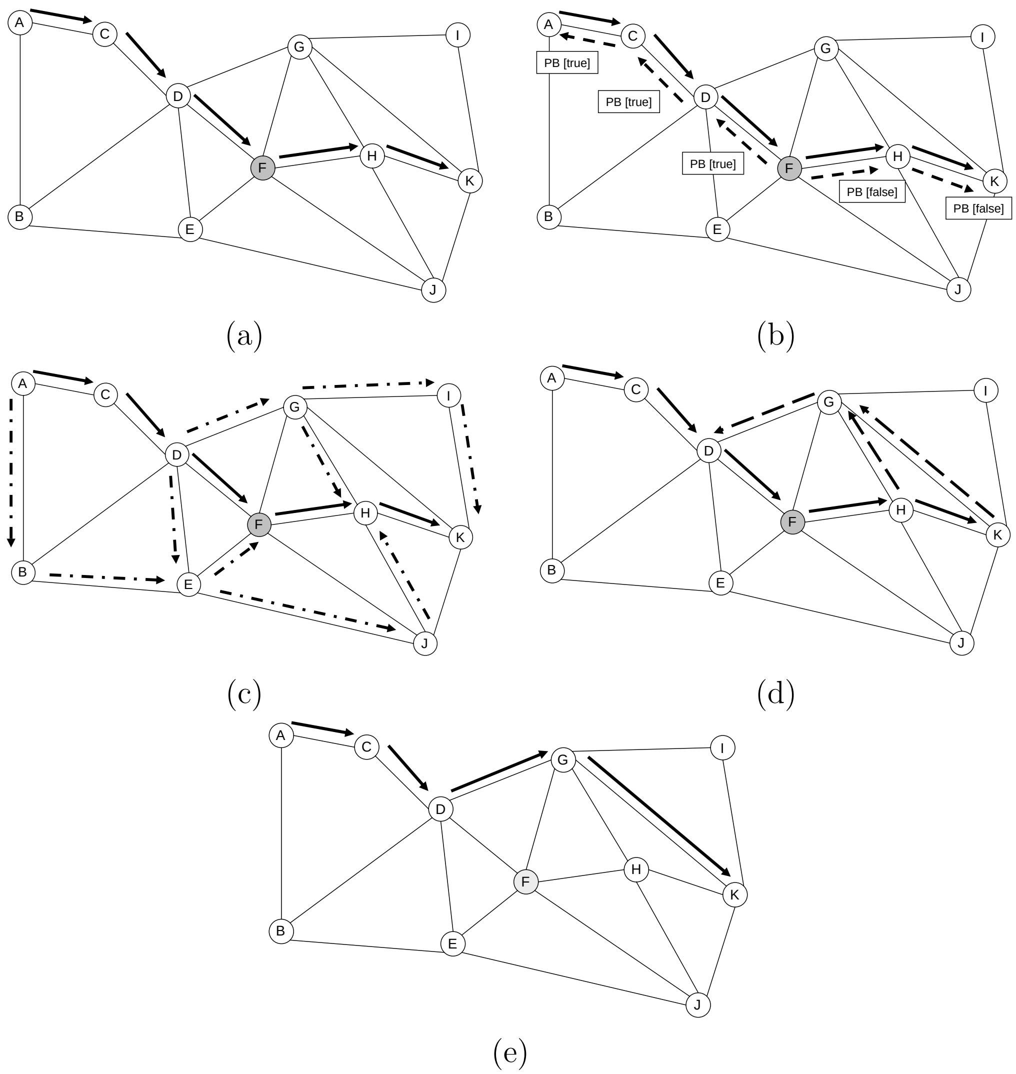


Figure 4.2: A sample CFR route maintenance

4.5 Discussions on CFR

Although we have implemented a complete route discovery and maintenance protocol, some revisions may be required to have optimal performance.

We use the C_i value on all of our routing packets to have the cost of paths on all intermediate nodes. The C_i field is filled on source and destination, and updated on intermediate nodes, but do we really need to use C_i of source and destination? If a source node have a little C_i value and tries to find a path to the destination, all alternative paths will have a C_i value less than or equal to C_i of the source. Then as all paths will have nearly equal C_i values, source can not select the path with maximum lifetime.

CFR selects paths that have minimal C_i value, but it doesn't have a special solution for having two paths with the same C_i value. Modifying the route selection algorithm to prefer shortest paths on equal (or in epsilon range) C_i values, will construct shorter paths and increase the overall lifetime of the network.

CFR protocol is tested and verified by a detailed simulator. All packets and algorithms are implemented nearly equal to the real implementation and their behavior is verified with code debugging and trace files. The evaluation and success rate of the protocol will be described in the next section.

Chapter 5

Evaluation

We implemented the CFR protocol as part of a simulator. The implementation proved the correctness of the protocol and shows that it is feasible to implement the protocol as part of an ad hoc network. Then we evaluated the proposed solution using the simulator. We did extensive simulation experiments. In this section we will report the results of those experiments and our findings. We will first describe our simulator.

5.1 Simulator

There are different ways of evaluating a new protocol. We can implement it on a real testbed, simulate it, or use mathematical models to analyze it. Since the implementation requires many ad hoc computers to use and therefore is costly, we decided to use simulation as our evaluation methodology.

We had two options to develop a simulator for simulating our protocol:

- *Writing a simulator from scratch*: This is generally the most difficult road to take. Since the simulator should be detailed enough to capture the real-life system and scenario, it will take too much time and effort to develop such a detailed simulator. All common algorithms and components used in many simulators have to implemented as well, such as the event processing engine.

- *Using a simulation library or platform*: There are many simulation libraries available providing the essential components already. A simulator then can be written using such a library, implementing only the parts necessary to simulate the protocol. But in this case, the developer should spend time on learning how to use the features of the library and also he/she is restricted with the capabilities of the library. If the library is not open source, those capabilities can not be modified.

We decided to follow the second approach. Since we would like to simulate a wireless ad hoc network routing protocol, it would be better if we have a tool/library simulating wireless channels and low level protocols related to wireless links, like the MAC protocol. Additionally, since we are interested in performance metrics like average packet delay, jitter, etc.; our simulator should be a packet-based simulator (instead of being a flow based simulator). A packet-based simulator keeps track of every packet sent in the network. Hence it can give quite detailed results. But some other course-grained simulator, like a flow-based simulator, can just simulate the establishment of flows with some duration, but can not simulate the behaviour of packets, hence can not give the detailed results that we are seeking.

Therefore, we selected **NS-2** (The Network Simulator) [8] as the base simulator into which we implemented our protocol. It is a widely accepted and trusted simulator.

NS-2 is an open-source software developed with C++. It enables scripting with TCL language and supports new protocol implementations. NS-2 is developed for simulating computer networks and have many ready-to-use features that simulate real-world networks accurately.

NS-2 has built-in support for simulation of ad hoc networks. CMU Monarch Group [4] implemented many ad hoc routing protocols into NS-2 and have made

```
r -t 0.01681 -Hs 22 -Hd -2 ... -Is 16.255 -Id -1.255 -It CFR ... REQUEST
r -t 0.01681 -Hs 24 -Hd -2 ... -Is 16.255 -Id -1.255 -It CFR ... REQUEST
s -t 0.01683 -Hs 22 -Hd -2 ... -Is 22.255 -Id -1.255 -It CFR ... REQUEST
s -t 0.01700 -Hs 22 -Hd -2 ... -Is 22.255 -Id -1.255 -It CFR ... REQUEST
...
d -t 0.01934 -Hs 9 -Hd -2 ... -Is 10.255 -Id -1.255 -It CFR ... REQUEST
...
s -t 0.02029 -Hs 15 -Hd 14 ... -Is 15.255 -Id -1.255 -It CFR ... REPLY
```

Table 5.1: Some lines from a sample trace file taken from NS2 Simulations

them publicly available as part of NS-2 distributions.

The main problem with NS-2 simulator is the difficulty in learning its environment and implementing new protocols. NS-2 is an open-source project and do not have a strict software architecture and well documentation. Many people contributed on the project, have implemented their solutions without any coding guidelines or other team management solutions, and many of the features still do not have any documentation. Therefore, in the beginning, it is quite hard to implement a new protocol into NS-2 environment. But after the learning period, it becomes feasible, and use of NS-2 brings lots of advantages. We implemented our CFR protocol by modifying CMU's AODV implementation with the help of many tutorials [14] and manuals [27].

The CFR protocol is based on MDR route discovery protocol; so we first applied the MDR algorithm on AODV and got a simulator of MDR with AODV. Then we applied the CFR maintenance algorithm on MDR and implemented the CFR simulator.

The results we will report are extracted from the detailed trace data generated by NS-2 (Table 5.1). During a simulation run, NS-2 traces the transmission of every packet between layers and between nodes. Therefore, the size of the trace data can get too large, in the order of gigabytes, even for a single run. Therefore it is impossible to read and analyze the trace data by eye. We used the tool Trace Graph [23] for analyzing these trace files and extracting information from them. Trace Graph can produce many different graphs and results.

We implemented scripts that run the simulator for different scenarios and random number seeds (Algorithm 5.1). For the output of the Trace Graph tool, we implemented a small software that reads files for different seeds of a scenario and protocol, and calculates the average values. Then we used these average values as part of results we report in this chapter.

```
for all Simulation Scenarios S do
    for all Protocols P (CFR, AODV, MDR) do
        for seed = 1 to n do
            Run NS with P for S on seed
            Run Trace Graph on output of NS-2
            Store Trace Graph output
            Delete trace files of NS-2
        end for
    end for
end for
```

Algorithm 5.1: Simulation Script

5.2 Scenarios

We evaluated our protocol by comparing it to the other similar ones for the same set of scenarios and parameters. We compared CFR against *base AODV* [26], and *MDR [19] with AODV*. All of the scenarios are repeated with the same parameters for all three protocols.

As the initial energies of nodes, in all scenarios, we used a random value to better reflect the real-life case. All of the nodes except the source and destination of the flows, have an initial energy between 0.01 Joules to 100.0 Joules. All the source and destination nodes are given 40.0 Joule of initial energy to prevent a failure during transmission.

We used a fixed seed for the random number generator to get the same network environment for all the algorithms and to compare them in an equal setting; but we repeated the simulations with different seed values and we averaged the results. We report these average values in next chapter.

All simulations were done on an AMD 2000+ computer with 1 GB of RAM. The computer worked nearly 4 weeks full-time to get these results. Most of the time is taken by the trace analyzer tool, Trace Graph [23]. The software has an optimized version, but it is not freely distributed.

For all of the following scenarios, nodes are placed 1.5 meters above the ground and use parameters of 915 MHz Lucent WaveLAN DSSS radio interface. The simulator uses Two-Ray Ground propagation model with Omni-Directional antennas.

As the traffic source, constant bit rate (CBR) generator is used. The MAC protocol is IEEE 802.11 MAC protocol.

We formed a network of 49 nodes having a 7x7 matrix topology with 150 m distance in between. Nodes in the network are only able to communicate with their neighbors around (see Figure 5.1).

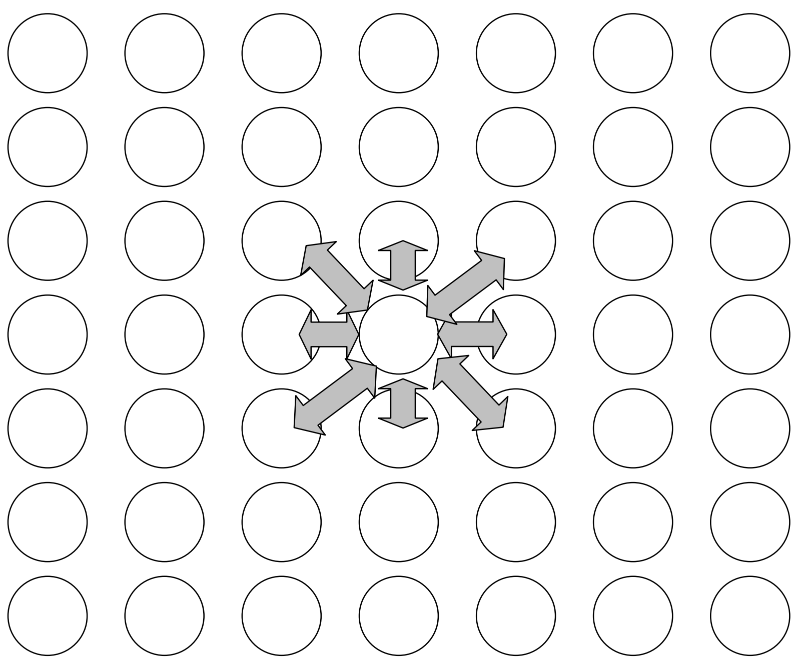


Figure 5.1: Network Topography and Connectivity of nodes

We defined three different flow (connection) scenarios in our simulations (Figure 5.2):

- **One Diagonal Flow (1D)**: A single node sends packets to a destination (a single flow). Nodes on the path are placed diagonally and there is no other effect on the transmission continuity other than the nodes' lifetimes.

- **Two Diagonal Flows (2D)**: Two flows are placed diagonally that will intersect each other. The intersecting nodes will have greater battery drain rate.
- **Two Diagonal and Two Linear Flows (2D2L)**: Four flows are placed; diagonally and vertically/horizontally. These four flows will intersect on some nodes and those nodes will have bigger load and therefore their batteries will drain faster.

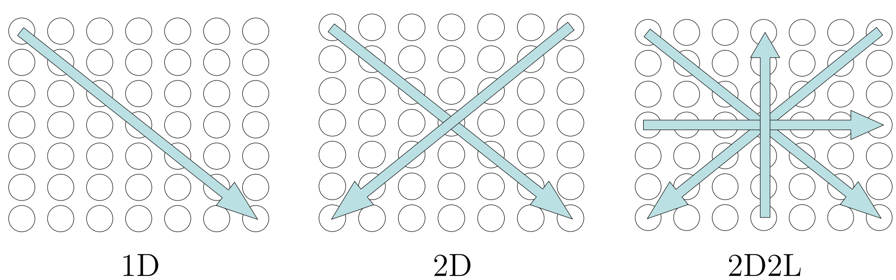


Figure 5.2: Simulation scenarios

Since we are more interested on the effect of our protocol to multimedia traffic, our traffic source generated traffic resembling to the characteristics of some multimedia applications. Our traffic source for a flow sends packets with 20 ms interval between packets. We also change the packet size as 160 bytes, 640 bytes, and 2560 bytes. This translates to flow bit-rates of 64 Kbps, 256 Kbps, and 1 Mbps, which is reasonable for a multimedia traffic.

We set some of the parameters of the CFR protocol as shown in Table 5.2:

Parameter Name	**Value**
Reduce Load Threshold	0.05 (Unit of C_i)
Rescue Node Threshold	0.01 (Unit of C_i)
Reduce Node Backup Route Request TTL	3
Calculate C_i interval	50 ms
Flow Cache Timeout	500 ms

Table 5.2: CFR Parameters

5.3 Results

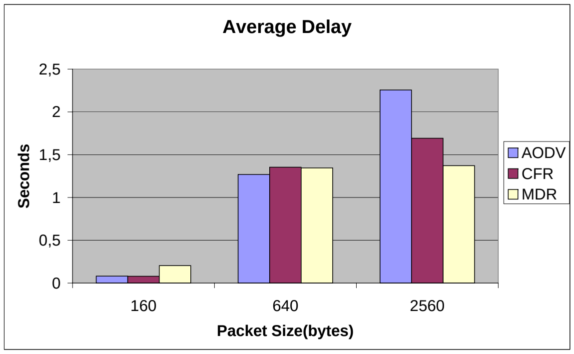
5.3.1 End-to-End Delay

End-to-end delay is the time spent between a packet's transmission from the source and its arrival to the destination. The end-to-end delay gets affected from many things: network condition, link states, buffer states, traffic load, the MAC protocol, and the routing protocol. Here we are interested in the effect of routing protocol on the end-to-end delay packets experience. In ad hoc networks, the routing protocol is responsible for selecting the paths; and the lengths of the paths, the current conditions of the paths, route failures and re-routing all affect the end-to-end delay.

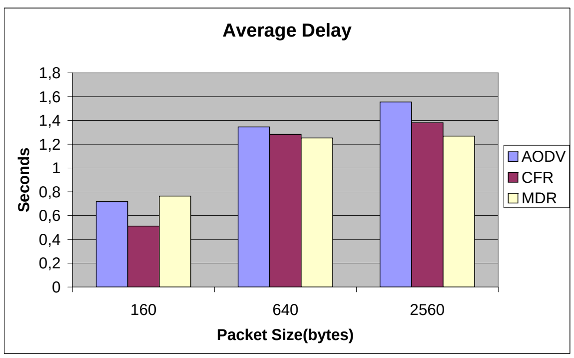
In this thesis, we propose a routing algorithm whose primary objective is not to select the shortest paths, but to select paths that are more stable. Hence when there is no route failures, the average end-to-end delays the packets experience may be little bit larger than the protocols that always select minimum-hop paths, or minimum-delay paths. However, considering also the route failures, a protocol that tries to minimize the route failures can also gain advantage for the average end-to-end delay, since each route failure increases the delay packets experience during the respective route repair. Therefore it is not always obvious which protocol will perform better in terms of average end-to-end delay without doing a careful simulation study.

As Figure 5.3 shows, CFR and MDR give better results than base AODV routing protocol in terms of end-to-end delay. Both of these protocols try to find more stable routes, and in a scenario where we have route failures in a quite big network, the benefit of stability comes into picture and we observe lower average end-to-end delay. However, if we compare CFR and MDR there is no significant difference between them in terms of end-to-end delay.

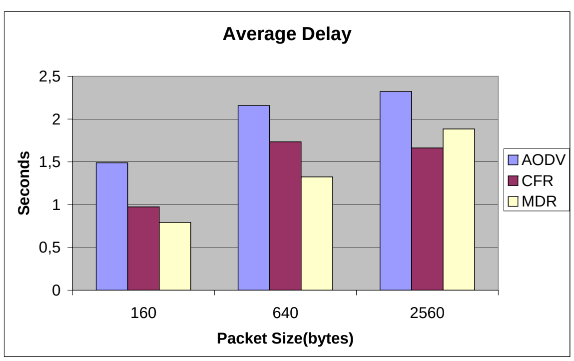
The success of CFR and MDR compared to base AODV is more clearly seen when we examine the maximum (worst case) end-to-end delay. Figure 5.4 shows the differences for different number of flows and packet sizes. The maximum delay



1D

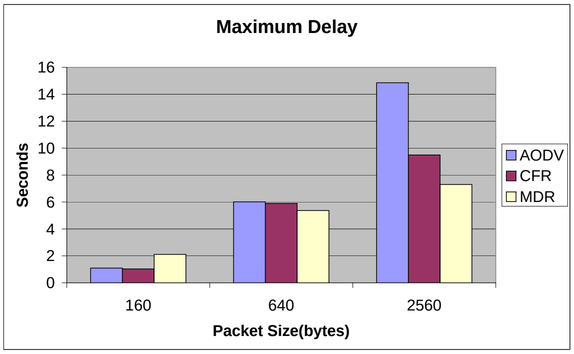


2D

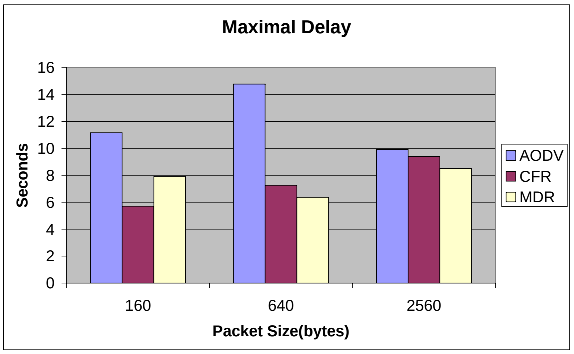


2D2L

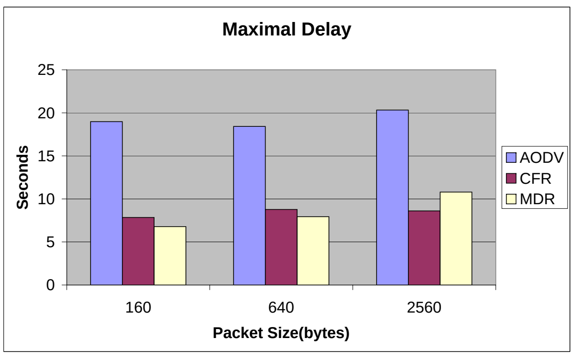
Figure 5.3: Average Delay Results



(a)



(b)



(c)

Figure 5.4: Maximum Delay Results

is large in AODV, because base AODV does not apply a proactive maintenance algorithm, and this may incur too high delay on packets when a route fails and route discovery is started to find a new route. During this time, packets can be lost as well, if buffers are filled up. In CFR, we follow a proactive approach and find a new route before an existing route completely fails.

The difference between AODV and other protocols on average delay is not as big as on maximum delay, because AODV always finds shortest available paths and other protocols try to find the most stable routes which can be longer.

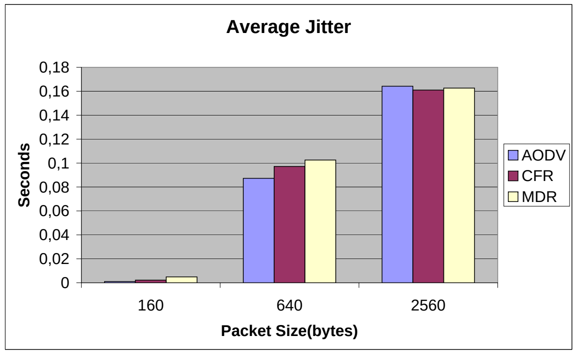
Compared to MDR, CFR does better in some scenarios but does nearly equal in some others because its route discovery scheme is an adapted version of MDR. CFR implements maintenance on MDR.

5.3.2 Delay Jitter

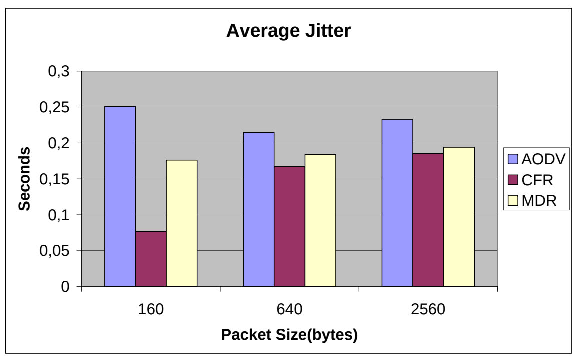
Delay jitter is variation in end-to-end delay. If the end-to-end delay is fixed, it is easy to handle; but if it varies, then the audio/video player at the received side should compensate for the jitter while playing the media. For this compensation, a jitter buffer can be used. A higher jitter requires a bigger buffer. Therefore it is better if we have low jitter for packets.

Any change in a network condition, or a route failure affects the delay experienced by packets of an ongoing flow; therefore generates jitter. If we reduce the variations on network conditions, or route failures, then we can also stabilize the jitter. Hence we expect lower jitter for protocols that are more stable.

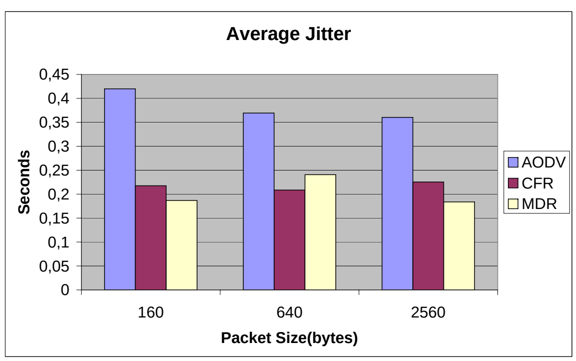
This is indeed what we observe in our results. As shown in Figure 5.5, base AODV protocol has much larger jitter than CFR and MDR protocols, since base AODV does not apply a proactive route maintenance scheme. Whenever a route failure occurs, it starts route discovery again at that time. This causes too much delay for packets that are generated at the source at the time of new route discovery.



1D



2D



2D2L

Figure 5.5: Average Jitter Results

CFR does better than MDR on some cases. CFR is more successful on jitter results, because its maintenance algorithm pro-actively protects flows from getting disturbed from route breaks.

In the following figures, we show the packet-delay versus time graphs, so that we can have an understanding of how the delay changes over time while a simulation run is executed. We first show the results for 1D flow; then for 2D flows.

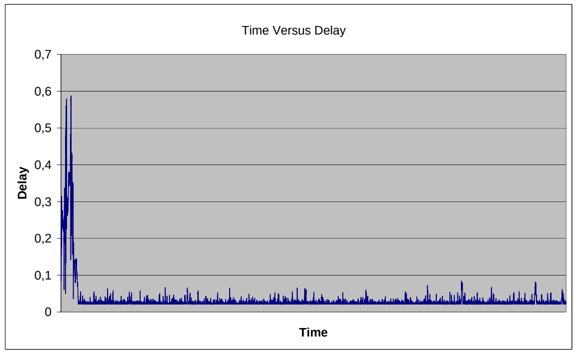
Figure 5.6 shows the delay versus time graphs for the scenario where we have only one flow for all three algorithms. As can be seen from the figure, the CFR protocol causes high delay values only during the initialization time. But in AODV and MDR we see many peaks in the graphs indicating high packet delays from time to time.

Figure 5.7 shows the delay versus time for the scenario where we have two flows in the network. This time CFR also has peaks, but not that much as AODV or MDR.

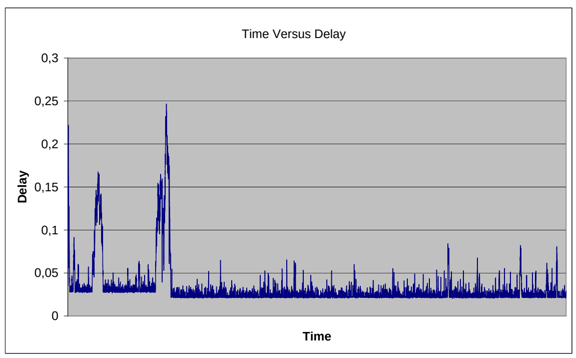
5.3.3 Packet Loss

Packets may dropped/lost in a network due to several reasons: a) collisions may occur at the MAC layer; b) unrecoverable bit errors may occur during transmission through a channel; c) buffers on nodes may get filled up and can not hold new incoming packets.

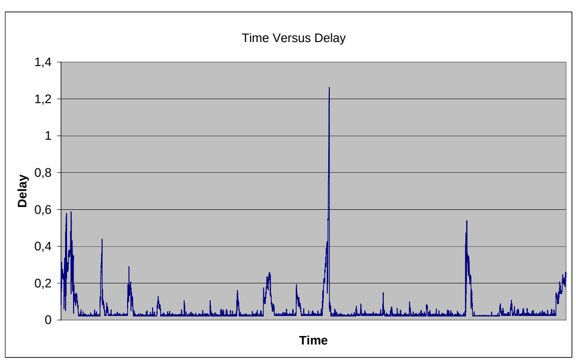
The operation of a routing algorithm can be effective in triggering the reason c). During a route failure, the packets generated by the source node will not be routed until the new route is constructed. Additionally, when the source node (or the node requesting backup route) understands that a failure has occurred, it can stop sending packets, and this will cause its buffer to fill up, and finally the packets generated by the traffic source will not be stored in the buffer and will be dropped.



(a)

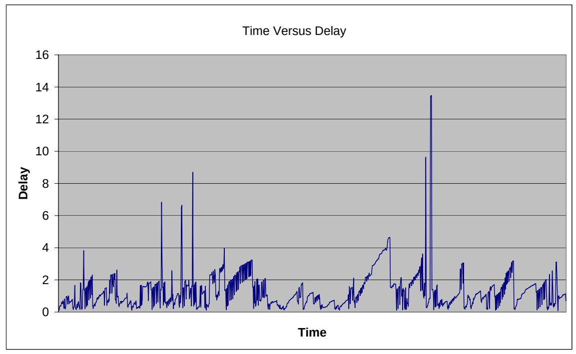


(b)

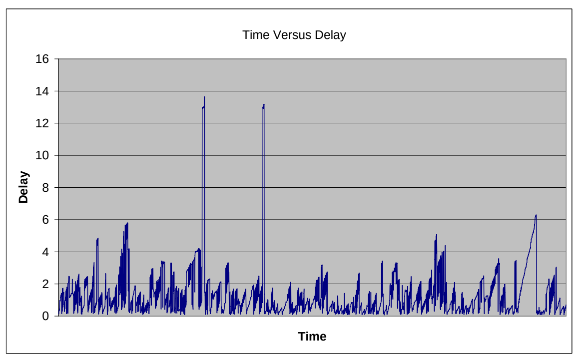


(c)

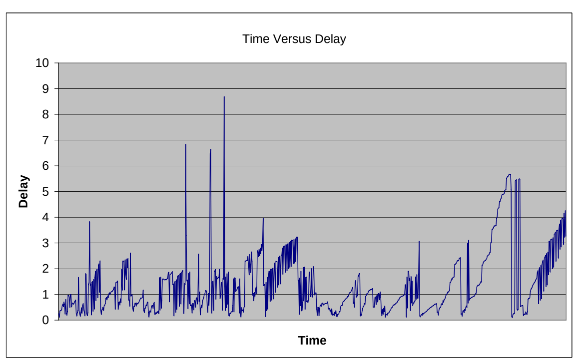
Figure 5.6: Time vs. Delay Values on 1D Simulations (a: CFR b: AODV c: MDR)



(a)

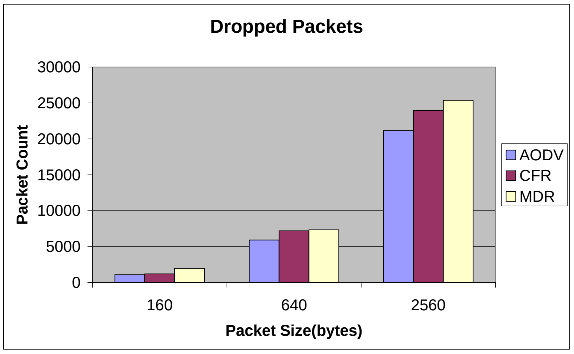


(b)

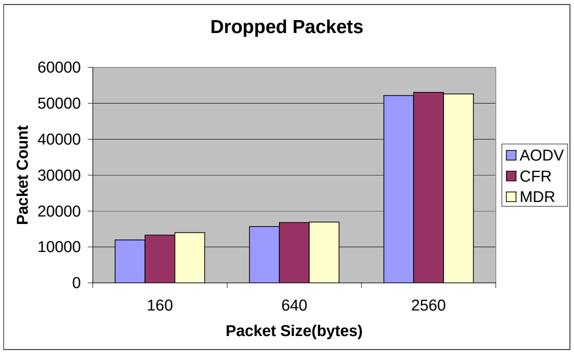


(c)

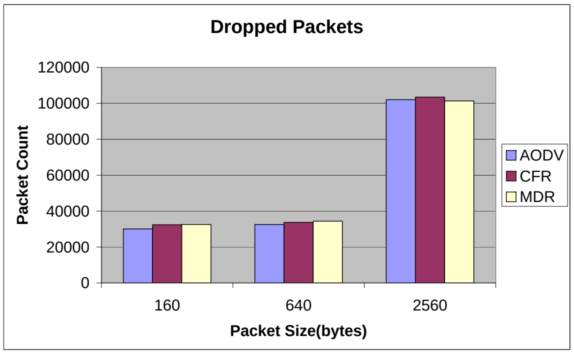
Figure 5.7: Time vs. Delay Values on 2D Simulations (a: CFR b: AODV c: MDR)



1D



2D



2D2L

Figure 5.8: Dropped Packet Results

We expect a routing protocol that is more stable to have less packet losses. But this is not something that we observed in our simulation results. We observed that all of three protocols we simulated have similar number of packet losses. This was not something that we expected. This may be due to the scenarios that we have used. Those scenarios may not have caused a heavy buffer overflow at the source due to route failures. This is something we will investigate further as part of future work.

5.3.4 Routing Control Packet Overhead

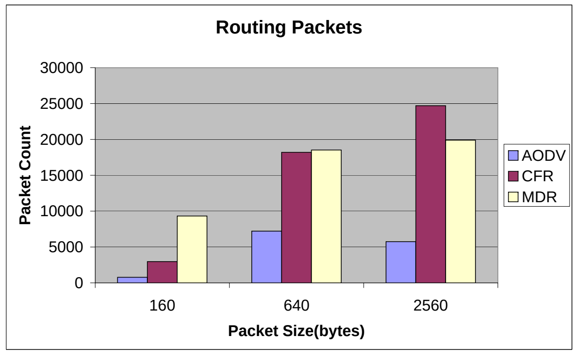
For a routing protocol, route construction and maintenance requires some control and management packets to be sent and received. This is the overhead imposed on the network, since those packets do not carry user information. For any routing protocol, routing overhead should not be too large. Otherwise, it means we are not utilizing the network resources well.

We measured the number of routing related control messages sent in the network for all the three routing algorithms that we compare. Figure 5.9 shows the results.

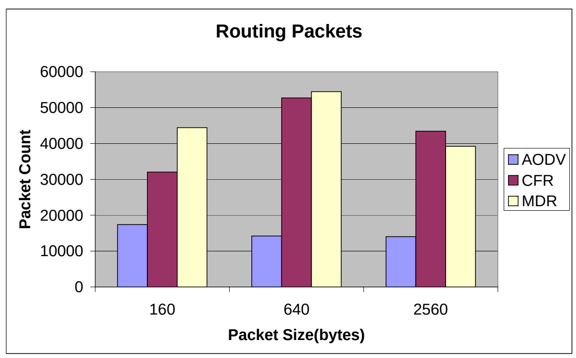
As the Figure shows, the AODV protocol, that does not apply a proactive route maintenance, has the least overhead. This is an expected result since AODV protocol is not using control packets for proactive maintenance and uses shorter paths during route discovery. The overhead of CFR and MDR protocols, on the other hand, are nearly the same, but CFR performs slightly better.

5.3.5 Effect of Packet Inter-Arrival Time

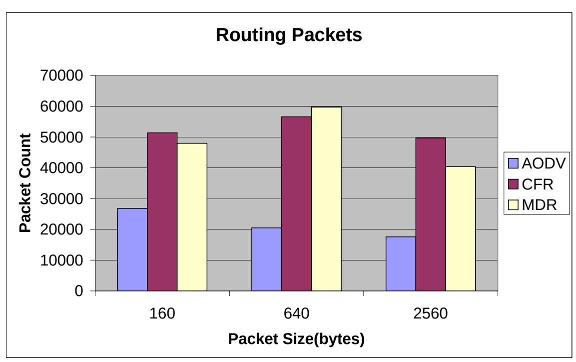
Previous results are taken while packet inter-arrival time is fixed to 20 ms. Packet inter-arrival time affects the rate of traffic injected into the network, therefore can be effective in filling the buffers sooner, causing more collisions, and increase the delay further. This is indeed what we observe in our results which are shown in



1D



2D



2D2L

Figure 5.9: Routing Overhead Results

Figure 5.10.

To speed-up simulations to get these results, we used 16 nodes which have a 4x4 matrix topology, with 0.01 to 10 joules of energy on nodes. We used the 2D scenario where we have two flows in the network.

As the figure shows, when the interval gets smaller (more traffic), the average delay and jitter increases. For this particular result, we see that AODV performs better when the interval is quite small. In this case we used a small network where the average path length is very small. Therefore, AODV can establish a new route very fast and we don't see the benefit of proactive maintenance. But when interval gets bigger, we again see that AODV has much larger average delay and jitter with respect to the two other protocols.

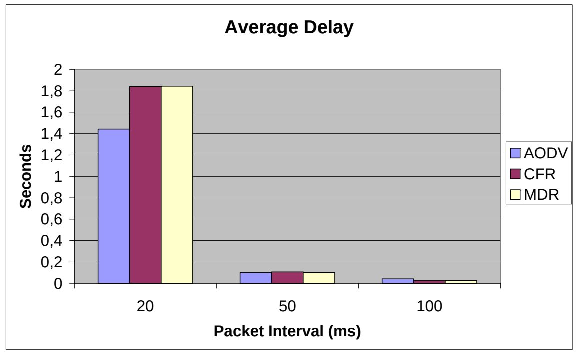
5.3.6 Results with Randomly Located Flows

We also wanted to observe results if we use random flows generated at arbitrary nodes in the network. In this scenario, we used a 50-nodes network. We construct 3 random node placements with 3 different connection patterns and run all combinations with 5 different seeds. Table 5.3 presents the results.

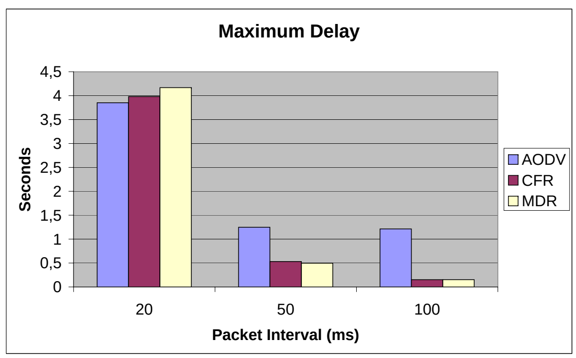
Measure	AODV	CFR	MDR
Average Delay (sec)	0.382	0.329	0.342
Maximum Delay (sec)	3.635	2.363	2.107
Average Jitter (sec)	0.0575	0.0569	0.0492
Dropped Packets (packets)	13676	14011	13836
Routing Packets (packets)	976	1462	1395

Table 5.3: Random Scenario Results

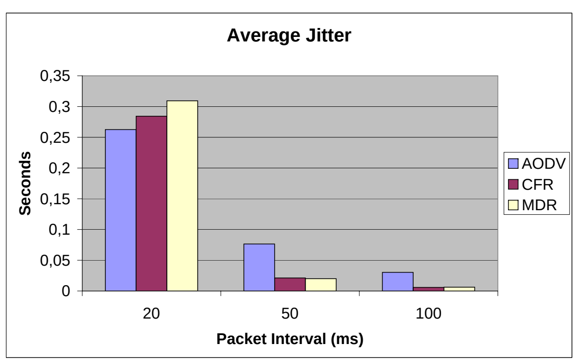
With random scenarios, we have the same conclusion that we have from our previous results. AODV has higher delay and jitter. CFR and MDR has nearly the same delay and jitter. CFR delay result is slightly better. The overhead of AODV is less than the overhead of CFR and MDR.



(a)



(b)



(c)

Figure 5.10: Packet Delay Results on Intervals

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In this thesis we propose an ad hoc network route discovery and maintenance solution (called CFR) which aims to support multimedia applications by reducing the adverse affects of route failures and high load on these applications. The proposed solution tries to find stable routes. A stable route is defined as the route with maximum lifetime left, considering the current energy levels and current battery drain rates of the nodes on the route.

CFR protocol finds routes with maximum lifetime during route discovery phase and also implements a proactive route maintenance scheme that re-routes multimedia flows from paths with low energy so that the flows are not disturbed by nodes that have very few energy left and will die soon. To decide when to trigger the maintenance, the protocol uses two different thresholds. One is used to distribute a high load that a node has to its neighbors; the other is used to re-route the whole traffic (all flows) that a node has through its neighbors or some other paths. The study proposes a scheme for finding alternative better routes when a flow has to be re-routed.

We evaluated our proposed protocol via simulation. We implemented the protocol as part of the NS-2 simulation environment and did extensive tests for testing whether the protocol is working correctly or not. After verifying and validating the protocol and its simulation, we did extensive simulation experiments to evaluate the protocol and compare it against some other similar protocols, such as AODV and MDR.

The simulation results show that, CFR and MDR together have better results than AODV in terms of average packet and jitter. However, AODV incurs less overhead on the network since it does not implement a proactive maintenance procedure. CFR is better in some cases compared to MDR; but in some other cases they perform very close to each other; and in some cases MDR performs better. In short, simulation results indeed show that CFR can be a good candidate as a routing and maintenance protocol that supports multimedia traffic in a wireless ad hoc network.

6.2 Future Work

We see many issues about CFR that can be improved with further study.

CFR is a routing protocol for optimizing route performance depending on the energy state of nodes in the network, but energy is not the only problem for an ad hoc network. They generally consist of mobile nodes, which we didn't consider in CFR protocol. Finding most stable routes requires finding paths which consists of most stable nodes. CFR route discovery and maintenance protocol can be extended to have mobility in mind. Using mobility detection and active node selection procedure of ARMP [3], we can extend CFR to have stable routes that are resistant to node movements.

The thresholds and the lifetime calculation period for nodes are set to some fixed values in the currrent protocol implementation. An adaptive scheme, however, can be applied and this may improve the performance and the ability of the protocol to adapt to changing network conditions.

In CFR, there is no collaboration among nodes to implement a better maintenance. There are some cases where individual route maintenance may harm the network, or collaboration may find better backup routes:

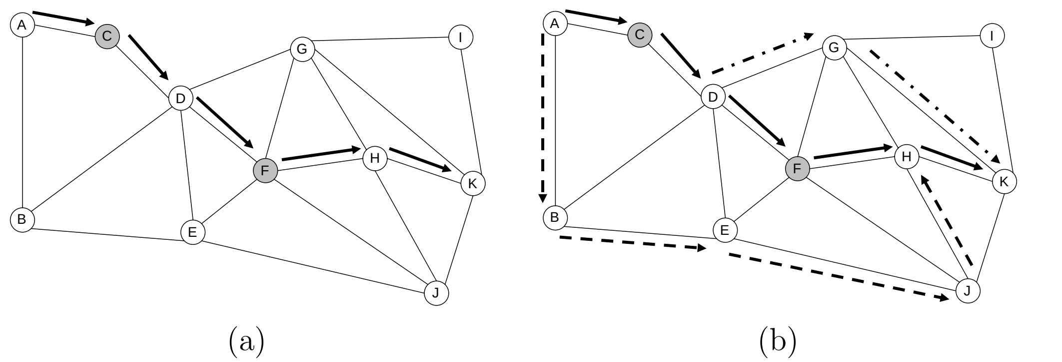


Figure 6.1: A sample for overlapping backup routes: (a) Initial route with two critical route, (b) After maintenance is applied

- Finding backup for two nodes: If two nodes on a route require a maintenance procedure at the same time, then a single backup route that covers both of the nodes might be more efficient. In current situation, the protocol triggers two backup routing finding operations, hence will lead to two new sub-routes to be established.
- Overlapping backup routes: Two nodes on a route may initiate a maintenance process and their backup routes may overlap (Figure 6.2).

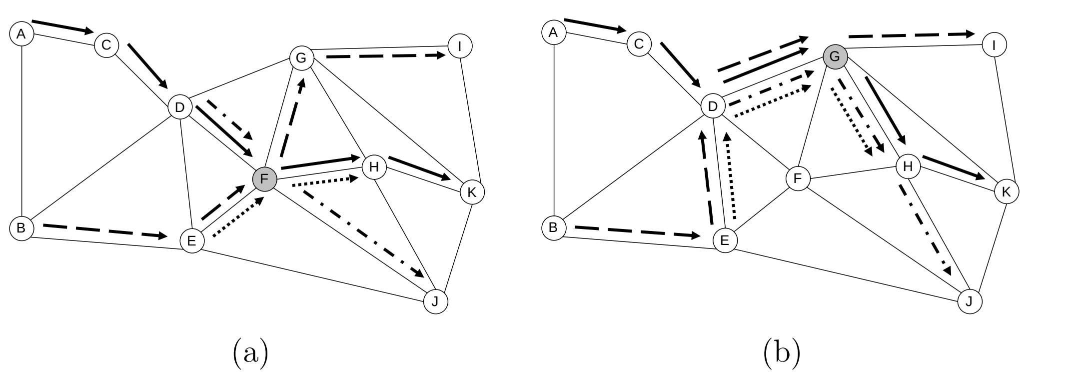


Figure 6.2: A sample for fluctuation of backup routes: (a) Node F has a high load, calls maintenance, (b) Now node G has a high load and it will call maintenance

- Fluctuation in backup route finding process: A node with high load will request a maintenance and reduce its load, but this time a neighboring node might get a high load and initiate another maintenance, which will send more traffic to the first node again. This can continue causing a fluctuation of routes (Figure 6.2).

We can also improve our evaluation of CFR protocol to better reflect the network characteristics and increase the understanding of protocols.

CFR is implementing a stability solution for energy levels of nodes, but what about total energy level of the network. MTPR [29] tries to reduce the total cost of a route on the network, but CFR and most of the other routing protocols do not care the total network energy. We could evaluate our protocols with the change in the total energy level and see their performance. This kind of a graph could introduce very interesting results and let us discuss our protocols with a different aspect.

In our evaluation we measured the packet loss rate and got the nearly same results on all protocols. But according to special handling mechanisms of CFR and MDR this shouldn't be the case. In a network a packet can be dropped because of:

- Buffer Overflow
- Node Failure
- Channel Error
- MAC Collisions

The number of packets dropped by these reasons should be different on our simulations. We should look at the trace files and investigate the reasons of packet drops to better understand the characteristics of our protocols.

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Appendix A

Table of Acronyms

1D	One Diagonal Flow
2D	Two Diagonal Flows
2D2L	Two Diagonal and Two Linear Flows
AMD	Advanced Micro Devices
AODV	Ad Hoc On-Demand Distance Vector Routing
ARMP	Active Route Maintenance Protocol
CBR	Constant Bit Rate
CFR	Continuous Flow Routing
CMU	Carnegie Mellon University
CSR	Clusterhead Gateway Switch Routing
DSDV	Destination-Sequenced Distance-Vector Routing
DSR	Dynamic Source Routing
DSSS	Direct-Sequence Spread Spectrum
FTP	Filet Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
LAN	Local Area Network
Kbps	Kilobits per second
MAC	Medium Access Control
Mbps	Megabits per second

MDR	Minimum Drain Rate Mechanism
MHz	Megahertz
MMBCR	Min-Max Battery Cost Routing
MTPR	Minimum Total Transmission Power Routing
NS	Network Simulator
QoS	Quality of Service
RAM	Random Access Memory
RTO	Retransmit Timeout
SSA	Signal Stability Based Adaptive Routing
TCL	Tool Command Language
TCP	Transmission Control Protocol
TORA	Temporally Ordered Routing Algorithm
UDP	User Datagram Protocol
WLAN	Wireless Local Area Network
WRP	The Wireless Routing Protocol