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Location-based incentive pricing for tree-based relaying in multi-hop cellular networks

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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. In this paper, we present a location-based incentive pricing scheme to enhance service availability for tree-based relaying topology. The proposed scheme adjusts the price of feedback incentives based on the degree of the mobile nodes contributing to successful hop-by-hop connections. Simulation results indicate that the location-based incentive pricing scheme results in higher service availability than the fixed-rate pricing scheme under different relationships between price of feedback and willingness of forwarding packets. Moreover, 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.

Keywords: Incentive pricing scheme; Location-based pricing; Multi-hop cellular networks

1. Introduction

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. Although many approaches in the literature have been proposed to improve the performance of cellular networks and multi-hop networks in isolation, 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.

Cooperation among nodes is an important prerequisite for the success of the relaying ad-hoc networks. Some research [1–8] has described how to stimulate intermediate nodes to forward data packets in multi-hop networks. Most of existing motivation-based approaches provide incentives for relaying services based on the number of the forwarding packets with fixed unit price. 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 importance of each mobile node in the network topology. Such approach cannot react effectively to the individual impact of each mobile node on service availability.

In this paper, we propose a location-based incentive pricing scheme to encourage collaboration based on the degree of the mobile nodes contributing to successful hop-by-hop connections. Cost savings and service availability are two major concerns of a network provider for adopting multi-hop cellular networks. 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

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of feedback incentives for each intermediate node according to the number of nodes that reside in its sub-tree. Monetary incentives not only influence the motivation of the intermediate nodes supporting relaying services but represent the costs of providing connection services in multi-hop cellular networks. 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. Simulation results indicate that the location-based incentive pricing scheme results in higher service availability than the fixed-rate pricing scheme under different relationships between price of feedback and willingness of forwarding packets.

The rest of this paper is organized as follows. In Section 2, we review the existing multi-hop cellular network models and incentive schemes for packets forwarding. Section 3 describes the detail of the proposed pricing scheme for tree-based relaying topology. Section 4 presents the simulation results and discussions. Finally, concluding remarks are recommended in Section 5.

2. Literature review

2.1. Multi-hop cellular network model

Much research has focused on integrating the cellular and multi-hop network models to leverage the advantages of each other. Opportunity Driven Multiple Access (ODMA) is an ad hoc multi-hop protocol that the transmissions from mobile hosts to the base station are broken into multiple wireless hops, thereby reducing transmission power [9–11]. In [12], Hsieh et al. investigate the impact of using peer-to-peer communications in cellular wireless packet data networks. 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 [13]. The authors extend the standard GSM radio interface with sufficiently flexible capabilities to support relaying. Qiao et al. present a network model called iCAR that integrates the cellular infrastructure and ad-hoc relaying technologies [14]. The proposed architecture places a number of Ad-hoc Relaying Stations (ARS) at strategic locations to relay data from one cell to another cell. Load balancing among different cells in the iCAR system not only increases system capacity, but also reduces transmission power for mobile terminals. Luo et al. propose a Unified Cellular and Ad-Hoc Network (UCAN) architecture to enhance the cell throughput. Each mobile device in the UCAN model has both 3G cellular link and IEEE 802.11-based peer-to-peer links. The 3G base station forwards packets for destination clients with poor channel quality to proxy clients with better channel quality [11].

Some studies have suggested that tree-based routing is appropriate for multi-hop cellular networks because of the simple characteristic and authentication requirements. A tree-based topology map for forwarding packets is preconstructed in the egress node connected to the fixed backbone. In [15], Hsiao et al. propose a load-balancing routing algorithm to achieve better network utilization by lowering bandwidth blocking rates for wireless access networks. A tree rooted at the egress node is constructed to greatly simplify routing by avoiding per-flow state. In [16], 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. 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. In [17], 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 and maximize network utilization.

2.2. Incentive scheme

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. Marti et al. describe two techniques to improve network throughput by detecting misbehaving nodes and mitigating their impact in ad hoc networks [1]. They use a *watchdog* to identify misbehaving nodes and a *pathrater* to avoid routing packets through these nodes. 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. 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 [2]. The request from the entity with negative reputation will not be executed. Buchegger et al. propose a protocol called CONFIDANT to detect and isolate misbehaving nodes, thus making it unattractive to deny cooperation [3]. Both two methods discourage misbehavior by identifying and punishing misbehavior nodes. However, they do not involve using positive cooperation incentives in the proposed methods.

The **motivation-based approach** provides incentives to foster positive cooperation in ad hoc networks. Buttyán et al. use a virtual currency called *nuglets* as incentives given to cooperative nodes in every transmission [4]. The proposed models do not discuss the number of nuglets should be feedback to the intermediate nodes. Buttyán et al. also propose a mechanism based on credit counter to stimulate packet forwarding [5]. The number of feedback nuglets depends on the number of forwarding packets in this method. In [8], 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. 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 [7]. The charging scheme is based on volume-based pricing models. A fixed price per unit is rewarded for forwarding traffic irrespective of the network conditions. In [18], the authors propose an incentive mechanism based on a charging/rewarding scheme in multi-hop cellular networks. Both the charge of sending the data packet and the reward of forwarding the data packet depend on the packet size in the proposed method.

3. Location-based incentive pricing scheme for tree-based relaying

Cost savings and service availability are two major concerns of a network provider for adopting multi-hop cellular networks. Since the price of feedback incentives reflects the costs and the probability of connections setup represents service availability, our proposed pricing scheme aims to increase the probability of connections setup with no extra cost of feedback.

3.1. Supply function for providing relaying services

The potential benefits of relaying depend on the willingness of participants to carry traffic for other parties [19]. 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. Consequently, cooperative behaviors can not be directly assumed [6]. Providing feedback incentives for the mobile nodes to cooperate as relaying entities in the groups of mutually unknown participants is reasonable.

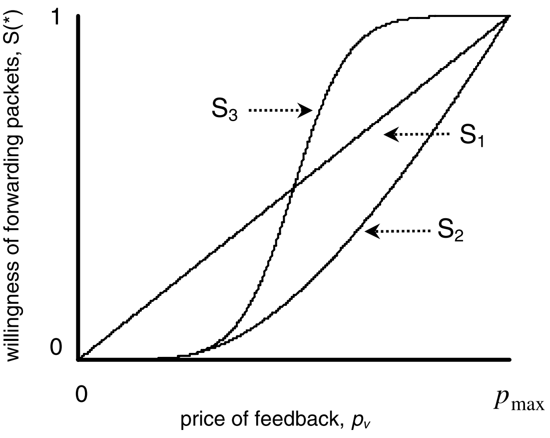
Monetary incentives can affect the motivation of mobile nodes providing services and is usually characterized by a supply function that represents the reaction of mobile nodes to the change of the price [20]. The general supply function describes that the producers are willing to produce more goods as the price goes up. Here, we consider three forms for the supply function as follows [21].

$$S(p_v) = p_v/p_{\max}, 0 \leqslant p_v \leqslant p_{\max}, \tag{1}$$

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

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

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. In our scheme, p_v is adjusted based on the degree of node v contributing to service availability in the multi-hop cellular networks. The proposed pricing scheme enhances service availability by increasing the price of the feedback incentives for the mobile nodes that affect more relaying connections. $S(p_v)$ 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. Fig. 1 illustrates the difference between the three supply functions with various supply flexibility. S_1 represents a linear relationship between price of feedback and willingness of forwarding packets. S_2 and S_3 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



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

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

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

Fig. 1. Three supply functions of price of feedback and willingness of forwarding packets.

to price changes. When prices are in the middle range, S_3 is much more sensitive than the others to small price changes.

3.2. Proposed location-based incentive pricing scheme

In this paper, we focus only on a single base-station cell. Assume a tree-based topology for packets delivery is pre-constructed by the central base-station as indicated in Fig. 2. 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. 2, 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.

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,

$$\mathrm{ALI} = \left(\sum_{v\in N} \mathrm{LI}_v\right) \Big/ \left(\sum_{v\in N} 1\right). \tag{4}$$

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

$$p_v = p_0 + (\mathrm{LI}_v - \mathrm{ALI}) * \frac{R_p}{R_{\mathrm{LI}}} * \frac{1}{\mathrm{LI}_v} \tag{5}$$

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

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

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 $1/\mathrm{LI}_v$ aims to balance total costs of feedback.

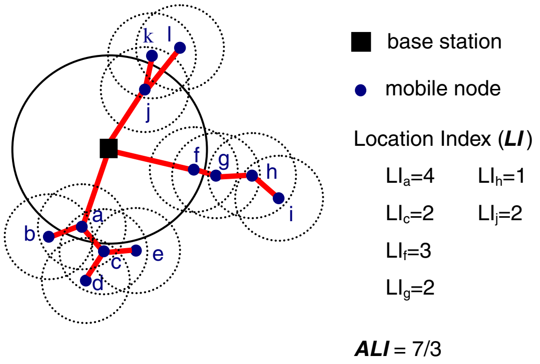


Fig. 2. An example of tree-based relaying topology in multi-hop cellular networks.

3.3. Location-based pricing v.s. fixed-rate pricing

Most of the motivation-based approaches in the literature do not discuss the price of feedback incentives or just employ fixed-rate pricing on number of packets or volume of traffic forwarded. Because each mobile node has different contributions to the service availability, the base station should assign different prices of feedback based on the individual importance of each mobile node. 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.

3.3.1. Total costs of the 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

$$\sum_{v\in N} (u *\ \mathrm{LI}_v\ *\ p_0). \tag{6}$$

The set N of nodes can divide into three subsets: $N_{\mathrm{LI}<\mathrm{ALI}}$ where location index of the node is below ALI, $N_{\mathrm{LI}=\mathrm{ALI}}$ where location index of the node is equal to ALI, and $N_{\mathrm{LI}>\mathrm{ALI}}$ 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

$$\begin{aligned}
&\sum_{v\in N_{\mathrm{LI}<\mathrm{ALI}}} \left(u * \mathrm{LI}_v * \left(p_0 - (\mathrm{ALI} - \mathrm{LI}_v) * \frac{R_p}{R_{\mathrm{LI}}} * \frac{1}{\mathrm{LI}_v}\right)\right) + \sum_{v\in N_{\mathrm{LI}=\mathrm{ALI}}} (u * \mathrm{LI}_v * p_0) \\
&\quad + \sum_{v\in N_{\mathrm{LI}>\mathrm{ALI}}} \left(u * \mathrm{LI}_v * \left(p_0 + (\mathrm{LI}_v - \mathrm{ALI}) * \frac{R_p}{R_{\mathrm{LI}}} * \frac{1}{\mathrm{LI}_v}\right)\right) \\
&= \left(\sum_{v\in N_{\mathrm{LI}<\mathrm{ALI}}} (u * \mathrm{LI}_v * p_0) + \sum_{v\in N_{\mathrm{LI}=\mathrm{ALI}}} (u * \mathrm{LI}_v * p_0) + \sum_{v\in N_{\mathrm{LI}>\mathrm{ALI}}} (u * \mathrm{LI}_v * p_0)\right) \\
&\quad + \frac{u *\ R_p}{R_{\mathrm{LI}}} \left(\sum_{v\in N_{\mathrm{LI}>\mathrm{ALI}}} (\mathrm{LI}_v - \mathrm{ALI}) - \sum_{v\in N_{\mathrm{LI}<\mathrm{ALI}}} (\mathrm{ALI} - \mathrm{LI}_v)\right) \\
&= \left(\sum_{v\in N_{\mathrm{LI}<\mathrm{ALI}}} (u * \mathrm{LI}_v * p_0) + \sum_{v\in N_{\mathrm{LI}=\mathrm{ALI}}} (u * \mathrm{LI}_v * p_0) + \sum_{v\in N_{\mathrm{LI}>\mathrm{ALI}}} (u * \mathrm{LI}_v * p_0)\right) \\
&\quad + \frac{u *\ R_p}{R_{\mathrm{LI}}} * 0 \\
&= \sum_{v\in N} (u * \mathrm{LI}_v * p_0).
\end{aligned} \tag{7}$$

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.

3.3.2. 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,

$$\mathrm{PA}_x = \prod_{v \in M_x} S(p_v). \tag{8}$$

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:

$$\mathrm{SA} = \left(\sum_{x \in K} \mathrm{PA}_x\right) \Big/ \left(\sum_{x \in K} 1\right). \tag{9}$$

Consider the relaying topology indicated in Fig. 2, 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. 2, 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 1 displays the comparison between fixed-rate pricing and location-based pricing for the tree-based relaying topology indicated in Fig. 2. For simplicity, the linear supply function (1) is used and 0.5 $p_{\max}$ ($S(0.5p_{\max}) = 0.5$) 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 1, we find that the location-based pricing scheme can provide higher service availability than the fixed-rate pricing scheme.

4. Simulations and analyses

In Section 3, 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 cellular network. In this section, we describe our simulator and discuss the simulation results.

4.1. Simulation model

The simulator was written in C++ language. Table 2 lists the simulation parameters. The simulation environment is a rectangular region of size 400 U by 400 U with a single base station located in the central point. The radius of the base station is 150 U and the radius of each mobile node is 100 U. 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.

The mobile nodes move according to the random waypoint mobility model [22]. Each mobile node starts its journey from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0 and 5 U/s). Once the destination is reached, another random

Table 2
Simulation parameters

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

Table 1
Comparison between fixed-rate pricing and location-based pricing for the tree-based relaying topology in Fig. 2

	Fixed-rate pricing	Location-based pricing
Price of feedback	$p_a = p_c = p_f = p_g = p_h = p_j = \mathrm{S}^{-1}(0.5) = 0.5p_{\max}$	$p_0 = 0.5p_{\max}$ $\min_{v \in N}\{\mathrm{LI}_v\} = 1$ $\max_{v \in N}\{\mathrm{LI}_v\} = 4$ $\mathrm{ALI} = \frac{7}{3}$ $R_p = 0.5p_{max}$ $R_{\mathrm{LI}} = \frac{5}{3}$ $p_a = 0.5p_{\max} + (4 - \frac{7}{3}) * (0.5p_{\max}/\frac{5}{3}) * (\frac{1}{4}) = 0.625p_{\max}$ $p_f = 0.5p_{\max} + (3 - \frac{7}{3}) * (0.5p_{\max}/\frac{5}{3}) * (\frac{1}{3}) = 0.567p_{\max}$ $p_c = p_g = p_j = 0.5p_{\max} + (2 - \frac{7}{3}) * (0.5p_{\max}/\frac{5}{3}) * (\frac{1}{2}) = 0.45p_{\max}$ $p_h = 0.5p_{\max} + (1 - \frac{7}{3}) * (0.5p_{\max}/\frac{5}{3}) * (\frac{1}{1}) = 0.1p_{\max}$
Path availability	$\mathrm{PA}_b = \mathrm{PA}_c = \mathrm{S}(p_a) = 0.5$ $\mathrm{PA}_d = \mathrm{PA}_e = \mathrm{S}(p_a)\mathrm{S}(p_c) = 0.25$ $\mathrm{PA}_g = \mathrm{S}(p_f) = 0.5$ $\mathrm{PA}_h = \mathrm{S}(p_f)\mathrm{S}(p_g) = 0.25$ $\mathrm{PA}_i = \mathrm{S}(p_f)\mathrm{S}(p_g)\mathrm{S}(p_h) = 0.125$ $\mathrm{PA}_k = \mathrm{PA}_l = \mathrm{S}(p_j) = 0.5$	$\mathrm{PA}_b = \mathrm{PA}_c = \mathrm{S}(p_a) = 0.625$ $\mathrm{PA}_d = \mathrm{PA}_e = \mathrm{S}(p_a)\mathrm{S}(p_c) = 0.281$ $\mathrm{PA}_g = \mathrm{S}(p_f) = 0.567$ $\mathrm{PA}_h = \mathrm{S}(p_f)\mathrm{S}(p_g) = 0.255$ $\mathrm{PA}_i = \mathrm{S}(p_f)\mathrm{S}(p_g)\mathrm{S}(p_h) = 0.026$ $\mathrm{PA}_k = \mathrm{PA}_l = \mathrm{S}(p_j) = 0.45$
Service availability	$\mathrm{SA} = (0.5 + 0.5 + 0.25 + 0.25 + 0.5 + 0.25 + 0.125 + 0.5 + 0.5)/9 = \mathbf{0.375}$	$\mathrm{SA} = (0.625 + 0.625 + 0.281 + 0.281 + 0.567 + 0.255 + 0.026 + 0.45 + 0.45)/9 = \mathbf{0.3956} > \mathbf{0.375}$

destination is targeted after a 10-s pause time. The arrival of new data transmission requests initiating in each mobile node forms a Poisson process with rate $\lambda = 0.05$ calls/s and the data transmission times are exponentially distributed with mean 20 s. Each mobile node sends data with a constant rate of 10 U per second. Each simulation is run for 200 s. All simulation results are obtained from averages of 50 simulated samples in every set of parameters.

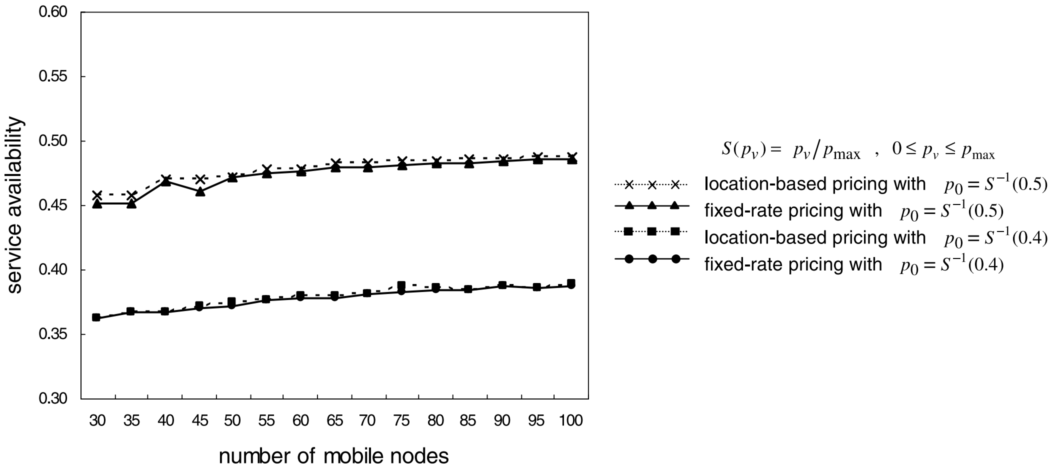


Fig. 3. Comparison of service availability by fixed-rate pricing and location-based pricing under different number of mobile nodes with supply function S_1.

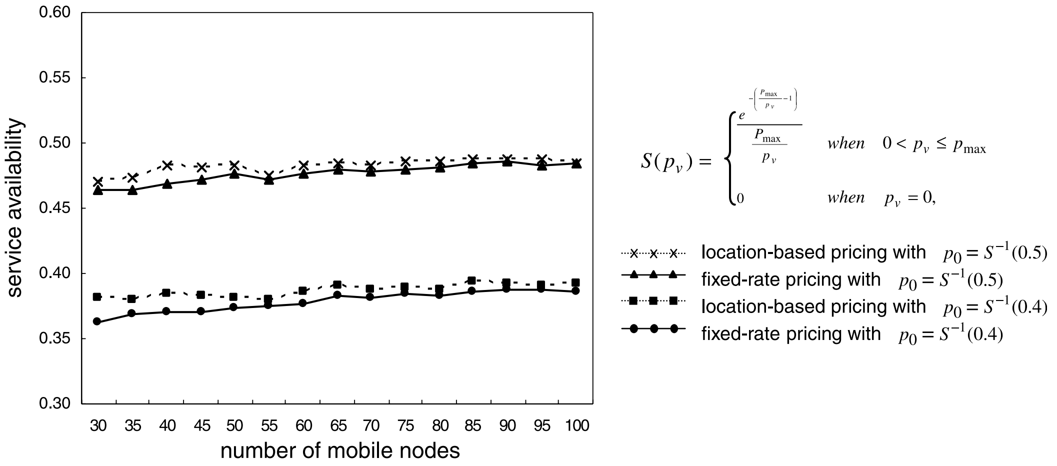


Fig. 4. Comparison of service availability by fixed-rate pricing and location-based pricing under different number of mobile nodes with supply function S_2.

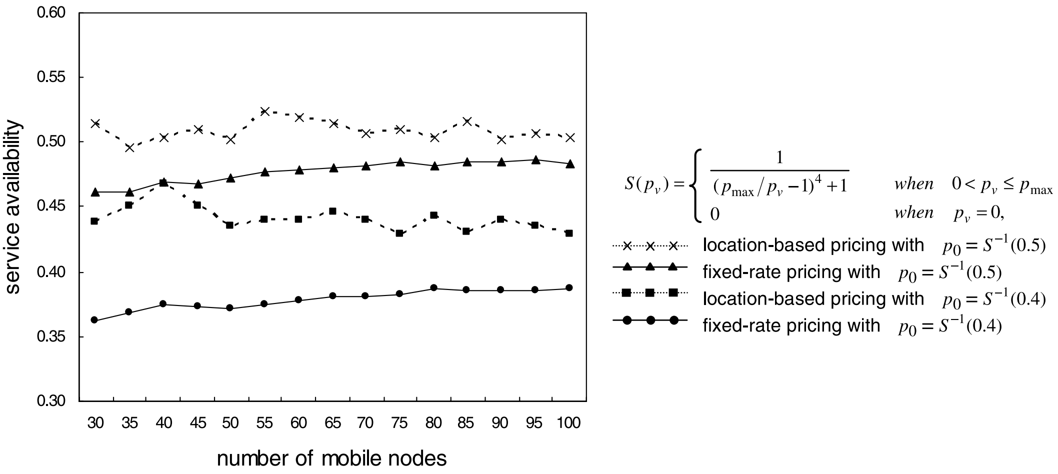


Fig. 5. Comparison of service availability by fixed-rate pricing and location-based pricing under different number of mobile nodes with supply function S_3.

4.2. Simulation results and discussions

4.2.1. 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 Section 3.

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 network is obtained from the average path availability of all new connection requests from the mobile nodes. In Figs. 3–5, 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.

In addition to comparing the service avilability between the location-based method and the fixed-rate method in Figs. 3–5, we observe the percentage of increase in service availability from the fixed rate pricing scheme to the location-based pricing scheme. Since the evaluation results are random variables depending on mobility model, call arrival and call duration, this study also computes the confidence intervals based on 50 simulated samples in every set of simulation parameters. A $100(1-\alpha)\%$ confidence interval for the population mean is [23].

$$\left(\mu - z_{1-\frac{\alpha}{2}}\frac{s}{\sqrt{n}},\ \mu + z_{1-\frac{\alpha}{2}}\frac{s}{\sqrt{n}}\right),$$

where μ is the sample mean, s is the sample standard deviation, n is the sample size and $z_{1-\frac{\alpha}{2}}$ is the $(1-\frac{\alpha}{2})$-quantile of a unit normal variety. The confidence interval indicates the interval for the real mean with a certain percentage confidence. Table 3 lists the average percentages of increase in service availability from fixed-rate pricing to location-based pricing and the 95% confidence intervals for the averages under different number of mobile nodes and supply functions. By examining Table 3, we notice:

- Comparing the average percentages of increase in service availability obtained by different supply functions, we find that with 95% confidence the location-based pricing scheme can achieve higher service availability than the fixed-rate pricing scheme with S_2 and S_3. However, with S_1, the average percentages are slightly larger than zero and the confidence intervals include zero, the enhancements obtained by S_1 are not obvious. In real word, S_2 and S_3 are more appropriate than the linear function S_1 to describe the user behaviors of a supplier. Consequently, the proposed pricing scheme can be

Table 3
The average percentage of increase in service availability from fixed-rate pricing to location-based pricing and the 95% confidence interval for the average under different number of mobile nodes and 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	0.0005 (−0.0115,0.0126)	0.0509 (0.033,0.0689)	0.2131 (0.1671,0.259)	0.0030 (−0.0068,0.0127)	0.0153 (0.006,0.0246)	0.1142 (0.0889,0.1394)
40	0.0023 (−0.006,0.0105)	0.0379 (0.0284,0.0474)	0.2491 (0.2213,0.2769)	0.0047 (−0.0054,0.0147)	0.0291 (0.0197,0.0384)	0.0743 (0.0531,0.0954)
50	0.0070 (−0.0005,0.0146)	0.0203 (0.0127,0.0279)	0.1713 (0.1453,0.1974)	0.0018 (−0.006,0.0096)	0.0129 (0.0039,0.0219)	0.0625 (0.0402,0.0847)
60	0.0020 (−0.0044,0.0083)	0.0242 (0.0171,0.0312)	0.1615 (0.1396,0.1833)	0.0006 (−0.0049,0.0061)	0.0147 (0.0096,0.0197)	0.0846 (0.0633,0.1059)
70	0.0014 (−0.0043,0.0072)	0.0154 (0.009,0.0217)	0.1593 (0.1457,0.1729)	0.0077 (0.0024,0.013)	0.0081 (0.0027,0.0136)	0.0509 (0.0342,0.0675)
80	0.0035 (−0.0013,0.0082)	0.0114 (0.0075,0.0152)	0.1474 (0.1316,0.1632)	0.0019 (−0.0014,0.0052)	0.0072 (0.0033,0.0111)	0.0447 (0.0346,0.0548)
90	0.0027 (−0.0005,0.0059)	0.0145 (0.0087,0.0203)	0.1394 (0.1269,0.1518)	0.0033 (−0.0011,0.0078)	0.0054 (0.0022,0.0087)	0.0346 (0.0238,0.0454)
100	0.0025 (−0.0004,0.0054)	0.0168 (0.012,0.0216)	0.1086 (0.099,0.1182)	0.0036 (0.0008,0.0064)	0.0045 (0.0013,0.0077)	0.0405 (0.0307,0.0503)

Table 4
Comparison of total costs of feedback incentives ($\times 10^3\ p_0$) 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.

adopted for motivating the users of wireless devices to provide relaying services in multi-hop cellular networks.

- Comparing the average percentages of increase in service availability obtained by different basic prices, we observe that the enhancements obtained in p_0 ($S(p_0) = 0.4$) are more significant for S_2 and S_3. Comparing the ranges of the confidence intervals for the average percentages of increase in service availability, we find that the variation of the results obtained in p_0 ($S(p_0) = 0.4$) is a little high 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 average percentages of increase in service availability obtained by different number of mobile nodes, we find the enhancements in small number of mobile nodes are usually 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.

4.2.2. Total costs of feedback incentives

In Section 3, 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 in reality. 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. In our simulations, the arrival of new data transmission requests forms a Poisson process and the data transmission times are exponentially distributed. Table 4 lists total costs of feedback incentives in the proposed incentive pricing scheme and 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. Table 5 summarizes the averages and the 95% confidence intervals for the percentage of increase in total relaying costs from the fixed-rate pricing scheme to the proposed location-based pricing scheme under different number of mobile nodes and supply functions. We observe that with 95% confidence the average percentage of increase in total relaying costs is between 1% and −1%. Simulation results represent no significant difference in total relaying costs between the proposed location-based pricing and the fixed-rate pricing.

5. Conclusions

Cost savings and service availability are two major concerns of a network provider adopting multi-hop cellular networking technology. In this paper, 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

Table 5
The average percentage of increase in total relaying costs from fixed-rate pricing to location-based pricing and the 95% confidence interval for the average under different number of mobile nodes and 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	0.0066 (0.0008,0.0125)	0.0079 (0.0044,0.0113)	0.0063 (−0.0014,0.014)	0.0077 (0.0000,0.0153)	0.0049 (0.0019,0.0078)	0.0018 (−0.0045,0.008)
40	−0.0001 (−0.0047,0.0044)	0.0013 (−0.0021,0.0047)	0.0002 (−0.0061,0.0065)	0.0042 (−0.0006,0.0091)	0.0013 (−0.001,0.0036)	0.0041 (0.0019,0.0063)
50	0.0018 (−0.0029,0.0065)	0.0005 (−0.0019,0.003)	−0.0028 (−0.0071,0.0015)	0.0040 (0.0002,0.0079)	−0.0006 (−0.0029,0.0016)	−0.0023 (−0.0077,0.003)
60	−0.0040 (−0.0071,−0.0008)	0.0008 (−0.0005,0.002)	0.0034 (−0.0007,0.0075)	−0.0019 (−0.0052,0.0014)	−0.0004 (−0.0018,0.001)	0.0030 (−0.0003,0.0062)
70	−0.0017 (−0.0052,0.0018)	−0.0005 (−0.0022,0.0011)	0.0009 (−0.0026,0.0043)	−0.0005 (−0.0031,0.0021)	0.0002 (−0.0009,0.0013)	0.0003 (−0.0033,0.0039)
80	0.0008 (−0.0021,0.0037)	−0.0002 (−0.0012,0.0008)	−0.0023 (−0.0056,0.0011)	0.0036 (0.0014,0.0059)	0.0020 (0.0013,0.0026)	0.0023 (−0.0003,0.0049)
90	0.0024 (−0.0001,0.0049)	0.0019 (0.0006,0.0031)	0.0012 (−0.0012,0.0036)	−0.0006 (−0.0031,0.002)	0.0002 (−0.0004,0.0009)	0.0019 (−0.0001,0.004)
100	0.0002 (−0.0019,0.0022)	−0.0016 (−0.0026,−0.0007)	0.0004 (−0.0018,0.0027)	0.0010 (−0.0013,0.0033)	0.0006 (−0.0004,0.0016)	0.0015 (−0.0003,0.0034)

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.

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