國立交通大學

資訊管理研究所

博士論文

混合多點跳躍與蜂巢式網路上

轉送服務動態定價之研究

Dynamic Incentive Pricing for Relaying Services

in Multi-hop Cellular Networks

研 究 生：林明華

指導教授：羅濟群 教授

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研　究　生：林明華　　Student：Ming-Hua Lin

指導教授：羅濟群　　Advisor：Chi-Chun Lo

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中 文 摘 要

混合多點跳躍與蜂巢式網路整合了蜂巢式網路與多點跳躍網路兩者的特性，在近幾年受到愈來愈多的注意，而提供適當的回饋以鼓勵無線網路節點提供轉送資料的服務是此種網路得以成功運作的重要因素。目前相關的研究大部分都是採用固定費率的方式，以節點所轉送的封包數目或資料量來決定回饋的多寡，這種方式無法有效反應無線網路變動頻繁的特性。本研究針對混合多點跳躍與蜂巢式網路上的轉送服務提出適當的回饋定價機制，同時考慮轉送成本與服務可獲得性。首先，以網路上有效節點數的多寡來決定提供轉送服務的回饋價格，希望在達到網路業者利潤最大的同時也能兼顧服務可獲得性。接著，本研究也利用每個節點所在位置對服務可獲得性所具有的不同貢獻度為基礎來給予不同的回饋價格。此研究所提出的定價機制將部分回饋從重要性較低的節點移轉到重要性較高的節點，藉以激勵重要性高的節點提供轉送服務的意願，如此可在不增加轉送成本的情況下提高整體網路的服務可獲得性。此外，當網路上未有預先建構好的繞徑拓樸時，每個節點的轉送服務重要性指標也可被用在連接到固定網路節點的選徑上。當每個節點的最大轉送數目有限制時，利用轉送服務重要性指標來選擇路徑所產生的成功建立連線機率會比一般常用的最短路徑選徑策略高。

Dynamic Incentive Pricing for Relaying Services in Multi-hop Cellular Networks

Student: Ming-Hua Lin　　　　Advisor: Dr. Chi-Chun Lo

Institute of Information Management

National Chiao Tung University

Abstract

Multi-hop cellular networks that integrate the characteristics of both cellular and mobile ad hoc networks have received increasing attention. Providing incentives to foster cooperation among nodes is an important prerequisite for the success of the multi-hop cellular networks. Most works on the incentive approaches for enabling forwarding packets just employ fixed-rate pricing. The purpose of this research is to present appropriate incentive pricing schemes for relaying services considering both relaying costs and service availability. First, this study proposes a pricing scheme that dynamically adjusts the price of the feedback incentives based on the number of mobile nodes to maximize the revenue of the network provider while maintaining service availability. Then, in order to consider the individual impact of each mobile node on supporting hop-by-hop connections, we introduce the concept of location-based incentive pricing for relaying services. The proposed pricing scheme shifts incentives from the nodes of low importance to the nodes of high importance so that it increases service availability without additional costs. Finally, the Quality-of-Relay (QoR) value of each mobile node is adopted to select a relaying path for connecting to the central base station. Simulation results indicate that the proposed QoR-based routing scheme causes a lower new call blocking probability than the shortest-path routing scheme under a certain constraint on maximum relaying capacity of each mobile node.

Table of Contents

List of Tables

List of Figures

Chapter 1　Introduction

1.1 Research Motivation and Purpose

Multi-hop cellular networking has been an active research area in recent years. In conventional cellular networks, mobile stations communicate directly with their assigned base station; in wireless multi-hop networks, mobile stations are located randomly and use peer-to-peer communications to relay their messages. Multi-hop cellular networks that integrate the characteristics of both cellular and mobile ad hoc networks to leverage the advantages of each other have received increasing attention. Figure 1.1 indicates the scenario of general multi-hop cellular networks, the service area of the cellular networks can be extended by adopting hop-by-hop connections at the boundaries of the cell.

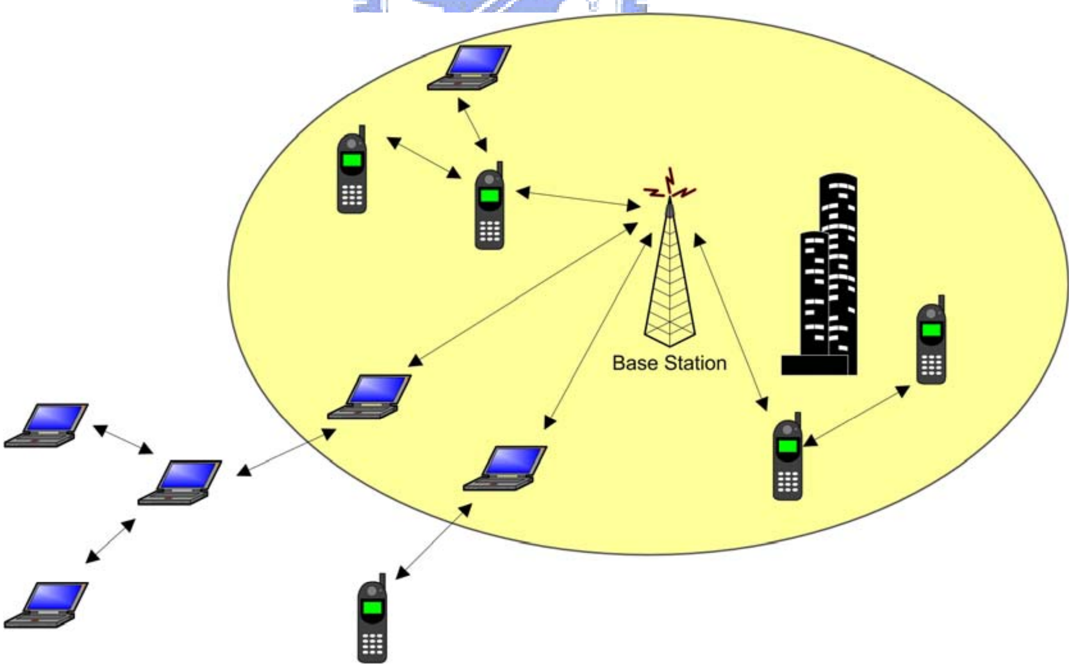


Figure 1.1　Scenario of general multi-hop cellular networks

Much research has evaluated and summarized the benefits of such a hybrid architecture [1][4][7][8]:

- The energy consumption of the mobile device can be conserved.
- The interference with other nodes can be reduced.
- The number of fixed antennas can be reduced.
- The capacity of the cell can be increased.
- The coverage of the network can be enhanced.
- The robustness and scalability of the system can be increased.

In multi-hop cellular networks, data packets must be relayed hop by hop from a given mobile node to a base station and vice-versa [8]. Cooperation among nodes is an important prerequisite for the success of the relaying ad-hoc networks. In cooperating groups, such as emergency and military situations, all nodes belong to a single authority and therefore have a good reason to support each other. However, in the groups of anonymous participants, such as emerging civilian applications, the nodes do not belong to a single authority and cooperative behaviors can not be directly assumed [15]. Moreover, forwarding data for others incurs the consumption of battery energy and the delay of its own data, the assumption of spontaneous willingness to relay data is unrealistic for autonomous mobile nodes [16]. Consequently, providing incentives for the mobile nodes to cooperate as relaying entities in the groups of mutually unknown participants is reasonable.

Much research [7-8, 15-22] has described how to stimulate intermediate nodes to forward data packets in multi-hop networks. The approaches can be classified into detection-based and motivation-based. The detection-based approach finds out misbehaving nodes and mitigates their impact in the networks. The motivation-based approach provides incentives to foster positive cooperation in ad hoc networks. Most works on the motivation-based approaches focus on its protocol and security aspects or just employ fixed-rate pricing on number of packets or volume of traffic forwarded. The major advantage of the fixed-rate pricing is that billing and accounting processes are simple. However, the price of the feedback incentives is independent of the actual state of the networks. Such system cannot react effectively to the dynamic and unpredictable variations of the wireless networks.

Cost savings and service availability are two major concerns of a network provider adopting multi-hop cellular networking technology. In this research, we propose a dynamic incentive pricing scheme to maximize the revenue of the network provider while maintaining service availability in the networks. Monetary incentives not only affect the motivation of the intermediate nodes supporting relaying services but represent the costs of providing connection services in multi-hop cellular networks. If the price of the incentives is too low, the number of successful connections will be small and the network provider can not get adequate profit from the relaying networks. However, if the price of the incentives is too high, the network provider can not cover the costs from the fee charged from end users. Consequently, dynamically adjusting the price of the incentives based on the network conditions is more appropriate than fixed-rate pricing for the network provider to make maximum revenue.

Since providing a uniform price of the incentives to all mobile nodes depending on the network situations neglects the distinct importance of each mobile node in the network topology, we also investigate how to give different amount of incentives for each mobile node that has different effects on supporting hop-by-hop connections. The base station should give more incentives to the nodes of high importance so that it can make more mobile nodes connect to the base station successfully. In order to react effectively to the individual impact of each mobile node on service availability, we present the concept of location-based incentive pricing for relaying services in multi-hop cellular networks. When a pre-constructed routing topology exists in the networks, the price of the feedback incentives for each intermediate node is adjusted according to the number of nodes that reside in its sub-tree. The willingness of an intermediate node relaying packets has a significant impact on the success of the multi-hop connections from all nodes in its sub-tree to the base station. The proposed pricing scheme shifts incentives from the nodes of low importance to the nodes of high importance in the routing topology so that it increases service availability without additional costs.

When a pre-constructed routing topology is not available in the networks, a new metric called Quality-of-Relay (QoR) is defined to evaluate the importance of each mobile node affecting other nodes that require hop-by-hop connections to reach the central base station. Shifting incentives from the nodes of low importance to the nodes of high importance in the networks also enhances service availability with only a slight increase in relaying costs. In addition to adopting the QoR value for incentive pricing, we present a routing scheme based on the QoR value of each mobile node in the networks to select an optimal relaying path for connecting to the central base station. Although shortest path is the most simple and common metric used in the routing protocol, it may route almost packets over a few paths and result in network congestion and resource unavailable in hot spot. The routing scheme that selects a relaying path with minimum sum of the QoR values of all intermediate nodes in the path can retain more valuable resource for later relaying requests, thereby accepting more relaying connections under a certain constraint on maximum relaying capacity of each mobile node.

1.2 Outline of This Thesis

This thesis is organized into six chapters. Chapter 1 outlines the motivation and the research purpose. In Chapter 2, we review the existing multi-hop cellular network models and incentive approaches. Then, we introduce the general supply function for providing relaying services. In Chapter 3, a dynamic incentive pricing scheme is presented to maximize the revenue of the network provider by adjusting the price of the feedback incentives based on the actual network conditions. Chapter 4 proposes a location-based incentive pricing scheme for relaying services with a tree-based routing topology. Chapter 5 describes Quality-of-Relay based incentive pricing and routing for relaying services without a pre-constructed routing topology. The pricing schemes presented in Chapter 4 and 5 encourage collaboration depending on the degree of each mobile node contributing to successful hop-by-hop connections. Finally, we conclude our research and suggest possible further research directions in Chapter 6.

Chapter 2　Literature Review

2.1 Multi-hop Cellular Network Model

In conventional cellular networks, mobile stations communicate directly with their assigned base station and do not interact with other mobile stations inside the same cell. In wireless multi-hop networks, mobile stations are located randomly and use peer-to-peer communications to relay their messages in an ad hoc fashion. Although many approaches in the literature have been proposed to improve the performance of cellular networks and multi-hop networks in isolation, more and more research focuses on integrating the cellular and multi-hop network models. In this section, we present a survey of existing multi-hop cellular network models.

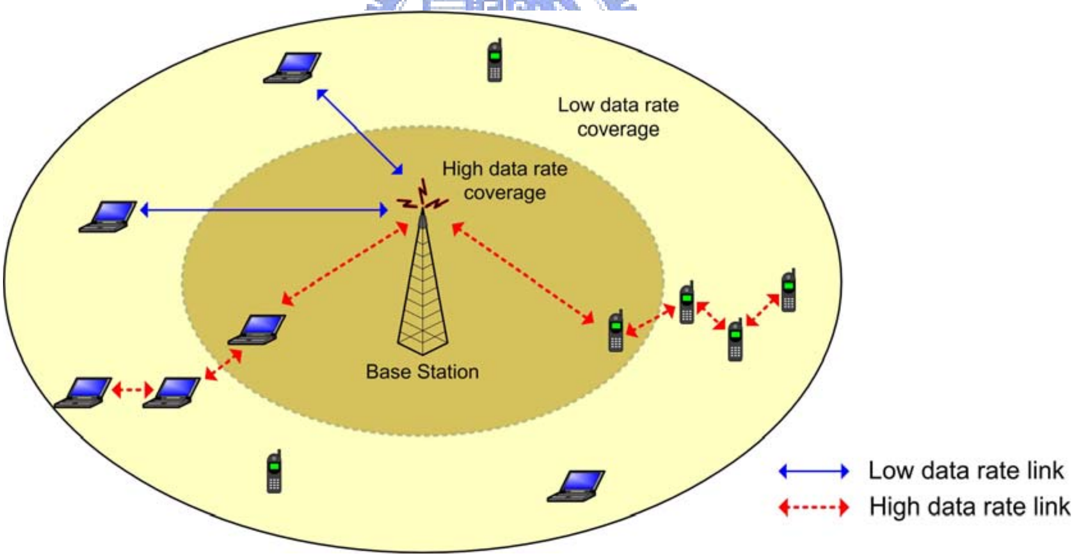


Figure 2.1　ODMA concept diagram

Opportunity Driven Multiple Access (ODMA) is a multi-hop relaying protocol that is used to increase the efficiency of Universal Mobile Telecommunication System (UMTS). In ODMA, the transmissions from mobile stations to the base station are broken into multiple wireless hops, thereby reducing transmission power. As the concept diagram illustrated in Fig. 2.1, the high-data-rate coverage of the cell can be increased at the boundaries by allowing mobile stations inside the original high-data-rate coverage area to act as relays for the mobile stations outside the high-data- rate coverage area [1-2].

Aggélou et al. describe an Ad Hoc GSM (A-GSM) system that presents a network layer platform to accommodate relaying capability in GSM cellular networks. Although the latest developments and experiments in GSM cellular networks aim to provide global roaming, there are still places where any present communication platform would fail to provide successful communication. These places, such as subway train platforms, indoor environments, and basements, are called dead spots. Since it is not economical to install additional antenna at each dead spot location, the authors integrate the standard GSM radio interface with sufficiently flexible capabilities to support relaying and extend communication at dead spot locations. Simulation results indicate that A-GSM multi-hop connections improve the system throughput for different mobile and dead spot populations [3].

Qiao et al. present a network model called iCAR that integrates the cellular infrastructure and ad-hoc relaying technologies. Limited capacity and unbalanced traffic are two fundamental problems in any cellular system. Some cells may be heavily congested while the other cells still have available channels. The localized congestion will cause call blocking and dropping even though the traffic load doesn't reach the maximum capacity of the entire system. The proposed architecture places a number of Ad-hoc Relaying Stations (ARS) at strategic locations to relay data from one cell to another cell. The mobile host in a congested cell can use a channel available in a nearby cell, therefore increasing the system capacity as well as the channel efficiency. As the relaying example in the iCAR system indicated in Fig. 2.2, a mobile node initiates a new call in a congested cell A. The call will be blocked in an existing cellular system when no free channel is available in cell A. However, the mobile node can switch over to the relay interface to communicate with an ARS in cell B through other ARS's in cell A in the iCAR system. Then the mobile node gets a free channel in cell B and sets up the call successfully. Load balancing among different cells in the iCAR system not only increases system capacity, but also reduces transmission power for mobile terminals [4].

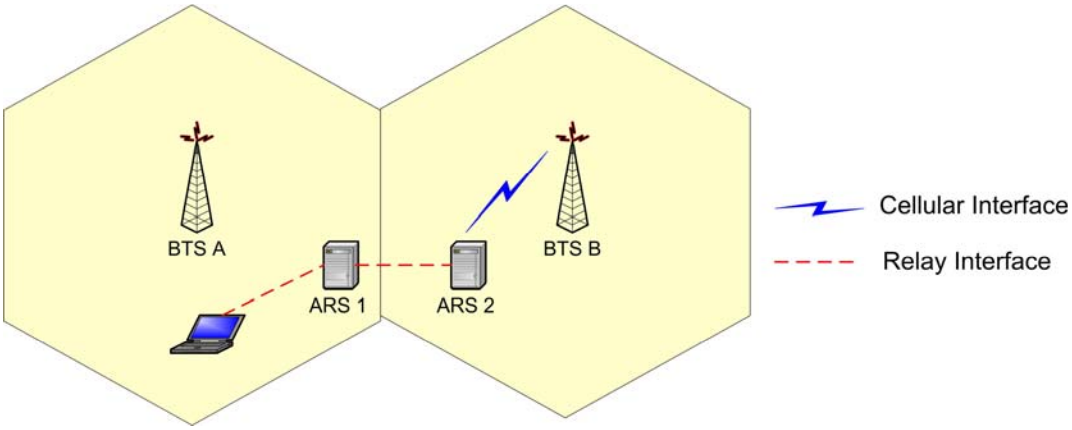


Figure 2.2 A relaying example in the iCAR system

(Source: [4])

Wu et al. propose a scheme called Mobile-Assisted Data Forwarding (MADF) to add an ad-hoc overlay to the fixed cellular infrastructure and special channels are assigned to connect users in a hot cell to its neighboring cold cells without going through the base station in the hot cell. The proposed method divides channels into forwarding channels and fixed channels. A mobile terminal in a hot cell may use the forwarding channels to transmit its data to a cold channel. An intermediate forwarding agent, such as a repeater or another mobile terminal, in the cold cell is required to relay the data to that cell. The authors find that under a certain delay requirement, the throughput can be greatly improved [5].

Luo et al. propose a Unified Cellular and Ad-Hoc Network (UCAN) architecture to enhance the cell throughput. Providing service to low-data-rate users is required for maintaining fairness, but at the cost of reducing the cell aggregate throughput. In the proposed method, each mobile device in the UCAN model has both 3G cellular link and IEEE

802.11-based peer-to-peer links. As the architecture indicated in Fig. 2.3, the 3G base station forwards packets for destination clients with poor channel quality to proxy clients with better channel quality. The proxy clients then use an ad-hoc network composed of other mobile clients and IEEE 802.11 wireless links to forward the packets to the destination, thereby enhancing cell throughput [6].

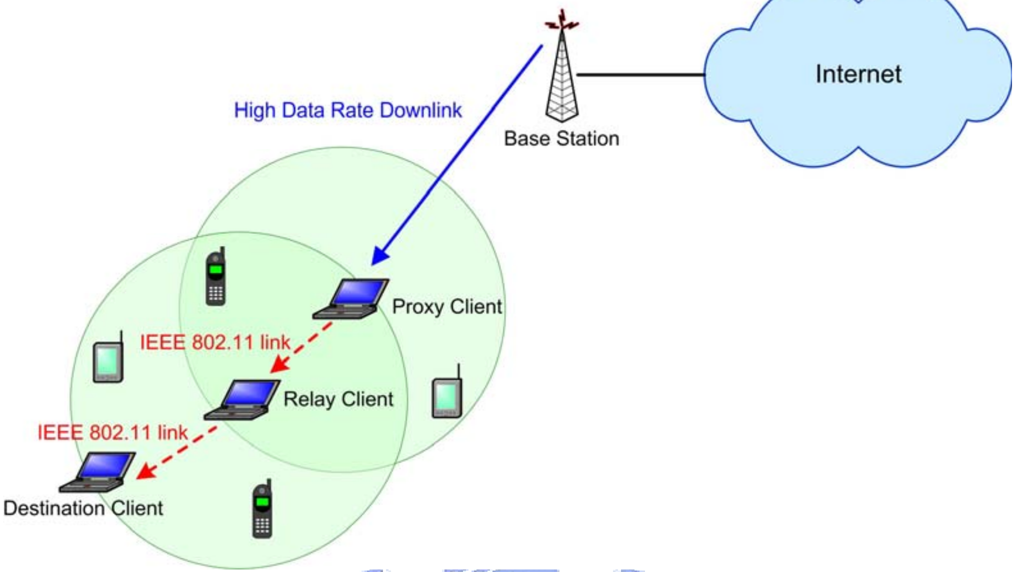


Figure 2.3 UCAN architecture

(Source: [6])

Table 2.1 summarizes the characteristics and main purposes of the different multi-hop cellular network models.

Table 2.1 Characteristics and main purposes of different multi-hop cellular network models

Network model	Characteristics	Main purposes
ODMA [1-2]	● Applied to cellular networks ● Mobile nodes are used to relay data	● Increasing the range of high-data-rate services

Network model	Characteristics	Main purposes
A-GSM [3]	● Applied to GSM cellular networks ● Dual mode handsets are used to relay data	● Solving the problem of dead spots to increase system throughput
iCAR [4]	● Applied to cellular networks ● Special devices (ARS) are used to relay data	● Solving the problems of limited capacity and unbalanced traffic to increase system capacity
MADF [5]	● Applied to cellular networks ● Mobile nodes or repeaters are used to relay data	● Dealing with the problem of fluctuating traffic in a cell to increase system throughput
UCAN [6]	● Applied to 3G cellular networks ● Mobile nodes are used to relay data	● Dealing with the problem of maintaining fairness and the cell aggregate throughput simultaneously

Much research has evaluated and summarized the advantages of the multi-hop cellular networking architecture [1][4][7][8]:

- The energy consumption of the mobile node can be conserved.
- The interference with other nodes can be reduced.
- The number of fixed antennas can be reduced.
- The capacity of the cell can be increased.
- The coverage of the network can be enhanced.
- The robustness and scalability of the system can be increased.

Although many benefits exist in the multi-hop cellular network model, the hybrid architecture has some disadvantages as follows:

- The complexity of the mobile nodes will be enhanced for providing relaying services.
- The battery consumption of the mobile node will be increased for forwarding packets.

2.2 Routing Scheme in Multi-hop Cellular Network Model

In multi-hop cellular networks, the communication between the base station and each mobile node is relayed by a number of other mobile nodes. Most of the multi-hop cellular networking models do not have a pre-constructed routing topology for relaying packets. The mobile nodes find relaying paths when they desire the path to transmit data. However, some studies have suggested that a tree-based routing topology is appropriate for multi-hop cellular networks because of the simple characteristic and authentication requirements. The packets simply follow the tree toward the destination. In this section, we review the routing schemes used in existing multi-hop cellular networks. We classify the routing schemes into

- Routing without a pre-constructed topology
- Routing with a pre-constructed topology

2.2.1 Routing without a Pre-Constructed Topology

When a pre-constructed routing topology does not exist in multi-hop cellular networks, the mobile node initiates a route recovery process to find a hop-by-hop path to reach the base station depending on different criteria, such as signal strength, path length and power consumption. The routing scheme is similar to the routing approach adopted in pure ad hoc networks.

Some research has reviewed and investigated existing multi-hop routing protocols, the protocols can be classified into *table-driven* and *demand-driven* [23, 28-29]. Table-driven routing protocols attempt to maintain routing information from each node to every other node in the networks. On-demand routing (source-initiated) protocols create routes only when desired by the source node. The common approach in most existing routing protocols is to consider the shortest-path routing. For simplicity, these protocols measure the distance of the path by the number of hops in the path. However, routing packets based on minimum hop count may take a considerable time to reach the destination because it may route almost packets over a few (shortest-distance) paths in the networks [25].

The ODMA system does not build a routing topology in advance but let mobile nodes find the relying paths to the destination on demand. Previous work on ODMA uses path loss between terminals as the metric to determine the routing path [9-10]. From the list of relaying routes available, the one with minimum aggregate transmit power along the route is selected. This is often implemented by selecting the one with minimum path loss. Rouse et al. present a routing scheme considering receiver interference on ODMA [1].

In A-GSM system [3], handover is initiated by a mobile node when a high possibility exists that the call will be lost or the quality of the ongoing connection seriously degraded. The mobile nodes measure the signal strength of the surrounding A-GSM nodes and the connected base stations. When the criteria for changing the serving base station or the serving relay is satisfied, such as the existing serving base station failure, the A-GSM handover will be triggered. If multiple neighboring nodes are available for a mobile node to build a relaying path to the base station, the mobile node selects a relaying link with strongest signal to initiate handover.

In iCAR system [4], a number of specific stations called ARS's are deployed at strategic locations to relay data from the congested cell to the neighboring non-congested cells. Each ARS collects neighbor information and maintains a routing table containing one entry for every reachable Base Transmission Stations (BTS). The ARS reports this information to a Mobile Switching Center (MSC) that controls a number of BTS's. The topology map can then be calculated by MSC's and only the updated part relevant to the ARS's is broadcast by the corresponding BTS to all ARS's in the cell. Whenever a mobile node needs a relaying path to one or more BTS's which have free channel available, the mobile node broadcast "route probe" message to all neighbor ARS's for asking information on the relaying path to any of these BTS's. After getting all replied relaying paths, the mobile node chooses the best ARS with the shortest path or the lowest power consumption as the proxy ARS to relay data to the target BTS.

In MADF approach [5], a forwarding agent that is willing to forward data first measures the local traffic in its cell. If the traffic load is lower than a certain threshold, the forwarding agent will broadcast a "free" signal to indicate its availability to relay data packets. The user in a hot cell collects the "free" signals and selects an agent according to the quality of the signal and the local traffic included in the "free" messages.

In UCAN model [6], the authors propose greedy and on-demand protocols for proxy discovery and ad-hoc routing. Each mobile node maintains a moving average of its 3G downlink channel rate. In the greedy protocol, all mobile nodes maintain their immediate neighbors' average downlink channel rates. When the route request message is issued, it is unicast to the neighbor with the highest downlink channel rate. The message then traverses greedily through the relay clients with increasing downlink channel quality and finally to the base station. In the on-demand protocol, mobile nodes do not maintain their neighborhood information. When the route request message is issued by a mobile node, it is broadcast to all its neighbors within a given range. The neighbor that has higher channel rate than the destination node writes its own channel rate into the route request message and forwards a copy of the message to the base station. After all route request messages arrive at the base station, the base station selects a mobile node with higher channel rate and shorter path length as the proxy client for the destination node.

Table 2.2 lists the routing criteria adopted in different multi-hop cellular network models.

Table 2.2 Routing criteria in different multi-hop cellular network models

Network model	Routing criteria
ODMA [1-2]	● Selecting a route with minimum aggregate transmit power
A-GSM [3]	● Selecting an A-GSM node with strongest signal
iCAR [4]	● Selecting an ARS with shortest path or the lowest power consumption
MADF [5]	● Selecting a forwarding agent according to quality of signal and traffic load
UCAN [6]	● Selecting a proxy client according to downlink channel rate

2.2.2 Routing with a Pre-Constructed Topology

Some studies have suggested that a tree-based routing topology is appropriate for multi-hop cellular networks because of the simple characteristic and authentication requirements. A tree-based topology map for forwarding packets is pre-constructed in the egress node connected to the fixed backbone. The packets simply follow the routing topology toward the destination.

Hsiao et al. propose an algorithm to construct a load-balancing routing tree for a wireless access networks. Via such a network, a mobile node, such as an information appliance, can send packets to and receive packets from an "egress node" that connects to the external networking infrastructure. The proposed tree-based routing approach can simplify routing by avoiding per-flow state and achieve better network utilization by lowering bandwidth blocking rates. Since the traffic model assumes that the primary mode of communications from wireless access networks will be access to the wired Internet, conventional per-destination routing information is not necessary. Outgoing packets from the nodes simply follow the tree toward the root, the egress node. Incoming packets follow explicit source-routed paths given by the egress node. The immediate routers aggregate load amount toward the root of the tree such that they do not maintain per-flow routing [11].

Zhang et al. present an IP-based virtual operator authentication, authorization and accounting (AAA) scheme in wireless LAN hot spots. The proposed solution can support accounting in the scenario where access points (AP) use ad-hoc networking to extend their service coverage. Packet-based accounting needs to properly identify the contributions of intermediate mobile nodes. In order to prevent collaborative cheating behaviors for getting feedback incentives, the authors suggest that a spanning tree rooted at the AP should be constructed to provide the routing path for any specific mobile node in cellular ad-hoc networks. The AP first determines all the mobile nodes that can be directly reached and includes these mobile nodes as trusted mobile nodes. Then the AP determines other mobile nodes that can be directly reach from the trusted nodes. Such a process is repeated until all reachable mobile nodes are included. Once the routing tree is determined, AP knows the branches and can figure out which mobile nodes are on the routing path for any specific mobile node [12].

Bejerano presents an efficient and low-cost infrastructure for connecting static multi-hop wireless networks with fixed backbone while ensuring Quality of Service (QoS) constraints such as bandwidth and delay. The proposed scheme divides the mobile nodes into clusters and selects a single access point at each cluster. A spanning tree rooted at the selected access point is used for message delivery to simplify the routing issue [13].

Table 2.3 compares the advantages and disadvantages of routing with a pre-constructed topology and routing without a pre-constructed topology in multi-hop cellular networks.

Table 2.3 Comparison between routing with a pre-constructed topology and routing without a pre-constructed topology in multi-hop cellular networks

	Routing with a pre-constructed topology	Routing without a pre-constructed topology
Advantages	● Simple for setting up a relaying path ● No additional mechanism to identify the intermediate nodes in the relaying path for accounting purpose	● Additional costs for route recovery when sending data ● Require additional mechanism to identify the intermediate nodes in the relaying path for accounting purpose
Disadvantages	● Additional costs for building the routing topology for the whole networks	● Do not need to build a routing topology for the whole networks

2.3 Incentive Scheme in Multi-hop Cellular Network Model

The potential benefits of relaying depend on the willingness of participants to carry traffic for other parties [14]. In cooperating groups, such as emergency and military situations, all nodes belong to a single authority and therefore have a good reason to support each other. However, in the groups of anonymous participants, such as emerging civilian applications, the nodes do not belong to a single authority and cooperative behaviors can not be directly assumed. In addition, forwarding data for others incurs the consumption of battery energy and the delay of its own data, the assumption of spontaneous willingness to relay data is unrealistic for autonomous mobile nodes [15-16]. Consequently, providing incentives for the mobile nodes to cooperate as relaying entities in the groups of mutually unknown participants is reasonable.

Much research has discussed the incentive schemes in pure ad-hoc or hybrid ad hoc networks. The approaches can be classified into *detection-based* and *motivation-based*. The detection-based approach finds out misbehaving nodes and mitigates their impact in the networks. The motivation-based approach provides incentives to foster positive cooperation in ad hoc networks.

2.3.1 Detection-based Incentive Approach

Marti et al. describe two techniques to improve network throughput by detecting misbehaving nodes and mitigating their impact in networks [17]. A node may misbehave by agreeing to forward packets and then fails to do so, because it is overloaded, selfish, malicious or broken. Since even a few misbehaving nodes can be a significant problem, they use a *watchdog* to identify misbehaving nodes and a *pathrater* to avoid routing packets through theses nodes. When a node forwards a packet, the node's watchdog verifies that the next node in the path also forwards the packet. As the topology indicated in Fig. 2.4, when B forwards a packet from S toward D through C, A can overhear B's transmission and verify that B pass the packet to C. The solid line indicates the packet sent by B to C, while the dashed line represents that A is within transmission range of B and can overhear the packet transfer. The pathrater combines knowledge of misbehaving nodes with link reliability to select the relaying path. Although the proposed solution fosters cooperation in ad hoc networks, it does not castigate malicious nodes but rather mitigates the burden of forwarding for others.

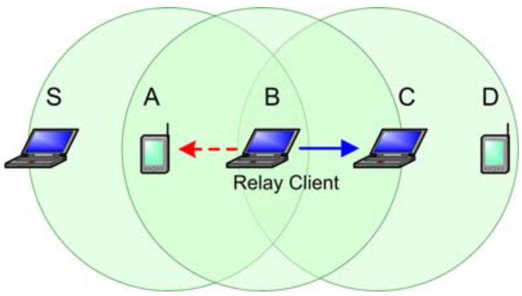


Figure 2.4 Watchdog in detecting misbehaving nodes

(Source: [17])

Michiardi et al. suggest a mechanism called CORE based on reputation to enforce cooperation among nodes and prevent denial of service attacks due to selfishness [18]. Reputation is formed and updated along time through direct observations and information provided by other members of the community. Reputation directly related to the cooperative behavior of an entity is calculated based on subjective observations and indirect information provided by other members. Besides, the reputation can be evaluated according to different functions, such as packet forwarding and routing. The overall evaluation of reputation is computed by the weight associated to the functional reputation value from subjective observations and indirect information. The request from the entity with negative reputation will not be executed. There is no advantage for an entity to misbehave since any resource utilization will be forbidden.

Buchegger et al. propose a protocol called CONFIDANT to detect and isolate misbehaving nodes, thus making it unattractive to deny cooperation [19]. Each node has four components: the Monitor, the Reputation System, the Path Manager and the Trust Manager. The Monitor detects deviations by the next node. The Trust Manager sends alarm messages to warn others of malicious nodes. The Reputation System manages a table consisting of entries for nodes and their rating. The rating is changed according to a rate function that assign different weights to the type of behavior detection. The weights for own experience are higher that for observations in the neighborhood. The Path Manager re-ranks the path according to the reputation of the nodes, deletes the path containing malicious nodes, and ignores the request for a route containing a malicious node. Non cooperating nodes are learnt from experienced, observed, or reported routing and forwarding behavior of other nodes.

Both CORE and CONFIDANT discourage misbehavior by identifying and punishing misbehavior nodes. However, they do not involve using positive cooperation incentives in the proposed methods.

2.3.2 Motivation-based Incentive Approach

Buttyán et al. use a virtual currency called *nuggets* as incentives given to cooperative nodes in every transmission [20]. Two approaches are proposed to reward intermediate nodes of packet forwarding: the *Packet Purse Model* and the *Packet Trade Model*. In the Packet Purse Model, the originator of the packet pays for the packet forwarding service. The source loads a number of nuggets in the packet and each intermediate node takes out nuggets for its forwarding service. As the example illustrated in Fig. 2.5, assume each node originally has 7 nuggets. Then, A loads 5 nuggets in the packet and sends it to the next hop B. B takes out 1 nugget from the packet and forwards it to the next hop C. Finally, C takes out 2 nuggets from the packet and forwards it to the destination D. Note that node B and C increase their stock of nuggets for forwarding the packet and node A decreases its stock of nuggets for originating the packet. The advantage of this model is that it discourages users from flooding the network but the problem is that it difficult to estimate the number of nuggets required for a given destination. In the Packet Trade Model, each packet is traded for nuggets by intermediate nodes. Each intermediate node buys the packet from the previous one for some nuggets and sells it to the next one for more nuggets on the path. As the example illustrated in Fig. 2.6, assume each node originally has 7 nuggets. Then, A sends the packet to the first hop B for free. B sells it to the next hop C for 1 nugget. Finally, C sells it to the destination D for 2 nuggets. Note that node B and C increase their stock of nuggets for forwarding the packet and node D decreases its stock of nuggets for receiving the packet. The advantage of this model is that the source does not need to know how many nuggets required to be loaded into the packet but malicious flooding of the network cannot be prevented [18]. Besides, the proposed models do not discuss the number of nuggets should be rewarded to the intermediate nodes.

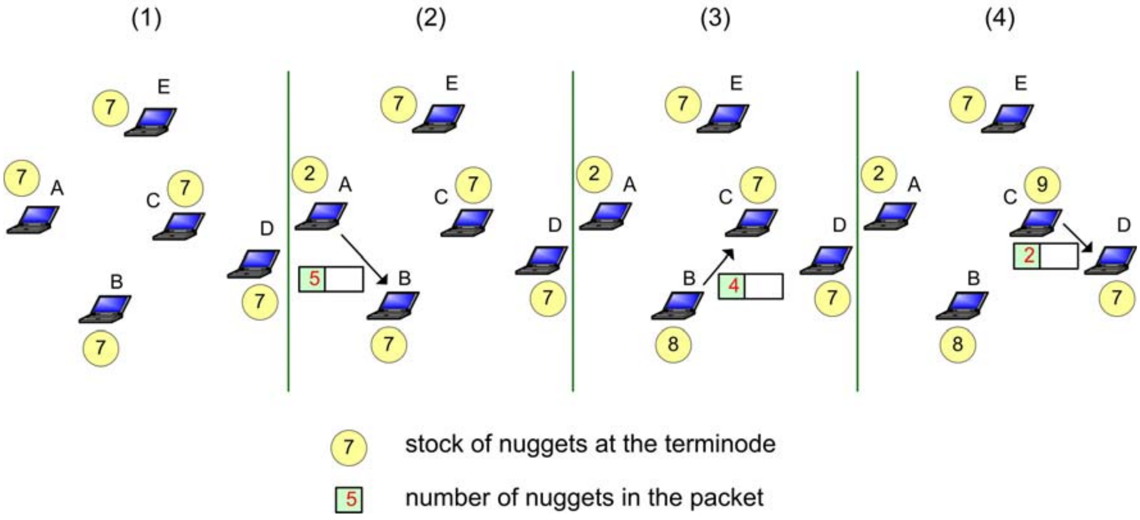


Figure 2.5 The Packet Purse Model

(Source: [20])

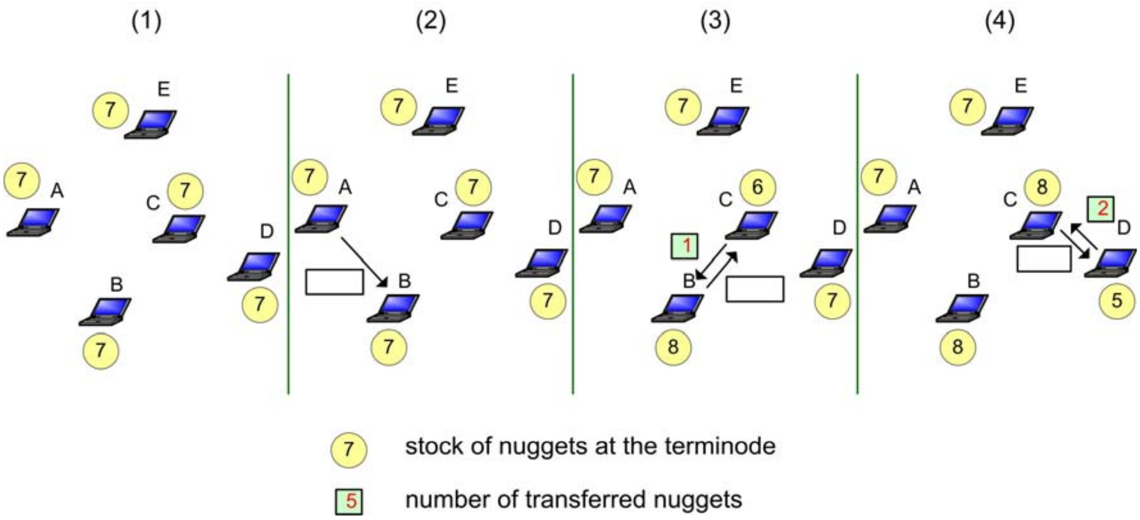


Figure 2.6 The Packet Trade Model

(Source: [20])

Buttyán et al. also propose a mechanism based on credit counter to stimulate packet forwarding [21]. Each node keeps track of its remaining energy and remaining number of nuggets. The nugget counter is decreased when the node sends an own packet, increased when the node forwards a packet. The number of feedback nuggets depends on the number of forwarding packets in this method. In [7], Jakobsson et al. present a micro-payment scheme that fosters collaboration and discourages dishonest behavior in multi-hop cellular networks. Packet originators associate subjective reward levels with packets according to the importance of the packet.

Zhong et al. propose a system to provide incentives for mobile nodes to cooperate and report actions honestly [15]. The proposed system is a pure-software solution and do not require any tamper-proof hardware at any node. A central authority is in charge of collecting receipts from the forwarding nodes and then determining the charge or the reward to each node depending on the reported receipts. The system focuses on selfish nodes and determines payment and charges from a game-theoretic perspective.

Lamparter et al. propose a charging scheme in hybrid cellular and multi-hop networks, which would be beneficial for Internet Service Provider (ISP) and the ad hoc nodes and thus motivates cooperation among mobile nodes [22]. The charging scheme is based on volume-based pricing models. A fixed price per unit is charged for sending or receiving traffic and is rewarded for forwarding traffic. The charging scheme is independent of the network conditions.

In [8], the authors propose an incentive mechanism based on a charging/rewarding scheme in multi-hop cellular networks and that makes collaboration rational for selfish nodes. The solution relies exclusively on symmetric cryptography to compliant with the limited resources of the mobile stations. In the proposed method, both the charge of sending the data packet and the reward of forwarding the data packet depend on the packet size and not on the number of forwarding nodes in the path.

From above reviews, we find most works on the motivation-based approaches focus on its protocol. The proposed incentive methods associate subjective reward levels or employ fixed-rate pricing on number of packets or volume of traffic forwarded.

Table 2.4 summarizes the difference between detection-based incentive pricing and motivation-based incentive pricing.

Table 2.4 Comparison between detection-based incentive pricing and motivation-based incentive pricing

	Detection-based incentive pricing	Motivation-based incentive pricing
Characteristics	● Identify and punish misbehaving nodes to discourage non-cooperation ● Appropriate for the mobile nodes belonging to a single authority ● Based on reputation evaluation	● Provide feedback incentives to foster positive cooperation among nodes ● Appropriate for the groups of anonymous participants
Advantages	● Do not involve accounting process	● The amount of the incentives can be adjusted according to the importance of the intermediate nodes
Disadvantages	● Avoid routing through malicious nodes only mitigates the burden of forwarding for others ● The only method to castigate misbehaving nodes is to reject its transmission requests	● Require accounting process

2.4 Supply Function for Providing Relaying Services

Pricing is an inducer for suppliers to provide services. Monetary incentives can affect the motivation of mobile nodes providing services and is usually characterized by a supply function that represents the reaction of mobile nodes to the change of the price [26]. The general supply function describes that the producers are willing to produce more goods as the price goes up. Herein we consider four forms for the supply function as follows [27]:

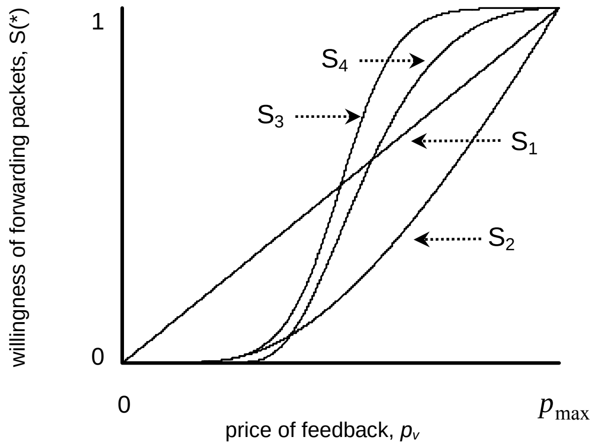
$$\text{S}_1\text{:}\quad S(p_v) = p_v / p_{\max} \quad , \quad 0 \le p_v \le p_{\max} \, , \tag{1}$$

$$\text{S}_2\text{:}\quad S(p_v) = \begin{cases} \dfrac{e^{-\left(\frac{p_{\max}}{p_v}-1\right)^2}}{\frac{P_{\max}}{p_v}} & when \quad 0 < p_v \le p_{\max} \\ 0 & when \quad p_v = 0, \end{cases} \tag{2}$$

$$\text{S}_3\text{:}\quad S(p_v) = \begin{cases} \dfrac{1}{(p_{\max}/p_v - 1)^4 + 1} & when \quad 0 < p_v \le p_{\max} \\ 0 & when \quad p_v = 0, \end{cases} \tag{3}$$

$$\text{S}_4\text{:}\quad S(p_v) = \begin{cases} e^{-\left(\frac{p_{\max}}{p_v}-1\right)^2} & when \quad 0 < p_v \le p_{\max} \\ 0 & when \quad p_v = 0, \end{cases} \tag{4}$$

where $p_{\max}$ is the maximum price that network provider can feedback, p_v is the price of the feedback incentives for node *v* per unit of relay data. $S(p_v)$ denotes the possibility of node v accepting the price to forward data packets. Note that $S(0) = 0$, which means that node v will not relay traffic for others if no feedback is provided for relaying services. The willingness of forwarding packets increases as the price of feedback increases. For $p_v = p_{\max}$, we have $S(p_{\max}) = 1$, which means that the maximum price is acceptable to all mobile nodes to provide relaying services. Figure 2.7 illustrates the difference between the four supply functions with various supply flexibility. S_1 represents a linear relationship between price of feedback and willingness of forwarding packets. S_2, S_3 and S_4 begin low for small p_v, then increase rapidly as p_v gets into a mid-range. When prices are low, S_1 is more sensitive to price changes. When prices are in the middle range, S_3 and S_4 are much more sensitive than the others to small price changes.



$$S_1 : S(p_v) = p_v / p_{\max}, \quad 0 \le p_v \le p_{\max}$$

$$S_2 : S(p_v) = \begin{cases} \dfrac{e^{-\left(\frac{p_{\max}}{p_v} - 1\right)}}{\frac{p_{\max}}{p_v}} & when \quad 0 < p_v \le p_{\max} \\ 0 & when \quad p_v = 0, \end{cases}$$

$$S_3 : S(p_v) = \begin{cases} \dfrac{1}{(p_{\max}/p_v - 1)^4 + 1} & when \quad 0 < p_v \le p_{\max} \\ 0 & when \quad p_v = 0, \end{cases}$$

$$S_4 : S(p_v) = \begin{cases} e^{-\left(\frac{p_{\max}}{p_v} - 1\right)^2} & when \quad 0 < p_v \le p_{\max} \\ 0 & when \quad p_v = 0, \end{cases}$$

Figure 2.7 Four supply functions of price of feedback and willingness of forwarding packets

Chapter 3 Dynamic Incentive Pricing in Multi-hop Cellular Networks

Cost savings and service availability are two major concerns of a network provider adopting multi-hop cellular networking technology because fewer base stations might be required but more customers could be served. Much research has discussed how to stimulate intermediate nodes to provide relaying services in multi-hop cellular networks, but most of them use static incentive pricing schemes and do not consider the current state of the networks. In this chapter, we present a dynamic incentive pricing scheme to maximize the revenue of the network provider. The proposed scheme adjusts the price of the feedback incentives based on the actual network conditions to influence the relaying capability of the network and therefore increases the revenue of the network provider. Besides, we investigate how to maximize the revenue of the network provider while ensuring Quality of Service (QoS) requirements such as new call blocking probability.

3.1 Dynamic Incentive Pricing Scheme for Relaying Services

Herein we focus only on a single base-station cell as indicated in Fig. 3.1. We define the *relaying capability* (RC) of the network as the percentage of the relaying service area in which mobile nodes can connect to the base station through peer-to-peer communications. Cooperation among nodes plays a critical role in the success of the multi-hop cellular networks, therefore the number of cooperative nodes has a significant impact on the relaying capability of the multi-hop cellular networks. We build a simulation model to observe the influence of the number of cooperative nodes on the relaying capability of the network when mobile nodes are randomly located inside the service area of the base station. As the relationship illustrated in Fig. 3.2, the relaying capability of the network increases as the number of cooperative nodes increases.

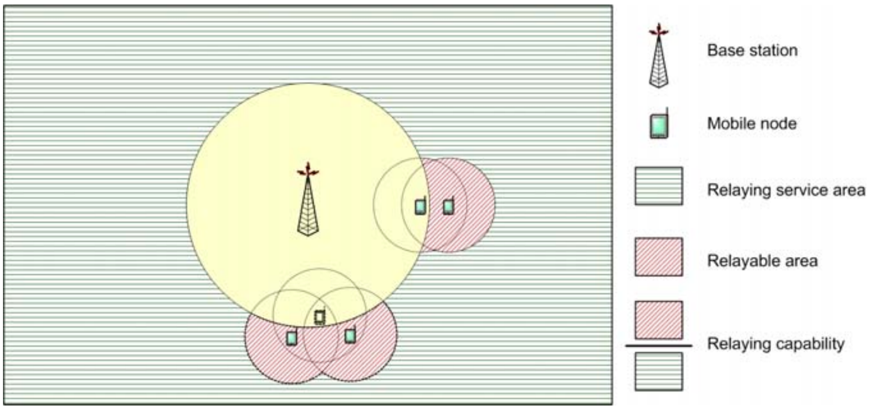


Figure 3.1 Networking model

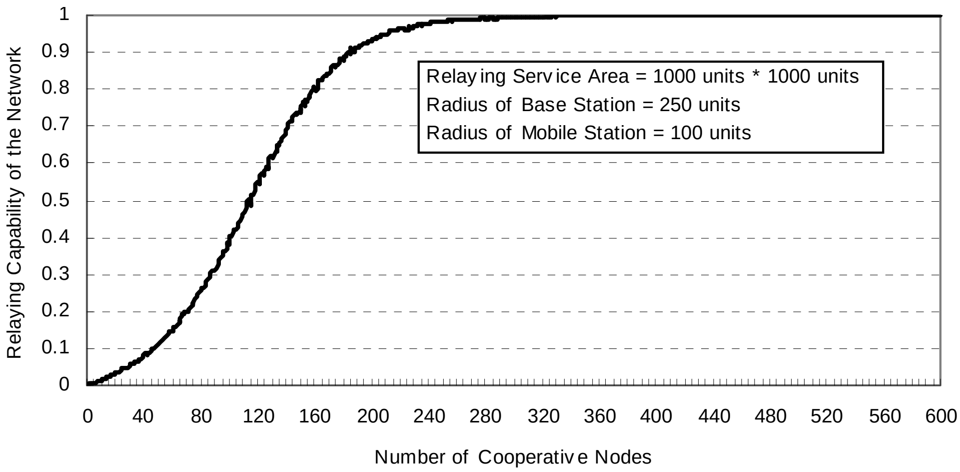


Figure 3.2 The relationship between the relaying capability of the network and the number of cooperative nodes

From above observation, we define the relaying capability of the network RC as a function of the number of cooperative nodes n, i.e., $RC = f(n)$, $f(n)$ is a function of n with the following properties:

$$0 \le f(n) \le 1; \quad f(n=0)=0; \quad \lim_{n\to\infty} f(n)=1. \tag{5}$$

Monetary incentives can affect the motivation of mobile nodes providing services. Here we use supply function S_4 to describe the reaction of mobile nodes to the change of the price.

$$S(p_t) = \begin{cases} e^{-\left(\frac{p_{\max}}{p_t}-1\right)^2} & when \quad 0 < p_t \le p_{\max} \\ 0 & when \quad p_t = 0. \end{cases} \tag{6}$$

Let p_t denotes the price of the feedback incentives per unit of relay data at time t, $p_{\max}$ is the maximum price that the network provider can feedback, $S(p_t)$ denotes the percentage of mobile nodes that will accept the price to forward data packets. Note that $S(p_{\max}) = 1$, which means that the maximum price is acceptable to all mobile nodes to provide relaying services. For $p_t = 0$, we have $S(0) = 0$, which means that no mobile node is willing to relay traffic for others if no feedback is provided for relaying service.

Let p_t denotes the price of the feedback incentives, N_t be the number of mobile nodes and RC_t be the relaying capability of the network at time t. From our observation, RC_t is a function of the number of cooperative nodes that depends on total number of mobile nodes and their willingness to support relaying services, that is,

$$RC_t = f(N_t S(p_t)). \tag{7}$$

Assume K_t is the number of mobile nodes that request data transmission at time t. The availability of the relaying paths is determined by RC_t, thus the number of successful connections M_t at time t is given by

$$M_t = K_t RC_t. \tag{8}$$

Assume the static usage-based charging model is accepted by the end users, i.e. end users agree to pay the network provider (base station) a fixed price u, per unit of data transmitted in each hop. Let v_i be the unit of data sent by user i, h_i be the number of hops exists between user i and the base station at time t, the revenue from the service for user i is $(u - p_t)h_i v_i$. Since the base station is interested in maximizing its revenue, the corresponding maximization problem at time t is given as follows:

$$\text{Maximize} \quad R = \sum_{i=1}^{M_t} ((u - p_t) h_i v_i) \tag{9}$$

$$\text{Subject to:} \quad M_t = K_t RC_t = K_t f(N_t S(p_t))$$

$$S(p_t) = \begin{cases} e^{-\left(\frac{u}{p_t} - 1\right)^2} & when \quad 0 < p_t \le u \\ 0 & when \quad p_t = 0. \end{cases}$$

In order to maximize the revenue, the network provider should increase p_t to enhance the relaying capability of the network and therefore increase the number of successful connections. However, the increase in p_t will decrease the revenue $(u - p_t)h_i v_i$ from user i. Consequently, the network provider should dynamically adjust p_t based on the actual network conditions to maximize the revenue.

For $p_t = 0$, we can obtain $M_t = K_t f(N_t S(p_t = 0)) = 0$, and for $p_t = u$, we can obtain $M_t = K_t f(N_t S(p_t = u)) = K_t f(N_t) \le K_t$. For $i = 1, ..., M_t$, the revenue $(u - p_t)h_i v_i$ received from user i decreases as p_t increases. For $p_t = 0$, we have $(u - p_t)h_i v_i = uh_i v_i$, and for $p_t = u$, we have $(u - p_t)h_i v_i = 0$.

Since both M_t and $(u - p_t)h_i v_i$ have a minimum and a maximum value over the closed interval $p_t \in [0, u]$, $R = \sum_{i=1}^{M_t} ((u - p_t)h_i v_i)$ also has a minimum and a maximum value over the same interval.

From the above discussion, the minimum value is obtained at the endpoints of the closed interval. Specifically, R is zero either when $p_t = 0$, which corresponds to the case that no successful relaying connection exists in the networks, or when $p_t = u$, which corresponds to the case that the charges from end users are equal to the costs of providing relaying services.

Let R_t^m be the maximum value of the revenue of the network provider at time t. From above analysis, we conclude that there exists at least one p_t value(s), denoted by p_t^i

($i = 0,1,...$), over interval $(0, u)$ such that:

$$R(p_t = p_t^i) = R_t^m . \tag{10}$$

If only one p_t^i exists that satisfies (10), the optimal price of the feedback incentives is $p_t^* = p_t^0$. If more than one different values of p_t^i satisfy (10), we set the optimal price of the feedback incentives to be $p_t^* = \sup_{i \in \{0,1,...\}} \{p_t^i \mid R(p_t^i) = R_t^m\}$, which is the highest price of the feedback incentives that can maximize the total revenue of the network provider. The reason we select the maximum p_t^i is that the number of successful connections increases as the price of the feedback incentives increases, therefore the network provider can support relaying services with a lower new call blocking probability.

3.2 Dynamic Incentive Pricing Scheme for Relaying Services with QoS Constraints

In this section, we add a constraint in the model to maximize the revenue of the network provider while ensuring Quality of Service (QoS) requirements. We define the QoS metric $Level_{qos}$ as follows:

$$Level_{qos} = 1 - P_b . \tag{11}$$

where P_b is the new call blocking probability.

In order to maintain the QoS metric $Level_{qos}$ above the required level L, the corresponding maximization problem at time t is modified as follows:

$$\text{Maximize } \; R = \sum_{i=1}^{M_t} ((u - p_t) h_i v_i) \tag{12}$$

$$\text{Subject to: } \; M_t = K_t RC_t = K_t f(N_t S(p_t))$$

$$S(p_t) = \begin{cases} e^{-\left(\frac{u}{p_t}-1\right)^2} & when \quad 0 < p_t \le u \\ 0 & when \quad p_t = 0, \end{cases}$$

$$Level_{qos} \ge L.$$

The QoS metric $Level_{qos}$ substantially depends on the price of the feedback incentives for relaying services. The lower the price of the feedback incentives, the lower the willingness of forwarding packets. Therefore a large number of calls will be blocked, which is also a great penalty to the QoS. Consequently, the network provider should set a threshold of the price of the feedback incentives based on actual network condition to meet QoS requirements. Since the acceptable threshold of the price for the network provider with the desired QoS level L and the number of total mobile nodes N_t at time t is $TP_L^{N_t} \in [0,u]$ and the revenue R has a maximum value over the closed interval $p_t \in [0,u]$, we can observe that R has a maximum value over the interval $[TP_L^{N_t}, u]$.

3.3 Simulation Model

In this section, we evaluate the performance of the proposed dynamic incentive pricing scheme in terms of the revenue of the network provider and new call blocking probability. The parameters used throughout our performance evaluation are as follows:

- A rectangular region of size 1000 units by 1000 units with a single base station located in the central point and various number of randomly distributed mobile nodes is used as the network topology. The radius of the base station is 250 units and the radius of each mobile node is 100 units.
- The number of active mobile nodes in the service area is varied with time. The variation of the number of the active mobile nodes during a 24-hour period used through out our study is indicated in Fig. 3.3.

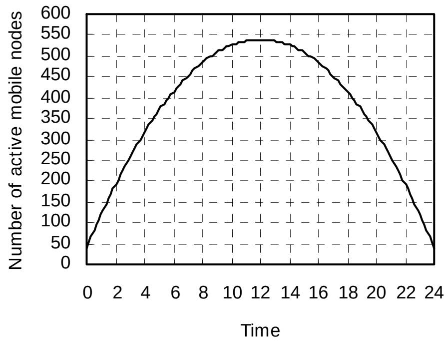


Figure 3.3 Number of active mobile nodes in the simulation area

- We assume all nodes in the relaying area request data transmissions to the base station. The volume of the data sent is randomly distributed between 0 and 100 units.
- For finding a successful connection between each mobile node and the base station, the shortest path routing protocol is used.
- In the following numerical study, we use the supply function as following:

$$S(p_t) = \begin{cases} e^{-\left(\frac{u}{p_t}-1\right)^2} & when \quad 0 < p_t \le u \\ 0 & when \quad p_t = 0. \end{cases} \tag{13}$$

where u is the price per unit of data transmitted in each hop charged from end users, and is also the maximum price that network provider willingly to feedback to the intermediate nodes for relaying services.

- The 24-hour period is divided into 10-minute sections. At the end of each section, the optimal price p_t^* of the feedback incentives to maximize the revenue is calculated.

3.4 Simulation Results and Discussions

We compare the proposed dynamic incentive pricing scheme with the static incentive pricing scheme. We use p_0 ($S(p_0)=0.25$), p_1 ($S(p_1)=0.5$), and p_2 ($S(p_2)=0.75$) as the fixed prices, which represent that 25 percent, 50 percent and 75 percent of the mobile nodes will accept this fixed price to forward data for others. Figures 3.4 and 3.5 demonstrate the simulation results by using (9) to determine the optimal price of the feedback incentives in the revenue maximization problem without QoS constraints.

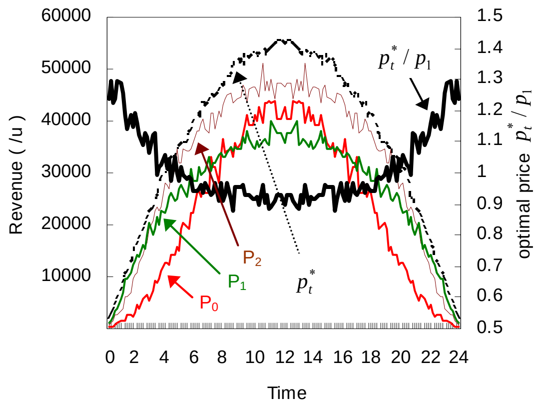


Figure 3.4 Optimal price and revenue of the network provider for different pricing schemes

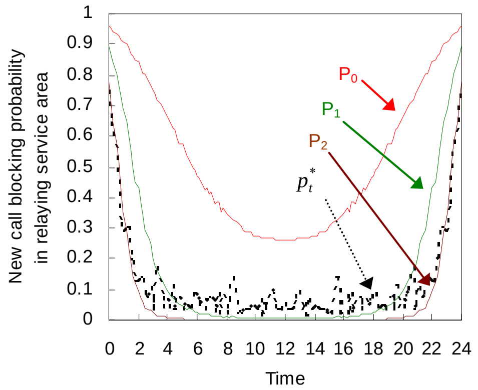


Figure 3.5 New call blocking probability in relaying service area for different pricing schemes

Figure 3.4 depicts how the price is adjusted according to the change of the network conditions during the 24-hour period. When the number of the cooperative nodes increases, i.e.

the relaying capability of the network increases, the network provider should decrease the price (p_t^* / p_1) of the incentives to maximize its revenue. Figure 3.4 also illustrates the revenue of the network provider by adopting the proposed scheme and the three static pricing schemes respectively. We find that the proposed pricing scheme results in higher revenue of the network provider than the static pricing schemes. Figure 3.5 indicates the new call blocking probability in the relaying service area for different pricing schemes. We find that the proposed pricing scheme has more revenue but does not cause a high new call blocking probability.

Figures 3.6 and 3.7 demonstrate the simulation results by using (12) to determine the optimal price of the feedback incentives and the maximum revenue of the network provider. Figure 3.6 depicts how the proposed pricing scheme adjusts the price of feedback incentives when QoS requirements L are 0.95, 0.8, 0.85 and 0 respectively. L=0 implies that the QoS level is not required in the pricing model. The optimal prices of incentives in the pricing model with QoS constraints are higher than that without QoS constraints. When fewer mobile nodes exist in the service area, the network provider should increase the optimal price of feedback incentives to satisfy the required QoS level. Because rewarding more incentives can increase the proportion of mobile nodes that willingly provide relaying services. Figure 3.7 indicates that the maximum revenue of the network provider is less when fewer mobile nodes exist in the service area. Because more incentives should be provided for relaying entity to maintain the desired QoS level, this increases relaying costs and decreases the revenue of the network provider.

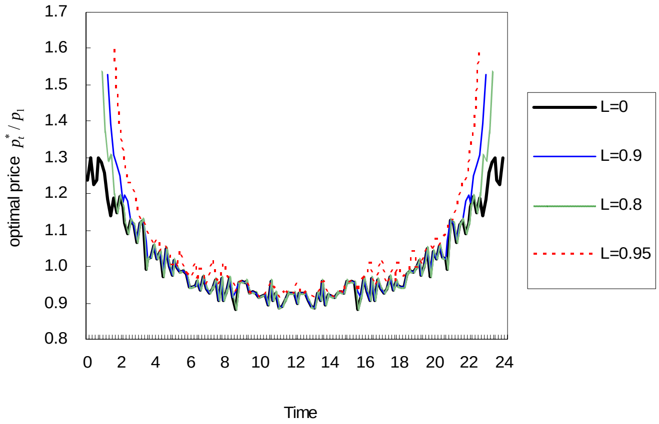


Figure 3.6 Optimal price of incentives under different QoS requirements

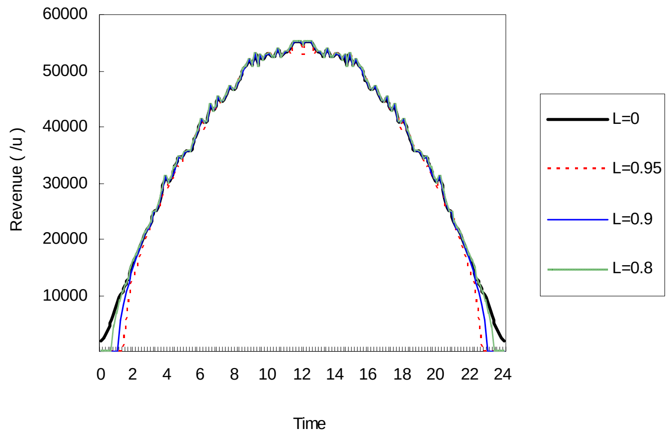


Figure 3.7 Maximum revenue of the network provider under different QoS requirements

3.5 Summary

Cost savings and service availability are the primary concerns that the network provider adopts multi-hop cellular networking technology. In this chapter, we present a dynamic incentive pricing scheme to maximize the revenue of the network provider. The proposed scheme adjusts the price of the feedback incentives based on the actual network conditions to affect the relaying capability of the network and therefore increases the revenue of the network provider. The simulation results demonstrate that the revenue can be increased by dynamically adjusting the price of the incentives for relaying services. Furthermore, the proposed pricing scheme does not cause a high new call blocking probability in relaying service area.

Chapter 4 Location-based Incentive Pricing with a Tree-based Routing Topology

4.1 Location-based Incentive Pricing Scheme for Relaying Service

Some studies have suggested that tree-based routing is appropriate for multi-hop cellular networks because of the simple characteristic and authentication requirements. In this chapter, we propose a location-based incentive pricing scheme to encourage collaboration based on the degree of each mobile node contributing to successful hop-by-hop connections. Our focus here is on the incentive pricing scheme to enhance service availability but do not cause higher costs. Since we assume the tree-based routing topology is used in multi-hop cellular networks, the proposed scheme adjusts the price of feedback incentives for each intermediate node according to the number of nodes that reside in its sub-tree. The proposed pricing scheme shifts incentives from the nodes of low importance to the nodes of high importance in the routing topology so that it increases service availability without additional costs.

Assume a tree-based topology for packets delivery is pre-constructed by the central base-station as indicated in Fig. 4.1. In order to evaluate the important degree of the location for each mobile node, we define the *location index* of a mobile node v, denoted by LI_v, as the number of nodes that reside in the tree rooted at node v. Because node v is one of the intermediate nodes on the paths from all nodes in its sub-tree to the base station, the willingness of node v for relaying packets has a significant impact on the success of the multi-hop connections from all nodes in its sub-tree to the base station. Therefore LI_v is defined in proportion to the number of nodes affected by node v. As the tree-based relaying topology depicted in Fig. 4.1, the respective location indices of node a, c, f, g, h, j are 4, 2, 3, 2, 1, 2 according to the definition of location index.

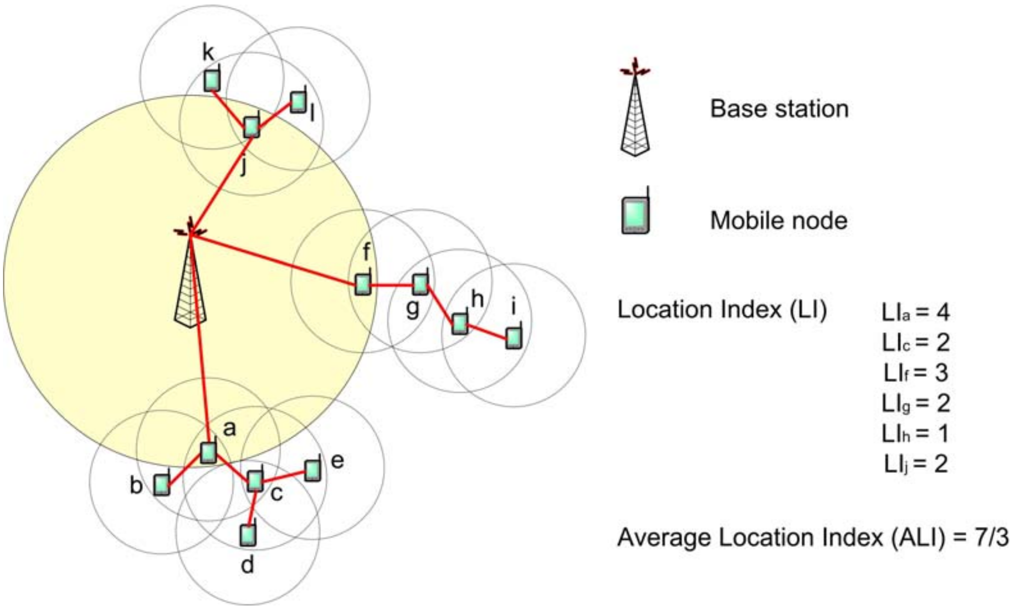


Figure 4.1 An example of tree-based relaying topology in multi-hop cellular networks

Let N be the set of intermediate nodes providing relaying services for mobile nodes that require hop-by-hop connections to the base station, ALI be the average location index of all nodes in N, that is,

$$ALI = (\sum_{v \in N} LI_v)/(\sum_{v \in N} 1)\,. \tag{14}$$

Then, the proposed location-based incentive pricing scheme assigns the price of the feedback incentives for node v, p_v, as follows,

$$p_v = p_0 + (LI_v - ALI) * \frac{R_p}{R_{LI}} * \frac{1}{LI_v} \tag{15}$$

where $R_p = \min\{p_0, \; p_{\max} - p_0\}$

$$R_{LI} = \max\{ALI - \min_{v \in N}\{LI_v\}, \; \max_{v \in N}\{LI_v\} - ALI\}\,.$$

p_0 is the price adopted in the fixed-rate pricing method, the proposed scheme employs p_0 as a basic price and derives p_v according to the difference between LI_v and the average location index ALI. The parameter R_p / R_{LI} is used to make p_v in the interval $[0,\ p_{\max}]$. The parameter $1/LI_v$ aims to balance total costs of feedback.

4.2 Location-based Pricing v.s. Fixed-rate Pricing

In this section, we compare the proposed location–based pricing scheme with fixed-rate pricing scheme by the total costs of the feedback incentives and the service availability of the networks.

4.2.1 Total Costs of Feedback Incentives

Assume each mobile node that requires relaying connections has identical traffic load u. Since LI_v is equal to number of nodes sending data through node v, the total costs of feedback for intermediate nodes in the fixed-rate pricing scheme with price p_0 is given by

$$\sum_{v \in N} (u * LI_v * p_0) . \tag{16}$$

The set N of nodes can be divided into three subsets: $N_{LI<ALI}$ where location index of the node is below ALI, $N_{LI=ALI}$ where location index of the node is equal to ALI, and $N_{LI>ALI}$ where location index of the node is above ALI. The total costs of feedback in the proposed pricing scheme with basic price p_0 is given by

$$\begin{aligned} & \sum_{v \in N_{LI<ALI}} \left(u * LI_v * \left(p_0 - (ALI - LI_v) * \frac{R_p}{R_{LI}} * \frac{1}{LI_v}\right)\right) + \sum_{v \in N_{LI=ALI}} (u * LI_v * p_0) \\ & + \sum_{v \in N_{LI>ALI}} \left(u * LI_v * \left(p_0 + (LI_v - ALI) * \frac{R_p}{R_{LI}} * \frac{1}{LI_v}\right)\right) \\ & = \left(\sum_{v \in N_{LI<ALI}} (u * LI_v * p_0) + \sum_{v \in N_{LI=ALI}} (u * LI_v * p_0) + \sum_{v \in N_{LI>ALI}} (u * LI_v * p_0) \right) \end{aligned} \tag{17}$$

$$+\frac{u*R_p}{R_{LI}}\Big(\sum_{v\in N_{LI>ALI}}(LI_v - ALI) \;-\; \sum_{v\in N_{LI<ALI}}(ALI - LI_v) \Big)$$

$$= \Big(\sum_{v\in N_{LI<ALI}}(u*LI_v*p_0) + \sum_{v\in N_{LI=ALI}}(u*LI_v*p_0) + \sum_{v\in N_{LI>ALI}}(u*LI_v*p_0) \Big) + \frac{u*R_p}{R_{LI}}*0$$

$$= \sum_{v\in N}(u*LI_v*p_0)\,.$$

From above computation, we can find that the total costs of the feedback incentives in the proposed pricing scheme is equal to that in the fixed-rate pricing scheme.

4.2.2 Service Availability

Let M_x be the set of intermediate nodes on the path from node x to the base station in the pre-constructed routing topology and PA_x be the *path availability* between node x and the base station. In multi-hop cellular networks, data packets must be relayed hop by hop from a given mobile node to a base station, thus the path availability from a mobile node to the base station depends on the individual willingness of each mobile node to forward packets on the routing path, that is,

$$PA_x = \prod_{v\in M_x} S(p_v)\,. \tag{18}$$

Since networking services provided by the base station are available when the mobile nodes can connect to the base station successfully, we define the service availability of the whole relaying networks as the average path availability of all mobile nodes using relaying connections. Let K be the set of the mobile nodes that require hop-by-hop connections to the base station, the service availability of the whole relaying networks is defined as follows:

$$SA = (\sum_{x\in K} PA_x)/(\sum_{x\in K} 1)\,. \tag{19}$$

Consider the relaying topology indicated in Fig. 4.1, the location-based pricing scheme decreases the price of feedback for the nodes close to leaf nodes and increases the price of feedback for the nodes close to the base station in the routing tree. In Fig. 4.1, the proposed pricing scheme gives higher price of feedback to node f than node h because node f affects three nodes and node h affects only one node in connecting to the base station. Table 4.1 displays the comparison between fixed-rate pricing and location-based pricing for the tree-based relaying topology indicated in Fig. 4.1. The linear supply function (1) is used and $0.5p_{\max}$ ($S(0.5p_{\max}) = 0.5$) is set as the fixed price in fixed-rate pricing scheme and the basic price in the location-based pricing scheme. From the service availability listed in Table 4.1, we find that the location–based pricing scheme can provide higher service availability than the fixed-rate pricing scheme.

Table 4.1 Comparison between fixed-rate pricing and location-based pricing for the tree-based relaying topology in Fig. 4.1

	Fixed-rate pricing	Location-based pricing
Price of feedback	$p_a = p_c = p_f = p_g = p_h = p_j = S^{-1}(0.5) = 0.5p_{max}$	$p_0 = 0.5p_{max}$ $\min_{v\in N}\{LI_v\} = 1$ $\max_{v\in N}\{LI_v\} = 4$ $ALI = \frac{7}{3}$ $R_p = 0.5p_{max}$ $R_{LI} = \frac{5}{3}$ $p_a = 0.5p_{max} + (4-\frac{7}{3}) * (0.5p_{max}/\frac{5}{3}) * (\frac{1}{4}) = 0.625p_{max}$ $p_f = 0.5p_{max} + (3-\frac{7}{3}) * (0.5p_{max}/\frac{5}{3}) * (\frac{1}{3}) = 0.567p_{max}$ $p_c = p_g = p_j = 0.5p_{max} + (2-\frac{7}{3}) * (0.5p_{max}/\frac{5}{3}) * (\frac{1}{2}) = 0.45p_{max}$ $p_h = 0.5p_{max} + (1-\frac{7}{3}) * (0.5p_{max}/\frac{5}{3}) * (\frac{1}{1}) = 0.1p_{max}$
Path availability	$PA_b = PA_c = S(p_a) = 0.5$ $PA_d = PA_e = S(p_a)S(p_c) = 0.25$ $PA_g = S(p_f) = 0.5$ $PA_h = S(p_f)S(p_g) = 0.25$ $PA_i = S(p_f)S(p_g)S(p_h) = 0.125$ $PA_k = PA_l = S(p_j) = 0.5$	$PA_b = PA_c = S(p_a) = 0.625$ $PA_d = PA_e = S(p_a)S(p_c) = 0.281$ $PA_g = S(p_f) = 0.567$ $PA_h = S(p_f)S(p_g) = 0.255$ $PA_i = S(p_f)S(p_g)S(p_h) = 0.026$ $PA_k = PA_l = S(p_j) = 0.45$
Service availability	SA = (0.5+0.5+0.25+0.25+0.5+0.25 +0.125+0.5+0.5)/9 = **0.375**	SA = (0.625+0.625+0.281+0.281+0.567+0.255 +0.026+0.45+0.45)/9 = **0.3956 > 0.375**

4.3 Simulation Model

In Section 4.2, we compare the proposed pricing scheme with the fixed-rate pricing scheme through the analysis of a simplified case, and show that the proposed location-based pricing scheme provides higher service availability than the fixed-rate pricing scheme. In order to study the proposed pricing scheme in a more general setting, we conduct simulations of a multi-hop celular network. In this section, we describe our simulator and discuss the simulation results.

The simulator was written in C++ language. Table 4.2 lists the simulation parameters. The simulation environment is a rectangular region of size 400 units by 400 units with a single base station located in the central point. The radius of the base station is 150 units and the radius of each mobile node is 100 units. For different number of mobile nodes randomly distributed in the rectangular region, the simulator constructs a tree-based topology to relay data between each mobile node and the base station. Herein a shortest path tree is built so that each mobile node connects to the base station with minimum number of hops.

Table 4.2 Simulation parameters

Parameter	Value
Space	400 units * 400 units
Radius of the base station	150 units
Radius of the mobile node	100 units
Mobility model	Random waypoint mobility model (speed : 0-5 units/s, pause time: 10 second)
Call arrival	Poisson process with arrival rate 0.05 calls/second
Call duration	Exponential with mean 20 seconds
Traffic Generator	10 units/second
Routing	Shortest path tree rooted at the base station
Simulation time	200 seconds

The mobile nodes move according to the random waypoint mobility model [24]. Each mobile node starts its journey from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0-5 units/s). Once the destination is reached, another random destination is targeted after a 10-second pause time. The arrival of new data transmission requests initiating in each mobile node forms a Poisson process with rate λ=0.05 calls/second and the data transmission times are exponentially distributed with mean 20 seconds. Each mobile node sends data with a constant rate of 10 units per second. Each simulation was run for 200 seconds.

4.4 Simulation Results and Discussions

4.4.1 Service Availability

In this section, we evaluate the performance of the proposed location-based incentive pricing scheme in terms of service availability with different supply functions described in Chapter 2.

We compare the proposed incentive pricing scheme with the fixed-rate pricing scheme by adopting p_0 ($S(p_0) = 0.5$, $S(p_0) = 0.4$) as the fixed price in the fixed-rate pricing scheme and the basic price in the proposed pricing scheme. When a mobile node initiates a new request for data transmission by relaying paths, we calculate the path availability from the mobile node to the central base station according to different prices of feedback set by the fixed-rate pricing scheme and the proposed location-based pricing scheme, respectively. Then the service availability of the whole relaying networks is obtained from the average path availability of all new connection requests from the mobile nodes. In Figs. 4.2 through 4.4, we observe that the location-based incentive pricing scheme results in higher service availability than the fixed-rate pricing scheme under various number of mobile nodes for different supply functions.

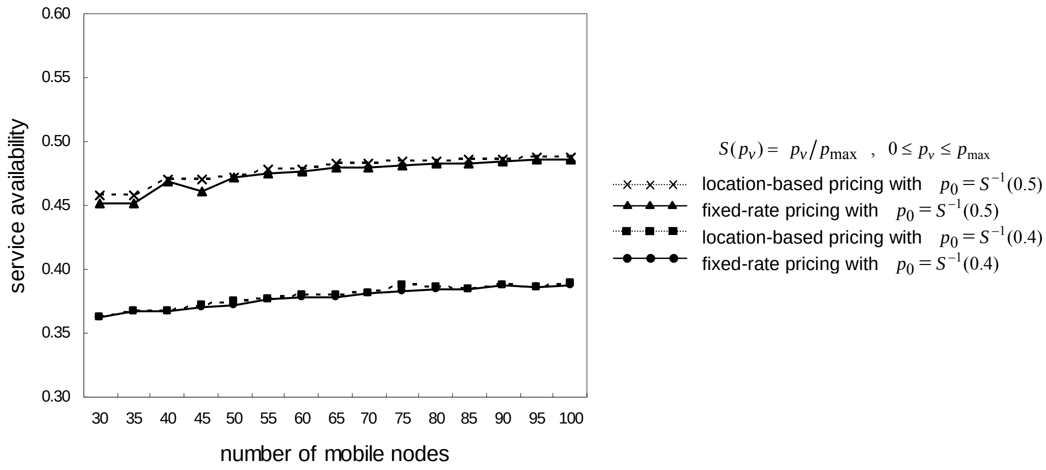


Figure 4.2 Comparison of service availability by fixed-rate pricing and location-based pricing under different number of mobile nodes with supply function S_1

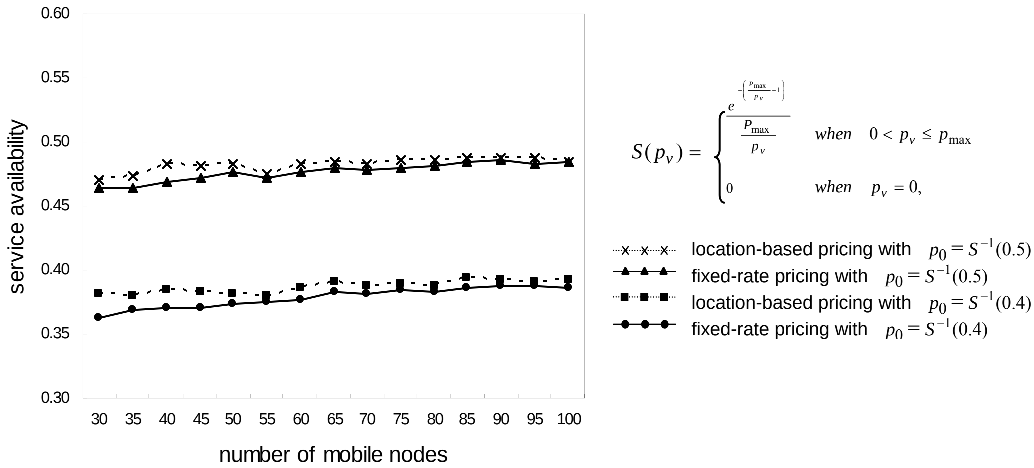


Figure 4.3 Comparison of service availability by fixed-rate pricing and location-based pricing under different number of mobile nodes with supply function S_2

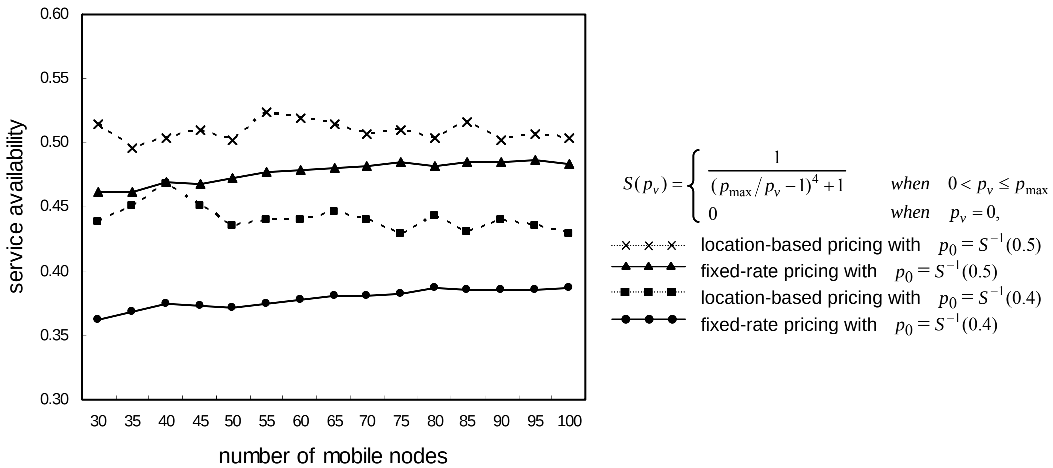


Figure 4.4 Comparison of service availability by fixed-rate pricing and location-based pricing under different number of mobile nodes with supply function S_3

According to Figs. 4.2 through 4.4, we summarize the increment in service availability between the fixed-rate pricing scheme and the proposed pricing scheme under various number of mobile nodes for different supply functions in Table 4.3. By examining Table 4.3, we notice:

- Comparing the increment in service availability obtained by different supply functions, we find the enhancements obtained by S_2 and S_3 are more significant. In real word, S_2 and S_3 are more appropriate than the linear function S_1 to describe the user behaviour of a supplier. Consequently, the proposed pricing scheme can be adopted for motivating the users of wireless devices to provide relaying services in multi-hop cellular networks.
- Comparing the increment in service availability obtained by different basic prices, we observe that the enhancement obtained in p_0 ($S(p_0) = 0.4$) is more significant for S_2 and S_3. Because mobile nodes are more sensible to the change of price of feedback in $p_0 = S^{-1}(0.4)$ than that in $p_0 = S^{-1}(0.5)$ for both S_2 and S_3. The enhancements obtained by different basic prices are not obviously distinct for the linear supply function S_1 with constant supply flexibility.
- Comparing the increment in service availability obtained by different number of mobile nodes, we find the enhancements in small number of mobile nodes are more significant than large number of mobile nodes. When fewer mobile nodes exist in the service area, each mobile node may play a critical role to forward data for others and its willingness of forwarding data has a greater impact on the success of the hop-by-hop connections. Consequently, shifting incentives from the nodes of low importance to the nodes of high importance in the routing topology by the proposed pricing scheme enhances more service availability for few mobile nodes staying in multi-hop cellular networks.

Table 4.3 Comparison of increment in service availability under various number of mobile nodes for different supply functions

Number of mobile nodes	$p_0 = S^{-1}(0.4)$			$p_0 = S^{-1}(0.5)$		
	S_1	S_2	S_3	S_1	S_2	S_3
30	0.0009	0.0186	0.0768	0.0011	0.0073	0.0525
40	0.0005	0.0141	0.0936	0.0022	0.0137	0.0348
50	0.0027	0.0075	0.0638	0.0003	0.0063	0.0298
60	0.0007	0.0091	0.0611	0.0011	0.0070	0.0405
70	0.0005	0.0059	0.0605	0.0037	0.0039	0.0246
80	0.0013	0.0044	0.0569	0.0009	0.0035	0.0216
90	0.0010	0.0056	0.0538	0.0016	0.0016	0.0168
100	0.0010	0.0065	0.0420	0.0017	0.0002	0.0196
Average	0.0011	0.0089	0.0636	0.0016	0.0054	0.0300

4.4.2 Total Costs of Feedback Incentives

In Section 4.2, we verify that the total costs of feedback are equivalent in the proposed method and the fixed-rate pricing method when all nodes connected by relaying paths send identical volume of traffic to the base station. However, the mobile nodes may not have identical traffic load. Consequently, we compare the total costs of feedback incentives when the mobile nodes connected by relaying paths send different volume of traffic to the base station. Table 4.4 lists total costs of feedback incentives in the proposed incentive pricing scheme and in the fixed-rate pricing scheme by adopting p_0 ($S(p_0) = 0.5$, $S(p_0) = 0.4$) as the fixed price in the fixed-rate pricing scheme and the basic price in the proposed pricing scheme. We summarize the percentage of increase in total relaying costs given to the intermediate nodes from the fixed-rate pricing scheme to the proposed location-based pricing scheme for different supply functions in Table 4.5. We observe that the percentage of increase in total relaying costs is between 1% and -1%. That represents no significant difference in total relaying costs between the proposed location-based pricing and the fixed-rate pricing.

Table 4.4 Comparison of total costs of feedback incentives (x 10^3 p_0) under various number of mobile nodes for different supply functions

Number of mobile nodes	$p_0 = S^{-1}(0.4)$						$p_0 = S^{-1}(0.5)$					
	S_1		S_2		S_3		S_1		S_2		S_3	
	FR pricing	LB pricing	FR pricing	LB pricing	FR pricing	LB pricing	FR pricing	LB pricing	FR pricing	LB pricing	FR pricing	LB pricing
30	12.79	12.87	12.87	12.95	13.65	13.71	15.77	15.87	15.67	15.72	16.17	16.20
35	14.78	14.76	18.46	18.46	17.00	17.24	18.95	19.05	18.48	18.49	18.29	18.32
40	17.64	17.64	19.06	19.11	20.03	20.05	20.78	20.85	21.71	21.72	21.42	21.59
45	19.07	19.14	22.34	22.32	23.88	23.95	24.11	24.08	24.11	24.10	26.13	26.10
50	22.21	22.23	24.88	24.90	27.31	27.24	28.05	28.15	25.73	25.70	27.05	27.00
55	23.21	23.31	30.20	30.16	29.10	29.12	31.41	31.32	30.27	30.25	30.68	30.81
60	26.70	26.60	31.14	31.17	31.02	31.10	33.01	32.93	31.99	31.98	32.65	32.75
65	29.23	29.24	30.78	30.77	34.88	34.96	35.43	35.44	35.44	35.43	33.75	33.62
70	32.07	32.01	35.36	35.37	36.64	36.65	40.29	40.28	39.93	39.93	40.22	40.22
75	32.69	32.72	38.02	38.11	38.47	38.47	41.44	41.51	41.86	41.86	42.28	42.21
80	33.99	34.01	39.25	39.25	42.04	41.95	43.15	43.30	43.91	43.98	42.76	42.85
85	36.98	36.94	41.83	41.83	44.72	44.77	47.65	47.57	46.79	46.82	47.21	47.11
90	37.78	37.86	45.48	45.55	46.09	46.14	49.00	48.97	46.78	46.79	48.20	48.31
95	41.63	41.61	49.55	49.48	49.07	49.10	52.42	52.50	52.94	52.91	51.02	51.02
100	44.43	44.44	50.54	50.46	51.54	51.55	54.95	55.00	53.12	53.15	53.50	53.57

FR pricing: fixed-rate pricing LB pricing: location-based pricing

Table 4.5 Percentage of increase in total relaying costs from fixed-rate pricing to location-based pricing for different supply functions

Number of mobile nodes	$p_0 = S^{-1}(0.4)$			$p_0 = S^{-1}(0.5)$		
	S_1	S_2	S_3	S_1	S_2	S_3
30	0.60%	0.65%	0.47%	0.65%	0.35%	0.23%
40	-0.02%	0.25%	0.09%	0.35%	0.04%	0.80%
50	0.07%	0.07%	-0.26%	0.37%	-0.11%	-0.21%
60	-0.38%	0.07%	0.28%	-0.24%	-0.01%	0.29%
70	-0.17%	0.01%	0.03%	-0.04%	0.00%	0.00%
80	0.06%	0.00%	-0.19%	0.35%	0.17%	0.21%
90	0.21%	0.14%	0.12%	-0.07%	0.03%	0.22%
100	0.03%	-0.16%	0.02%	0.10%	0.05%	0.13%

4.5 Summary

In this chapter, we present a location-based incentive pricing scheme to enhance service availability by adjusting the price of feedback incentives based on the importance of the mobile nodes in the routing topology. The proposed scheme shifts incentives from the nodes of low importance to the nodes of high importance in the routing topology so that it increases service availability without additional costs. Simulation results indicate that the proposed pricing scheme results in higher service availability than the fixed-rate pricing scheme under different forms for supply function of price of feedback and willingness of forwarding packets.

Chapter 5 QoR-based Incentive Pricing and Routing without a Pre-Constructed Routing Topology

5.1 QoR-based Incentive Pricing Scheme for Relaying Services

In this chapter, we propose a Quality of Relay (QoR)-based pricing scheme to determine the price of the feedback incentives for intermediate nodes based on the individual importance of each mobile node contributing to successful hop-by-hop connections. The proposed pricing scheme shifts incentives from the nodes of low importance to the nodes of high importance in the networks so that it enhances service availability with only a slight increase in relaying costs. We focus only on a single base-station cell as indicated in Fig. 5.1. The base station can enhance the service coverage by adopting relaying connections supported by the mobile nodes.

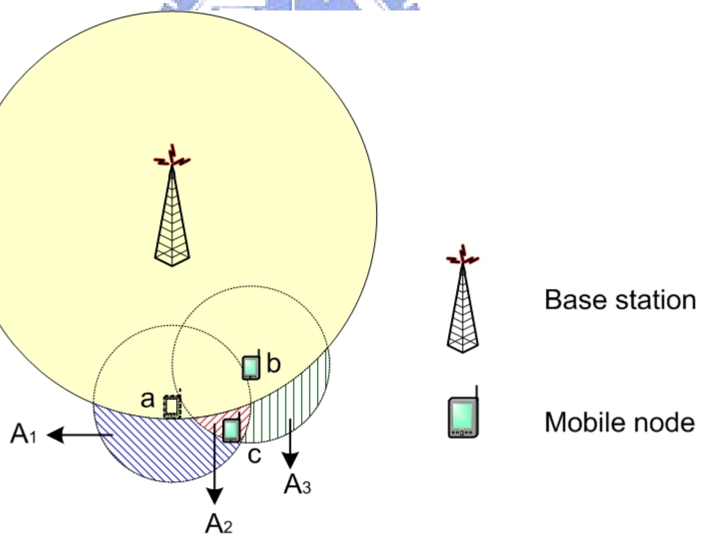


Figure 5.1 An example of multi-hop cellular networks with a single base-station

In order to evaluate the degree of a mobile node contributing to the service availability of the multi-hop cellular networks without a pre-constructed routing topology, we introduce a new metric called Quality of Relay (QoR) as follows:

$$QoR_v = \sum_{i \in C_v} \frac{1}{RI_i}. \qquad (20)$$

C_v is the set of positions inside the coverage of the node v where the mobile node requires hop-by-hop connections to reach the base station, RI_i is the *relay index* (RI) of position i that is defined to be the number of mobile nodes capable of relaying traffic for a mobile node staying in position i. As the example indicated in Fig. 5.1, $RI_{i\in A_1}$ is 1 because only node a can relay data for the mobile nodes reside in area A_1; $RI_{i\in A_2}$ is 2 because both node a and node b can relay data for the mobile nodes reside in area A_2. The degrees of node a and node b contributing to the service availability of networks are evaluated by their QoR values as follows:

$$QoR_a = \sum_{i\in C_a} \frac{1}{RI_i} = \sum_{i\in (A_1 \cup A_2)} \frac{1}{RI_i} = (A_1 * \frac{1}{RI_{i\in A_1}}) + (A_2 * \frac{1}{RI_{i\in A_2}}) = A_1 * \frac{1}{1} + A_2 * \frac{1}{2} \tag{21}$$

$$QoR_b = \sum_{i\in C_b} \frac{1}{RI_i} = \sum_{i\in (A_2 \cup A_3)} \frac{1}{RI_i} = (A_2 * \frac{1}{RI_{i\in A_2}}) + (A_3 * \frac{1}{RI_{i\in A_3}}) = A_2 * \frac{1}{2} + A_3 * \frac{1}{1} \tag{22}$$

From above equations, QoR_a is greater than QoR_b because the coverage of area A_1 is larger than that of area A_3. There are two conditions that node v has a higher QoR value:

- The node v has larger C_v, which implies it can support larger coverage where mobile nodes necessitate hop-by-hop connections to reach the base station.
- The positions inside C_v have lower RI values, which implies the mobile nodes inside C_v can be supported by fewer nodes. That is, the node v can provide relaying services to the nodes that others cannot support.

Consequently, a node with a higher QoR value represents that it has more contributions to the relaying capability of the networks, so that its high willingness of forwarding data packets can enhance the service availability of the networks. Since the higher QoR value represents that the resource of the mobile node is more valuable, the base station can apply the QoR value of a mobile node as a reference to give incentives for increasing the willingness of providing relaying services.

Let N be the set of intermediate nodes forwarding data for mobile nodes to reach the base station, $AQoR$ be the average QoR value of all nodes in N, that is,

$$AQoR = (\sum_{v \in N} QoR_v) / (\sum_{v \in N} 1) . \tag{23}$$

Then, the proposed QoR-based incentive pricing scheme assigns the price of the feedback incentives for node v, p_v, as follows:

$$p_v = p_0 + (QoR_v - AQoR) * \frac{R_p}{R_{QoR}},$$

$$\text{where } R_p = \min\{p_0, \ p_{\max} - p_0\} \tag{24}$$

$$R_{QoR} = \max\{\max_{v \in N}\{QoR_v\} - AQoR, \ AQoR - \min_{v \in N}\{QoR_v\}\}$$

p_0 is the price adopted in the fixed-rate pricing method, the proposed scheme employs p_0 as a basic price and derives p_v according to the difference between QoR_v and $AQoR$. The parameter R_p / R_{QoR} is used to adjust p_v in the interval $[0, \ p_{\max}]$.

5.2 QoR-based Routing Scheme in Multi-hop Cellular Networks

Limited capacity is a major problem in existing wireless networks, this makes only a limited number of connections can be built. Besides, forwarding data for others utilizes the resources of the mobile nodes such as battery energy, link bandwidth, buffer space and processing time. Consequently, the mobile nodes may accept only a certain number of relaying requests. In A-GSM system [3], a protocol parameter "relaying capacity" is used to tell neighboring nodes the number of calls a mobile node can simultaneously relay.

Although shortest path is the most simple and common metric used in the routing protocol, it may route almost packets over a few (shortest-distance) paths and result in network congestion and resource unavailable in hot spot [25]. In this section, we propose a new metric for routing data in multi-hop cellular networks. The proposed routing scheme selects a relaying path with minimum sum of the QoR values of all intermediate nodes in the path.

Let IM_r be the set of intermediate nodes (the nodes in the route except the source and the destination) in route r, $TQoR_r$ be the sum of the QoR values of all intermediate nodes on the route r, that is,

$$TQoR_r = \sum_{v \in IM_r} QoR_v \; . \tag{25}$$

Let R_i be the set of routes from node i to the base station, we select the route with minimum $TQoR$ value as the relaying route to connect node i to the base station. That is, the routing criteria is

$$\min_{r \in R_i} \{TQoR_r\} \; . \tag{26}$$

As the example illustrated in Fig. 5.1, node c has two choices to route data to the base station: $c \to a \to BaseStation$, $c \to b \to BaseStation$. The $TQoR$ values of these two routes are as follows:

$$TQoR_{c \to a \to BaseStation} = QoR_a \; . \tag{27}$$

$$TQoR_{c \to b \to BaseStation} = QoR_b \; . \tag{28}$$

In our routing scheme, node c selects the relaying path $c \to b \to BaseStation$ because QoR_b is less than QoR_a. The reasons that we select a relaying path with minimum $TQoR$ value are:

- As the QoR value defined in previous section, the mobile node with a higher QoR value represents that its resource is more valuable. That is, it can support larger coverage or provide relaying services to the nodes that others cannot support. The proposed routing scheme selects a relaying path with minimum $TQoR$ value first makes the valuable resource retain for later relaying connections or serve the mobile nodes that others cannot support.

- When the QoR-based incentive pricing scheme is adopted, a node with a higher QoR value will get a higher price of the feedback incentives. Selecting a relaying path with minimum *TQoR* value means that the mobile node can pay minimum costs to set up relaying connections.

5.3 Simulation Model

We compare the proposed QoR-based incentive pricing scheme with the fixed-rate pricing scheme and the proposed QoR-based routing scheme with the shortest-path routing scheme. The simulation environment is a rectangular region of size 400 units by 400 units with a single base station located in the central point. The radius of the base station is 150 units and the radius of each mobile node is 100 units. Each simulation runs for 100 seconds. The mobile nodes move according to a random waypoint mobility model [24]. Each mobile node starts its journey from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0-12 units/s). Once the destination is reached, another random destination is targeted after a 10-second pause time. The arrival of new data transmission requests initiating in each mobile node forms a Poisson process with rate λ=0.2 calls/second and the data transmission times are exponentially distributed with mean 10 seconds.

5.4 Simulation Results and Discussions

5.4.1 QoR-based Pricing v.s. Fixed-rate Pricing

In this section, we compare the proposed QoR-based pricing scheme with the fixed-rate pricing scheme. For different number of mobile nodes randomly distributed in the rectangular region, the simulator computes the probability that a mobile node outside the coverage of the base station can connect to the base station successfully. Since a pre-constructed routing topology is not available in the networks, herein we assume the mobile nodes randomly select one of the neighboring nodes that have relaying paths to the base station. We adopt p_0 ($S(p_0)=0.5$, $S(p_0)=0.4$) as the fixed price in the fixed-rate pricing scheme and the basic price in the proposed pricing scheme, which represents the mobile node will accept the price to relay data with the probability of 0.5 and the probability of 0.4 under the fixed-rate pricing scheme. In Figs. 5.2 through 5.4, we observe that the QoR-based incentive pricing scheme results in higher service availability than the fixed-rate pricing scheme under various number of mobile nodes for different supply functions.

According to Figs. 5.2 through 5.4, we summarize the percentage of improvement in service availability from the fixed-rate pricing scheme to the QoR-based pricing scheme for different supply functions in Table 5.1. Since relaying costs is one of major concerns for adopting multi-hop cellular networking model, we also list the percentage of increase in relaying costs per connection that are rewarded to the intermediate nodes in Table 5.1. By examining Table 5.1, we notice:

- The increase in service availability obtained in p_0 ($p_0 = S^{-1}(0.4)$) is more significant for S_2 and S_3. Because mobile nodes are more sensible to the change of price of feedback in $p_0 = S^{-1}(0.4)$ than that in $p_0 = S^{-1}(0.5)$ for both S_2 and S_3. The increases obtained by different basic prices are not obviously distinct for the linear supply function S_1 with constant supply flexibility.
- The QoR-based pricing scheme results in higher relaying costs per connection than the fixed-rate pricing scheme. Because the QoR-based pricing scheme gives more incentives to the nodes that affect more relaying connections to enhance service availability. However, the proposed scheme also decreases incentives for the node of low impact on relaying connections. Consequently, the increase in relaying costs

is much lower than that in service availability.

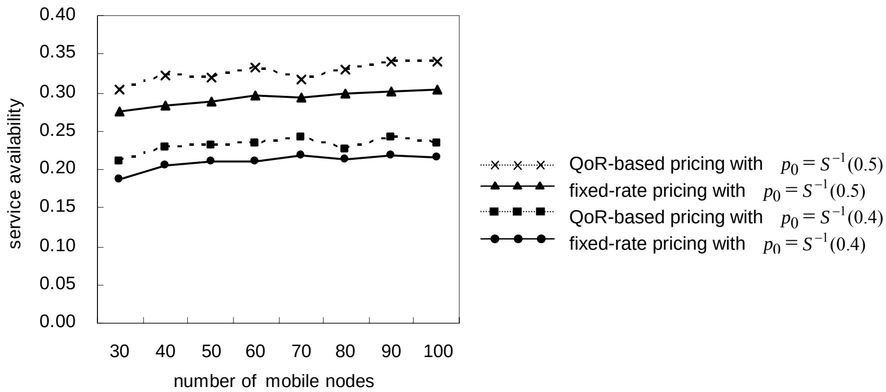


Figure 5.2 Comparison of service availability by fixed-rate pricing and QoR-based pricing under different number of mobile nodes with supply function S_1

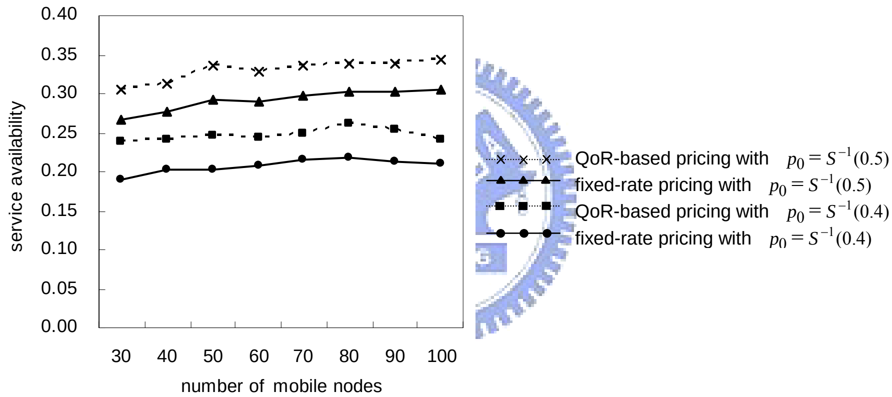


Figure 5.3 Comparison of service availability by fixed-rate pricing and QoR-based pricing under different number of mobile nodes with supply function S_2

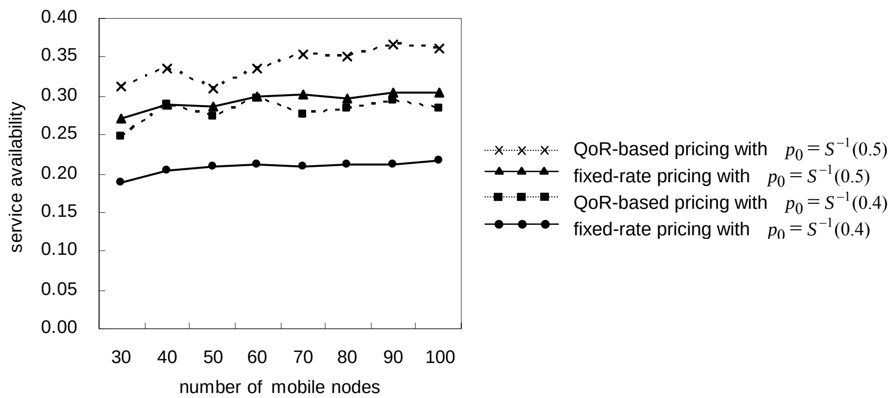


Figure 5.4 Comparison of service availability by fixed-rate pricing and QoR-based pricing under different number of mobile nodes with supply function S_3

Table 5.1 Percentage of increase in service availability and relaying costs per connection for different supply functions

	S_1		S_2		S_3	
	$p_0 = S^{-1}(0.4)$	$p_0 = S^{-1}(0.5)$	$p_0 = S^{-1}(0.4)$	$p_0 = S^{-1}(0.5)$	$p_0 = S^{-1}(0.4)$	$p_0 = S^{-1}(0.5)$
increase in service availability	10.05%	11.22%	19.13%	12.97%	34.76%	15.82%
increase in relaying costs	4.12%	4.39%	1.61%	1.18%	4.44%	4.62%

5.4.2 QoR-based Routing v.s. Shortest-path Routing

In this section, we compare the proposed QoR-based routing scheme with the shortest-path routing scheme. Herein the shortest path is determined by the relaying path with minimum hops. In order to observe the performance of different routing schemes under limited relaying resource, each mobile node only accepts a certain number of relaying requests. Herein the maximum relaying capacity for each mobile node is set as 4 or 6. In Figs. 5.5 through 5.7, we observe that the QoR-based routing scheme provides a lower new call blocking probability than the shortest-path routing scheme under various number of mobile nodes for different supply functions. Moreover, in Figs. 5.8 through 5.10, we find that the average path length in the QoR-based routing scheme is higher than that in the shortest-path routing scheme since the shortest-path routing scheme has minimum hops to reach the base station. However, the difference is not obvious. According to Figs. 5.5 through 5.10, we summarize the percentage of decrease in new call blocking probability and increase in average path length from the shortest-path routing scheme to the QoR-based routing scheme for different supply functions in Table 5.2. By examining Table 5.2, we find the increase in average path length is much lower than the decrease in new call blocking probability.

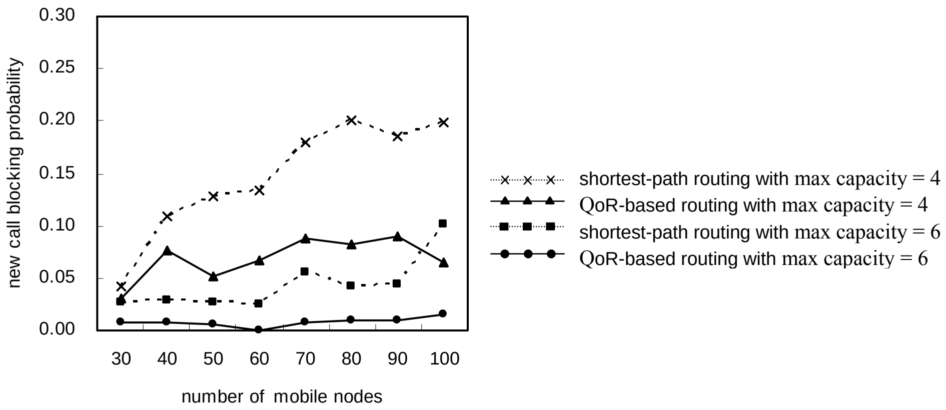


Figure 5.5 Comparison of new call blocking probability by QoR-based routing and shortest-path routing under different number of mobile nodes with supply function S_1

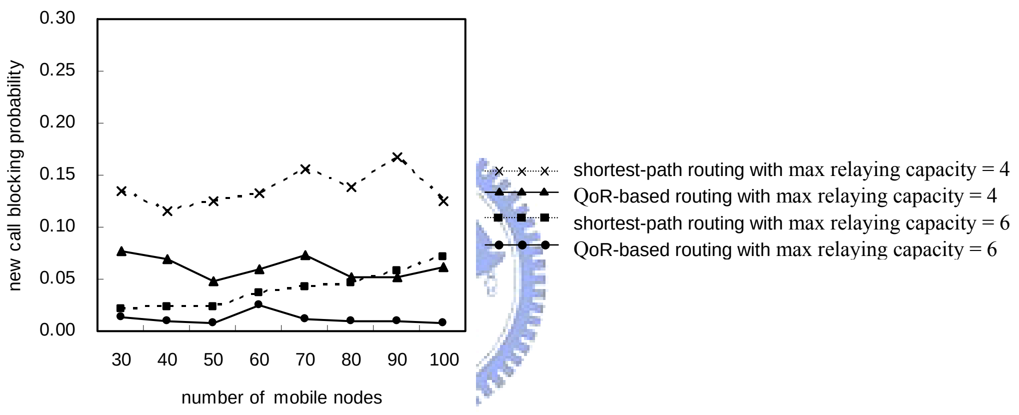


Figure 5.6 Comparison of new call blocking probability by QoR-based routing and shortest-path routing under different number of mobile nodes with supply function S_2

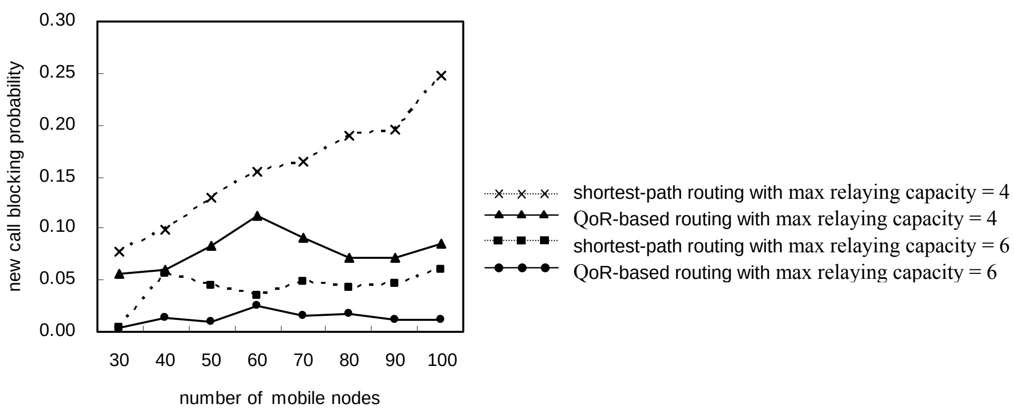


Figure 5.7 Comparison of new call blocking probability by QoR-based routing and shortest-path routing under different number of mobile nodes with supply function S_3

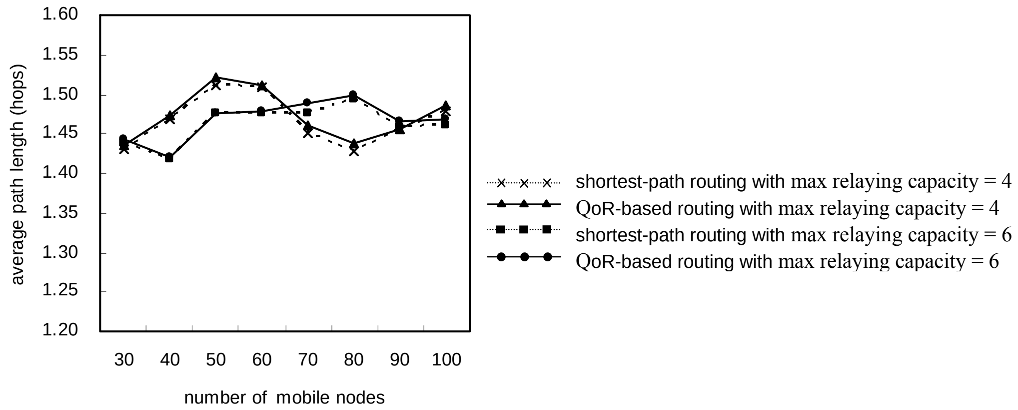


Figure 5.8 Comparison of average path length by QoR-based routing and shortest-path routing under different number of mobile nodes with supply function S_1

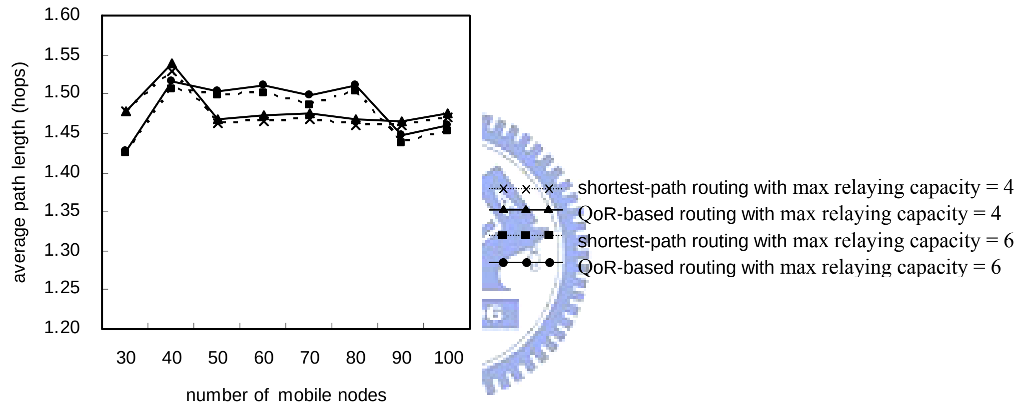


Figure 5.9 Comparison of average path length by QoR-based routing and shortest-path routing under different number of mobile nodes with supply function S_2

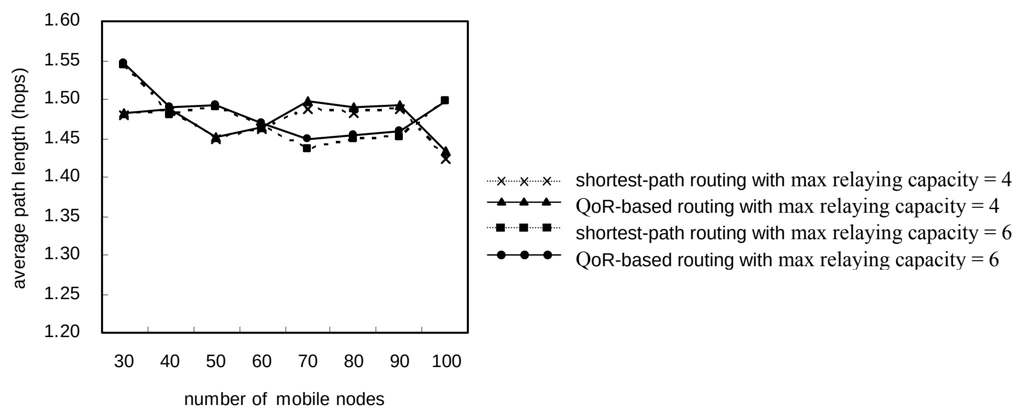


Figure 5.10 Comparison of average path length by QoR-based routing and shortest-path routing under different number of mobile nodes with supply function S_3

Table 5.2 Percentage of decrease in new call blocking probability and increase in average path length from shortest-path routing to QoR-based routing for different supply functions

maximum relaying capacity	S_1		S_2		S_3	
	4	6	4	6	4	6
decrease in new call blocking probability	49.17%	81.04%	54.16%	63.33%	45.79%	58.57%
increase in average path length	0.43%	0.33%	0.38%	0.59%	0.36%	0.38%

5.5 Summary

In this chapter, we present a QoR-based incentive pricing scheme to enhance service availability by adjusting the price of the feedback incentives based on the importance of the mobile nodes for providing relaying services. The proposed method increases incentives for nodes of high importance and decreases the incentives for nodes of low importance so that it enhances service availability with only a slight increase in relaying costs. Then, we also present a new routing scheme to select the relaying path depending on the QoR value of each intermediate mobile node in the path. The proposed routing scheme can retain more valuable resource for later relaying requests, thereby accepting more relaying connections. Simulation results indicate that the proposed QoR-based pricing scheme results in higher service availability than the fixed-rate pricing scheme. Moreover, the proposed QoR-based routing scheme causes a lower new call blocking probability than the shortest-path routing scheme under a certain constraint on maximum relaying capacity of each mobile node.

Chapter 6 Conclusions and Future Works

Cost savings and service availability are two major concerns of a network provider adopting multi-hop cellular networking technology. Monetary incentives not only affect the motivation of the intermediate nodes supporting relaying services but represent the costs of providing connection services in multi-hop cellular networks. In this research, we propose incentive pricing schemes for relaying services considering both relaying costs and service availability in multi-hop cellular networks. In order to react effectively to the dynamic and unpredictable variations of the wireless networks, we present an incentive pricing scheme based on the actual network conditions to maximize the revenue of the network provider while maintaining service availability in the networks. Simulation results demonstrate that the revenue can be increased by properly changing the price of the incentives according to the number of mobile nodes capable of providing relaying services. Furthermore, the proposed pricing scheme does not result in a high new call blocking probability in relaying service area. Consequently, dynamically adjusting the price of the incentives is more appropriate than fixed-rate pricing for the network provider to make maximum revenue.

In addition to providing a uniform price of the incentives to all mobile nodes depending on the network situations, we also investigate how to give different amount of incentives for each mobile node that has different effects on supporting hop-by-hop connections. When a pre-constructed routing topology exists in the networks, we present a location-based incentive pricing for relaying services. Since all packets simply follow the routing topology toward the destination, each intermediate node has a significant impact on the success of the multi-hop connections from all nodes in its sub-tree to the base station. The proposed location-based pricing scheme adjusts the price of the feedback incentives for each node according to the number of nodes that reside in its sub-tree. The proposed scheme shifts incentives from the nodes of low importance to the nodes of high importance in the routing topology. Simulation results indicate that the proposed pricing scheme results in higher service availability than the fixed-rate pricing scheme under different forms for supply function of price of feedback and willingness of forwarding packets.

Since the high costs of building a pre-constructed routing topology, we propose another pricing scheme for the multi-hop cellular networks without a pre-constructed routing topology. A new metric called Quality-of-Relay (QoR) is defined to evaluate the importance of each mobile node affecting other nodes that require hop-by-hop connections to reach the central base station. As the location-based pricing for tree-based relaying services, the QoR-based pricing scheme also shift incentives from the nodes of low importance to the nodes of high importance. Simulation results indicate that the QoR-based pricing scheme can enhance service availability with only a slight increase in relaying costs. Besides, we adopt QoR value of each mobile node in the networks to select a relaying path for connecting to the central base station. Although shortest path is the most simple and common metric used in the routing protocol, it may route almost packets over a few paths and result in network congestion and resource unavailable in hot spot. The routing scheme based on QoR value can retain more valuable resource for later relaying requests, thereby accepting more relaying connections. Simulation results indicate the proposed QoR-based routing scheme causes a lower new call blocking probability than the shortest-path routing scheme under a certain constraint on maximum relaying capacity of each mobile node.

Here, we would like to mention the following areas of investigation which may merit further study.

- The supply flexibility in providing relaying services can be considered as a factor in the incentive pricing scheme.
- Performance of the proposed QoR-based routing scheme is evaluated by comparing

with the shortest-path routing scheme. In this research, the QoR-based pricing scheme causes minimum relaying costs because the network provider is assumed to adopt the QoR-based incentive pricing scheme. The comparison in relaying costs between these two routing schemes when using different pricing schemes can be conducted in the future.

- In the location-based incentive pricing scheme, a basic price must be determined to adjust the price of the feedback incentives for each mobile node. The optimal price derived in the pricing model based on number of mobile nodes may be utilized as the basic price for the location-based incentive pricing scheme and the QoR-based incentive pricing scheme. The revenue of the network provider in the location-based incentive pricing scheme or the QoR-based incentive pricing scheme can be further investigated and compared to the maximum revenue of the network provider.

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