Route Optimisation in Mobile Ad-Hoc Networks

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Abstract

In this essay, we present a mobile ad hoc network, its characteristics and its constraints, we show how routes within networks are optimised in terms of proportionally fair rate allocation and resource control based on congestion pricing and we establish the stability and the performance of static and mobile networks respectively, by simulating a model of ad hoc network simulator, which uses the Desmo-J framework.
1. Introduction

In areas in which there is little or no communication infrastructure or the existing infrastructure is expensive or inconvenient to use, wireless mobile users may still be able to communicate through the formation of an ad-hoc network \([1]\). Kelly et al. \([2]\) present a model for the operation of a mobile ad hoc network where the nodes cooperate to form the necessary infrastructure that makes multi-hop communications possible. Unlike cellular telephony networks and IEEE 802.11 wireless networks in infrastructure mode which relay their inter-cell traffic via a base station, ad hoc networks do not have a base station.

Transmission energy restrictions prevent a node in an ad-hoc network from communicating with a distant partner. Instead, each node forwards traffic received from other nodes. Traffic is thus forwarded from a source node via one or more forwarding (transit) nodes to a destination node. However, transit nodes expend energy and bandwidth when forwarding traffic, and unless they receive a reward for doing so, they may choose not to act as transit nodes.

A system of incentives to promote collaboration in ad hoc networks is presented in \([2]\). The incentives are formulated in terms of congestion-based prices for the consumption of bandwidth and power. These prices encourage suitably located nodes to carry transit traffic, since by doing so, despite expending energy on transceiving traffic, they earn credits which they need in order to send their own traffic. The pricing mechanisms are also used to determine energy-efficient routes.

In our work, we study Kelly’s model and we present some fundamentals of mobile ad-hoc networks. We define a mobile ad-hoc network and give some examples of their use. We present some characteristics and show how traffic flows behave on different routes of a mobile ad-hoc network. Next, we study the capacity constraint and energy management of the network according to Kelly’s model.

In the third chapter, we study how congestion-based price functions are developed from their original formulation in optimisation-based flow control.

First, we define a pricing framework, by describing how a system’s optimal rate problem can be decomposed into two simpler problems. One involves the maximization of user’s utility subject to its willingness-to-pay and is known as the user’s utility maximization problem. The other involves the fairness allocation of rate flows, the network optimisation problem. We present the way prices along routes are defined, the equations describing the dynamic adaptations of power and bandwidth prices, as well the discount of the credit balance. Secondly, we present how the network’s resources, namely bandwidth and power, are used.

Last, we examine how the network’s resources are controlled according to the congestion prices in terms of resource usage and power consumption.

In the fourth chapter, we present a simulation of the mobile ad hoc network. This simulator uses the Desmo-J simulation framework \([3]\) to reproduce the results presented by Kelly for the bandwidth and power prices, and for the credit balances. To reproduce this result, we consider a static network, and also a mobile network in the case where one node is moving toward the
centre of the network.

Note that according to Kelly’s paper, we use in this work the terms node and user interchangeably. The term user is more closely associated with a person who desires to send traffic to other users in the network and pays congestion costs for doing so. In comparison, the term node has a topological meaning, in terms of position, velocity, capacity constraints and routing.
2. Mobile Ad-Hoc Networks

2.1 Fundamentals of Mobile Ad-Hoc Networks

A mobile ad-hoc network is a temporary network formed by a collection of dynamic wireless nodes in the absence of an existing infrastructure or a centralized administration [1].

Examples of the uses of an ad-hoc network include:

- Students using laptop computers to participate in an interactive lecture,
- Business associates sharing information during a meeting,
- Emergency disaster relief personnel coordinating efforts after a hurricane or an earthquake [1].

2.1.1 Modelling

A mobile ad-hoc network can be modelled by a graph $G_t = (V_t, E_t)$ where:

$V_t$ is a set of mobile nodes that are equipped with directional wireless antennas with $N = |V_t|$ being the number of nodes at time $t$ [2] and $E_t$ models the set of all connections between nodes at time $t$.

If $e = (u, v) \in E_t$, it means that nodes $u$ and $v$ can communicate directly at time $t$ [4].

2.1.2 Characteristics of Ad-Hoc Networks

A mobile ad-hoc network is characterized by nodes which are autonomous and dynamic.

Nodes rely on each other to establish communication, thus each node acts as a router, and must be willing to forward traffic for other nodes, and in this way expends energy and bandwidth without receiving any direct gain from doing so.

In a mobile ad-hoc network, a packet can travel from a source to a destination either directly, or through a set of intermediate packet forwarding nodes. If a node only considers its own short-term utility, then it might choose not to participate in forwarding traffic within the network.

Thus, for effective collaboration the concept of incentives was introduced into the network’s infrastructure. This leads to the use of pricing mechanisms, by which nodes recover costs associated with bandwidth and energy [2].

Nodes in a mobile ad-hoc network are mobile, which causes network topology to change rapidly and unpredictably.
Traffic flow between any two nodes can be seen as a movement of packets between them. This is possible within the network only if a route exists between those two nodes.

The node which sends traffic is called a source, and the one which receives traffic is called a destination. A set of routes between each source and destination pair is determined, where a route \( r \in V_t \) is a non-empty subset of the set of nodes.

Define \( R \) as the set of routes within the network, we can define \( R^S(s) \) as the subset of routes that originate at source \( s \), and \( R^D(d) \) as the subset of routes that terminate at destination \( d \).

If we consider a traffic flow at a specific point in time, each source is transmitting a total amount of traffic \( x_s \). This may be split between different routes \( r \in R^S(s) \), as shown in the following figure (2.1):

![Figure 2.1: Total flow at node \( x_s \)](image)

The traffic flow along a particular route \( r \) is given by \( y_r \), where \( y_r \geq 0 \) and

\[
x_s = \sum_{r \in R^S(s)} y_r \tag{2.1}
\]

The variable \( x_s \) represents the total flow originating at node \( s \). The traffic flow \( y_r \) represents successful transmission of the traffic along route \( r \).

The probability of successful packet transmission is denoted \( P_s \). The throughput rate \( y_r \) is then related to the actual transmission rate \( Y_r \) as follows [2]:

\[
y_r = Y_r P_s \tag{2.2}
\]

### 2.2 Capacity Constraint

We assume that a node can only have one transceiver and has a limit on its capacity to transmit or receive traffic. This limit on its capacity is defined by the number of frequency bands allowed, spectrum allocation, and by the medium access protocol.

The figure(2.2) below shows the traffic flow through node \( j \), which can be a source, a destination or a transit node:

We define \( f_{rj} \) to be the node that \( j \) will forward traffic to, when using route \( r \).
Figure 2.2: Traffic flow through node $j$

The total capacity constraint can be modelled by calculating the total capacity usage, where traffic that is forwarded by a node must be both received and transmitted [2]:

$$c_j = \sum_{r \in R_S(j) \cup R_D(j)} y_r + \sum_{r \in R_S(j) \cup R_D(j)} 2y_r$$  \hspace{1cm} (2.3)

The capacity usage is constrained by

$$c_j \leq C_j, \forall j \in V_t$$  \hspace{1cm} (2.4)

where $C_j$ is the finite capacity of node $j$.

### 2.2.1 Remarks

The first term in equation (2.3) represents the capacity used where $j$ is a source or a destination node and the second term represents the capacity usage where $j$ is a transit node.

The constraint (2.4) does not capture the interference issue that arises in wireless networks, but it is a simplification that ensures that a node cannot receive traffic from, or transmit traffic to, two of its neighbours simultaneously [2].

### 2.3 Energy Management

An important issue in mobile ad-hoc networks is energy efficiency, which can be achieved through traffic management and optimal routing of flows.

Transmitting traffic from node $i$ to node $j$ consumes energy. The energy consumed per unit-flow is represented by the variable $e_{ij}^{(tx)}$.

Receiving traffic also consumes energy but, it is independent of the node from which the traffic was transmitted. This energy consumption is represented by the variable $e^{(rx)}$.

The variables $e_{ij}^{(tx)}$ can vary with time, due to the mobility of the system. Also, we write $e_{ij}^{(tx)} = \infty$ if a node $j$ cannot be reached from a node $i$ [2].

The power consumed by a node $j$ is given by:
\[ \gamma_j = \sum_{r \in R^S(j)} y_r e^{(tx)}_{jr} + \sum_{r \in R^D(j)} y_r e^{(rx)}_{jr} + \sum_{r \notin R^S(j) \cup R^D(j)} y_r \left( e^{(rx)}_{jr} + e^{(tx)}_{jr} \right) \] (2.5)

Power consumption is constrained at each node, due to the rate of discharge of the node’s battery [2]. This leads to the following power constraint at each individual node:

\[ \gamma_j \leq \Gamma_j, \quad \forall j \in V_t \] (2.6)

where \( \Gamma_j \) depends on the specification of the node’s power supply.

### 2.3.1 Remark

The first term in equation (2.5) above represents the power consumed by node \( j \) when transmitting traffic. The second term represents the power consumed by node \( j \) when receiving traffic, and the third term represents the power consumed by node \( j \) when forwarding traffic.
3. Congestion Pricing

3.1 Pricing Framework

3.1.1 Quality of Service (QoS)

The level of service that a user obtains from a network is known as the Quality of Service. The goal of QoS offered is to ensure a better delivery of information carried by the network, and a better utilization of the network’s resources.

The network provides a set of service guarantees such as minimum bandwidth, maximum delay, and maximum packet loss rate while transporting a packet stream from the source to the destination [5].

To optimize flow allocations within the network, the concept of pricing was developed. Consider a network (2.1.1) with a set $V_t$ of resources (mobile nodes), and let $C_j$ be the finite capacity of resource $j$, for $j \in V_t$ [6].

We know from (2.1.2) that a route is a non-empty subset of $V_t$, and that $R$ is the set of all possible routes within the network.

Let

$$A_{jr} = \begin{cases} 1, & \text{if } j \in r \\ 0, & \text{otherwise} \end{cases}$$  \hspace{1cm} (3.1)

We define the following $(0, 1)$ matrix:

$$A = (A_{jr}, j \in V_t, r \in R)$$  \hspace{1cm} (3.2)

The rate $x_s$ allocated to a user $s$ has utility $U_s(x_s)$ to the user. Assume that the utility $U_s(x_s)$ is an increasing, strictly concave and continuously differentiable function of $x_s$ over the range $x_s \geq 0$ [6].

Assume further that utilities are additive, so that the aggregate utility of rates $x = (x_s, s \in r, r \in R)$ is

$$\sum_{s \in r \in R} U_s(x_s)$$  \hspace{1cm} (3.3)

Let $U = (U_s(\cdot), s \in r, r \in R)$ and $C = (C_j, j \in V_t)$. Under this model the system’s optimal rates solve the following problem [6]:

$$\begin{align*}
\text{SYSTEM} & : (U, A; C) : \\
\text{Subject to} & : \\
\text{max} & \sum_{r \in R} U_s(x_s) \\
Ax & \leq C \\
x & \geq 0
\end{align*}$$  \hspace{1cm} (3.4)
where the first constraint shows that the system cannot provide service over its total capacity and the second indicates the non-negativity constraint whereby a negative flow rate can never exist within the system.

While this optimisation problem is mathematically tractable, it involves utilities $U$ that are unlikely to be known by the network.

We are thus led to consider two simpler problems [6]. Suppose that each user $s$ has a parameter $\omega_s(t)$ known as the willingness-to-pay which can be seen as an amount that a user chooses to pay per unit time in exchange for receiving a flow rate $x_s$ in return. This flow rate is proportional to $\omega_s$, say $x_s = \omega_s / \lambda_s$, where $\lambda_s$ could be regarded as a charge per unit flow for the user.

This brings us to the concept of proportional fairness where the assignment of a flow rate to the users is inversely proportional to its cost in terms of resource consumption. For example, a node that is far from the destination node may achieve a lower flow rate than one closer to the destination node, since the first will need more transits than the second.

Thus, the user $s$ adjusts its flow rate on each route $r_s$ (where $r_s \in R^S(s)$) as a function of time, and according to the congestion prices announced by relevant nodes [2]. Then the utility maximisation problem for user is [6]:

$$
\text{USER}_s \left( U_s; \lambda_s \right) : \max_{\omega_s \geq 0} U_s \left( \frac{\omega_s}{\lambda_s} \right) - \omega_s
$$

A vector of rates $x = (x_s, s \in r, r \in R)$ is *proportionally fair* if it is feasible, that is $x \geq 0$ and $Ax \leq C$, and if for any feasible vector $x^*$, the aggregate of proportional changes is either zero or negative [6]:

$$
\sum_{s \in r} \frac{x_s^* - x_s}{x_s} \leq 0
$$

Next suppose that the network knows the vector $\omega = (\omega_s, s \in r, r \in R)$ and attempts to maximise the function $\sum_{s \in r} \omega_s \log x_s$ with the aim of achieving proportional fairness, which arises naturally from inclusion of a log function.

Hence, the network’s optimisation problem is:

$$
\text{NETWORK} \left( A, C; \omega \right) : \max \sum_{s \in r} \omega_s \log x_s
$$

subject to

$$Ax \leq C$$

over

$$x \geq 0$$
A vector of rates $x$ solves the $NETWORK(A, C; \omega)$ problem if and only if the rates per unit charge are proportionally fair [6].

It is known that there always exist vectors $\lambda = (\lambda_s, s \in r, r \in R)$ and $x = (x_s, s \in r, r \in R)$, satisfying $\omega_s = \lambda_s x_s$ for $s \in r$ and $r \in R$ such that $\omega_s$ solves $USER_s(U_s, \lambda_s)$ and $x$ solves $NETWORK(A, C; \omega)$. Furthermore, the vector $x$ is then the unique solution to $SYSTEM(U, A; C)$ [6].

Under the decomposition of the problem $SYSTEM(U, A; C)$ into the problems $NETWORK(A, C; \omega)$ and $USER_s(U_s; \lambda_s), s \in r$ and $r \in R$, the utility function $U_s(x_s)$ is in fact not required by the network, and only appears in the optimisation problem faced by user $s$ [6].

The Lagrangian for the problem $NETWORK(A, C; \omega)$ is

$$L(x, z; \mu) = \sum_{s \in r} \omega_s \log x_s + \mu^T(C - Ax - z)$$

(3.8)

where $z \geq 0$ is a vector of slack variables and $\mu$ is a vector of Lagrangian multipliers [6].

Then

$$\frac{\partial L}{\partial x_s} = \frac{\omega_s}{x_s} - \sum_{j \in r} \mu_j,$$  

(3.9)

The second member of the righthand side of equation (3.9) follows from the scalar product of vector $\mu^T$ and the $(0,1)$ vector, derivative of the vector $Ax$ with respect to $x_s$ for $s \in r$, while, the derivatives of vectors $C$ and $z$ with respect to $x_s$ are zero in the Lagrangian (3.8).

And the unique optimum for the system when $\partial L / \partial x_s = 0$ is given by:

$$x_s = \frac{\omega_s}{\sum_{j \in r} \mu_j}$$

(3.10)

The result at (3.10) shows that the rate flow which is a solution of $NETWORK(A, C; \omega)$ is proportionally fair.

It follows that a user $s$ can maximize its flow rate by selecting the lowest cost paths according to the expression:

$$x_s(t) = \frac{\omega_s}{\min_{r \in R^s(s)} \sum_{j \in r} \mu_{jr}(t)}$$

(3.11)

where $\mu_{jr}(t)$ is the price that node $j$ charges for forwarding a unit flow along route $r$. This reflects what will occur in a mobile ad-hoc network in practice.

Prices along route $r$ are defined according to the following equation [2]:

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

(3.12)

Here the congestion prices $\mu^p_j(t)$ and $\mu^B_j(t)$, for power and bandwidth respectively, are dynamically
adapted according to the equations [2]:

\[
\begin{align*}
\frac{d}{dt} \mu^B_j(t) & = \kappa \frac{\mu^B_j(t)}{C_j(t)} (C_j(t) - C_j) \\
\frac{d}{dt} \mu^P_j(t) & = \kappa \frac{\mu^P_j(t)}{\Gamma_j} (\gamma_j(t) - \Gamma_j)
\end{align*}
\] (3.13)

with \( \kappa \) acting as the parameter which adjusts the speed of price adaptions.

### 3.1.2 Balancing the Congestion Cost

The concept of incentive introduced above (2.1.2) grants an initial credit endowment of 1 to a user who arrives for the first time into the system. The user accumulates its credit from the total credit for congestion costs from each individual source with routes passing through it [2].

To send its own traffic, the user should transfer an amount of credit equal to the congestion costs to each downstream resource, and its credit balance \( b_s(t) \) is correspondingly adjusted in doing so.

To control its credit balance, the user should adjust its willingness-to-pay parameters \( \omega_s(t) \), according to the level of its credit balance, by following a rule of the form [2]:

\[ \omega_s(t) = \alpha_s b_s(t) \]

for some parameter \( \alpha_s > 0 \) known as the ratio of balance the user is willing to spend.

The credit balance itself is discounted over time,

\[
\frac{db_s}{dt} = -\beta (b_s(t) - 1) - \omega_s(t) + \sum_{j \in r} y_r \mu^r_j(t)
\] (3.14)

where \( \beta > 0 \) is the parameter which adjusts the speed of credit balance discounting.

### 3.2 Resource Usage

Although our work does not focus on protocol studies, we will refer to the CDMA-Based MAC protocol since it is used to improve the mobile ad-hoc throughput.

CDMA is a type of communication in which each transmitter-receiver pair has a pseudo-random noise code for transmitting over a common channel [7].

Let \( W \) be the number of bits per second in a spreading signal, known as the chip rate, in CDMA. The bit-energy-to-noise density ratio \( E_b/N_o \) at a receiver \( k \), either a transit or a destination node, is given by [8]:

\[
\left( \frac{E_b}{N_o} \right)_k = \frac{W}{Y_{ik} I_k} \frac{g_{ik} p_{ik}}{I_k + \eta_k}
\] (3.15)

where \( Y_{ik} \) is the transmission rate, \( p_{ik} \) is the transmission power for data being sent and \( g_{ik} \) is the path gain between node \( i \) and node \( k \). \( I_k \) is the power of the interference created around node \( k \) and \( W/Y_{ik} \) is the spreading factor. Lower spreading factors allow the transmission of larger data volumes, but a lower transmission rate, and \( \eta_k \) is the power of background noise.
The main resources consumed by a user in a mobile ad-hoc network are the bandwidth and power, while sending, transceiving and receiving traffic.

Since the bit-energy-to-noise density ratio \( \left( \frac{E_b}{N_0} \right)_k \) determines the bit error rate (BER), its value corresponds to the signal quality [8].

Let \( \sigma_k \) be the target bit-energy-to-noise density ratio required to achieve a particular BER. In order to achieve this target, the transmission power is adjusted by a fast closed-loop power control algorithm. If we assume perfect power control, then [8]:

\[
\left( \frac{E_b}{N_0} \right)_k = \sigma_k \tag{3.16}
\]

When sending traffic, node \( j \) consumes bandwidth and power. These consumptions are expressed in terms of throughput rate and transmission energy. Hence, the resource used at node \( j \) while sending traffic is

\[
y_{re}^{(tx)}_{jfrj} \tag{3.17}
\]

To forward traffic for other nodes whose routes pass through it, node \( j \) consumes both bandwidth and power while receiving and transmitting traffic to the destination nodes. Thus, the resource used at node \( j \) is

\[
y_{re}^{(rx)} + y_{re}^{(tx)}_{jfrj} \tag{3.18}
\]

Receiving traffic also consumes power and bandwidth. The resource used at node \( j \) while receiving traffic is

\[
y_{re}^{(rx)} \tag{3.19}
\]

where \( e^{(rx)} \) and \( e^{(tx)}_{jfrj} \) are defined in (2.3), and \( y_r \) is the throughput rate along route \( r \).

### 3.3 Resource Control Based on Congestion Pricing

To control resources used within the network while a user sends, forwards and receives traffic, is a challenge for ad-hoc networks. In attempt to compensate for this, users are constrained to pay a congestion price per unit resource consumed.

The utility function that is used in this section is appropriate for elastic traffic, i.e traffic from applications that are able to modify their data transfer rate according to the available bandwidth within the network. We consider the case where users value only the average throughput of successful data transmission. This throughput will be the product of the transmission rate and the probability of successful packet transmission, which itself is a function of the target bit-energy-to-noise-density ratio \( \sigma \) [8].

Thus this utility function has the form

\[
U(Y_r P_\sigma(\sigma)), \tag{3.20}
\]
where $Y_r$ is the transmission rate, and $P_s$ the probability of successful packet transmission [8].

The charges incurred by a user while sending traffic are equal to $\lambda y_r e^{(tx)}_{jjfr_j}$, which are proportional to the user’s resource usage. Controlling the level of charges for resource usage makes it possible to provide the right incentives for the efficient use of the network’s resources. Hence, the user optimisation problem becomes [8]

$$\begin{align*}
\text{maximise} & \quad U_j(Y_{jk} P_s(\sigma_k)) - \lambda y_r e^{(tx)}_{jjfr_j} \\
\text{over} & \quad y_r \geq 0, e^{(tx)}_{jjfr_j} \geq 0
\end{align*}$$

(3.21)

While forwarding traffic, a user transforms to charges $\lambda y_r (e^{(rx)} + e^{(tx)}_{jjfr_j})$. Thus, our user optimisation problem becomes

$$\begin{align*}
\text{maximise} & \quad U_j(Y_{jk} P_s(\sigma_k)) - \lambda y_r (e^{(tx)}_{jjfr_j} + e^{(rx)}) \\
\text{over} & \quad y_r \geq 0, e^{(tx)}_{jjfr_j} \geq 0, e^{(rx)} \geq 0
\end{align*}$$

(3.22)

The reception of traffic also consumes resources, and the charges incurred by a user receiving traffic are $\lambda y_r e^{(rx)}$. The user optimisation problem now becomes [8]

$$\begin{align*}
\text{maximise} & \quad U_j(Y_{jk} P_s(\sigma_k)) - \lambda y_r e^{(rx)} \\
\text{over} & \quad y_r \geq 0, e^{(rx)} \geq 0
\end{align*}$$

(3.23)

where the parameter $\lambda$ is the price per unit resource, and $y_r e^{(tx)}_{jjfr_j}$ is the resource used at the source node. The resource used at transit node will be $y_r (e^{(tx)} + e^{(tx)}_{jjfr_j})$ and that used at destination will be $y_r e^{(rx)}$. These prices are independent of the node’s position.

Nodes that are far from the destination incur a higher charge for the same throughput rate since they consume more energy.
4. Simulations

In this section we use a simulation model of a mobile ad hoc network to reproduce the results of congestion-based prices for the consumption of bandwidth and power, and for the credit balances at nodes. The simulator uses the Desmo-J simulation framework [3].

We consider a network of ten users located according to a uniform distribution within a geographical area of $100m \times 100m$, where each node is equipped with a single transceiver with range $56m$. The nodes lying within the range of this transceiver are defined as the neighbours of that node within the network, as shown in figure (4.1) [2].

We will model two types of networks. First, a static network in which there are no arrivals nor departures of users and where no node moves. Secondly, we will consider a mobile network where one node, $N_1$, moves toward the centre of the network.

For the case of a static network, we consider four representative nodes within the network. Node $N_1$ is of interest because it is the most extreme node; it has only two neighbours. The node $N_5$ is $42m$ and $N_0$ is $53m$ away from it. So, it can only select routes from a fairly restricted set of possible paths. Node $N_7$ on the other hand is an extreme node, which along with node $N_3$, is nevertheless close to node $N_9$; thus, their traffics transit at node $N_9$. And, node $N_8$ is used as a transit node for almost all nodes within the network. Because it is nearest the geographical centre of the network, it thus has a large number of neighbours. Hence, a higher number of routes to choose from, in order to send traffic to a particular destination. For the case of a mobile network, we consider three representative nodes. Node $N_1$, as it is at the edge of the network, moves toward the centre near $N_8$ to earn some credits by transceiving traffic. And, consequently, once $N_1$ passes the centre, $N_4$ becomes its closest neighbour.

4.1 Static Networks

To check the stability of the system, we simulate a static network topology for $100,000s$ where the mean duration of a connection is $0.5s$, and a user is idle for a mean period of $0.5s$ after completing a connection. The users update their prices every $0.01s$.

The parameters used in the system are set to $\alpha_s = 0.3$, $\beta = 0.01$ and $\kappa = 0.05$. The bandwidth capacity is set to $C = 7.5$ for all nodes in the network, while the maximum power is $\Gamma = 0.5$. The energy parameters associated with transmitting and receiving traffic are given by $e_{ij}^{(tx)} = 10^{-4}\|z_i - z_j\|_2^2$ and $e_{ij}^{(rx)} = 10^{-3}$, with $z_i$ and $z_j$ giving the geographical position of nodes $i$ and $j$, respectively [2].

The credit balances for the four representative nodes of the network are plotted in figure (4.2) where we have plotted the credit balances of nodes $N_1$, $N_7$, $N_8$ and $N_9$. We notice that node $N_1$, as the most extreme node in the network, does not accumulate credits. This is because it is not in demand, to transceive traffic for other nodes. Node $N_8$ on the other hand accumulates more credit due to its position near the centre of the network, and as such is in great demand.
Figure 4.1: Topology of the mobile ad hoc network

for carrying traffic for other nodes which are at the edges of the network. Node $N_9$ is in demand by nodes $N_3$ and $N_7$ to carry their traffic, and to forward traffic from other nodes to them; thus it accumulates credits by doing so. Node $N_7$ does not accumulate more credit since less traffic transits to it, because of its position close to the edge.

The power prices for the four representative nodes of the network are plotted in figure (4.3). We note that the power prices of nodes $N_1$ and $N_7$ are almost zero, due to their position close to the edges, they are not in demand for transceiving traffic from other nodes, so they do not consume a lot of energy. Hence, they pay for the power they use for sending and receiving their own traffic. In contrast, nodes $N_8$ and $N_9$ consume a lot of energy by transceiving traffic for
other nodes, and by sending and receiving their own traffic. Thus, they pay a higher amount for the energy they consume.

The stability of bandwidth prices for nodes $N1, N7, N8$ and $N9$ are plotted in figure (4.4)
Figure 4.3: Static Network Power Price
Section 4.2. Mobile Network

Figure 4.4: Static Network Bandwidth Prices

4.2 Mobile Network

Unlike the static network where no node moves, in the mobile network we consider the situation where one node does move in fact. Node $N_1$ which is the most extreme node within the network, chooses to move toward the centre of the network. While moving along its path, it enters in competition with node $N_8$ when it reaches the centre of the network since, it is now in demand for transceiving traffic for other nodes, as a result of its new position. When it moves away from the centre, it will no longer be in demand; because it moves to the other edge of the network, and is now the nearest neighbour of node $N_4$ as shown in figure (4.5).
We plot the bandwidth and the power prices, and the credit balances for the three representative nodes $N_1$, $N_4$ and $N_8$ to show the performance of the network.

The credit balances for those nodes are plotted in figure (4.6). Once node $N_1$ reaches the centre of the network, its credit increases since it is now in demand for transceiving traffic. It is also in competition with $N_8$, whose credit decreases slightly. When node $N_1$ moves to the other edge of the network, its credit decreases because of the lack of demand to forward traffic from other nodes due to its new position at the edge of the network. As it is no longer in competition with $N_8$, the credit at node $N_8$ increases once more.
Node $N1$ faces two more problems; namely the congestion prices for the bandwidth and power used while transceiving traffic; because the increase in demand implies a corresponding increase in resource usage.

The bandwidth and power prices for the three representative nodes $N1$, $N4$ and $N8$ of mobile network are respectively plotted in figures (4.7) and (4.8) below.

As node $N1$ moves toward the centre of the network, its bandwidth and its power prices increase at the same time with its credit. This is because, once at the centre of the network, it uses more bandwidth and more power than when it was at the edge, to transceive traffic for other nodes.
Node $N_8$ sees its bandwidth and power prices decrease because it is now in competition with $N_1$. It no longer uses as much bandwidth and power since the traffic through it is correspondingly reduced. When node $N_1$ moves away from $N_8$ to the other edge close to $N_4$, its bandwidth as well the power prices decrease accordingly. Correspondingly, the bandwidth and power prices of node $N_8$ increase again.

Figure 4.7: Mobile Network Bandwidth Prices
Figure 4.8: Mobile Network Power Prices
5. Conclusion

We have shown how flows along a route can be optimised in a mobile ad hoc network by using pricing mechanisms to recover resources used within the network at source, transit and destination nodes.

First, we illustrated two simpler problems, namely the user’s utility maximization problem and the network optimisation problem; these follow directly from the system’s optimal rate problem. In the first case, we demonstrated that a user which has been allocated a flow rate along route \( r \), can maximise its utility function in terms of its willingness-to-pay. And, in the second case, we have proved that this flow rate is the unique optimum of the system, and is proportionally fair.

Next, we presented the way that a network’s resources, namely power and bandwidth, are consumed by users while sending, transceiving and receiving traffic. We also presented problems which allow us to control resource’s usage within the network, subject to the congestion price per unit resource.

Lastly, we verified the stability of the network, by simulating a static network topology for 100,000s. We also verified the performance of a mobile ad hoc network under the condition that one extreme node moves toward the centre of the network.

Since routing in mobile ad hoc networking depends on many factor like topology, selection of routers and availability of bandwidth, further studies may include the development of a new routing algorithm for the mobile ad hoc network.
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Bibliography


