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Research Article

Optimal Incentive Pricing on Relaying Services for Maximizing Connection Availability in Multihop Cellular Networks

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This paper investigates an incentive pricing problem for relaying services in multihop cellular networks. Providing incentives to encourage mobile nodes to relay data is a critical factor in building successful multihop cellular networks. Most existing approaches adopt fixed-rate or location-based pricing on rewarding packets forwarding. This study applies a mathematical programming model to determine an optimal incentive price for each intermediate node that provides relaying services. Under the obtained incentive price, the connection availability of the networks is maximized by using the same relaying costs as other pricing schemes. A signomial geometric programming problem is constructed, and a deterministic optimization approach is employed to solve the problem. Besides, quality-of-service constraints are added in the proposed model to mitigate the unfairness between connection availabilities of individual nodes. Computational results demonstrate that the proposed model obtains the optimal incentive price on relaying services to maximize connection availability of the networks.

1. Introduction

Over the past few years, wireless networks and wireless devices have rapidly developed and undergone significant advances. More and more services that dramatically affect personal and business communications are provided by wireless access networks. How to build a seamless wireless network has received increasing attention from the practitioners and the researchers. Most wireless networks are based on cellular architecture, which means that a mobile host is handled by a central base station in a limited range. Cellular networks have inherent limitations on cell coverage and the dead spot problem. Traditionally, the network providers utilize more infrastructure equipments such as base stations, to solve these problems. However, this method is expensive. Therefore relaying technology has been developed to solve this problem. In the last decade, multihop cellular networks have been proposed to harness the benefits of conventional cellular networks and emerging multihop ad hoc networks. In cellular networks, a mobile device directly connects with the base station; in multihop networks, a mobile device communicates with others over peer-to-peer connections. Figure 1 indicates the scenario of general multihop cellular networks. Adopting hop-by-hop connections can extend the service area at the boundaries of the network and eliminate dead spots, including indoor environments and basements. Much research has evaluated and summarized the advantages of multihop cellular networks over existing single-hop cellular networks as follows [1–5].

(i) Increases the speed of data transmission.

(ii) Reduces total transmission power.

(iii) Extends the service area.

(iv) Increases system capacity.

(v) Balances traffic load.

(vi) Reduces the interference with other nodes.

(vii) Reduces the number of base station sites.

Cooperation among nodes is a critical factor for ensuring the success of the relaying ad hoc networks [2, 6]. In recent years, a number of approaches have been proposed to encourage mobile nodes to relay data for others in ad hoc networks. Most of existing motivation-based approaches focus on a charging protocol and use fixed-rate pricing that gives identical reward level on per unit of packet forwarded. Although the major advantage of fixed-rate pricing is that billing and accounting processes are simple, providing identical reward level to all mobile nodes neglects the distinct importance of each mobile node in the networks. Lo and Lin [2] developed a location-based incentive pricing scheme rewarding each mobile node based on its degree of contribution to successful hop-by-hop connections. Simulation results indicate that their method provides higher connection availability compared to the fixed-rate pricing scheme.

This paper constructs a mathematical programming model to the problem of optimal pricing on relaying services provided by the mobile nodes in the multihop cellular networks. The formulated model that maximizes connection availability of the networks under identical relaying costs used by the fixed-rate pricing scheme and the location-based pricing scheme [2] is a signomial geometric programming (SGP) problem. Convexification strategies and piecewise linearization techniques are employed to reformulate the problem into a convex mixed-integer nonlinear programming (MINLP) problem that can be solved by conventional MINLP methods to reach a global solution. We also add quality-of-service (QoS) constraints in the constructed model to guarantee each mobile node with a minimum successful connection probability, therefore mitigating the unfairness between connection availabilities of individual nodes. Computational experiments are conducted to compare the proposed method with existing pricing schemes. Simulation results indicate that the proposed method obtains higher connection availability of the networks than the existing pricing methods without additional relaying costs.

The rest of the paper is organized as follows. Section 2 reviews existing multihop cellular networking models and incentive pricing models. In Section 3, an incentive pricing model for maximizing connection availability is proposed to determine the optimal price on

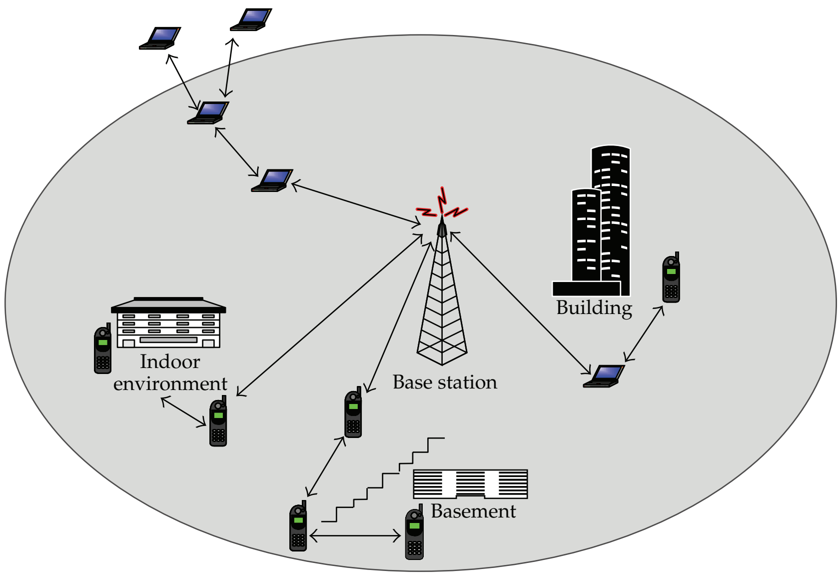

Figure 1: Scenario of general multihop cellular networks.

relaying services provided by mobile nodes. Section 4 provides a solution approach based on variable transformations and piecewise linearization techniques. In Section 5, we present the computational experiments, and finally concluding remarks are made in Section 6.

2. Literature Review

Opportunity-driven multiple access (ODMA) is an ad hoc multihop protocol where the transmissions from the mobile hosts to the base station are broken into multiple wireless hops, thereby reducing transmission power [4]. The high-data-rate coverage of the cell can be increased by adopting relaying technologies for the mobile nodes outside the high-data-rate coverage area. The Ad Hoc GSM (A-GSM) system is a network protocol platform that accommodates relaying capability in GSM cellular networks. Although the GSM system aims to provide global roaming, the dead spot problem still exists, for example, in subway stations and basements. Since installing additional base stations at each dead spot location is not economical, the A-GSM system extends the data communication through the mobile nodes [7]. Qiao and Wu [3] presented an integrated cellular and ad hoc relay (iCAR) system to combine the cellular infrastructure with ad hoc relaying technologies. All cellular networks have problems of limited capacity and unbalanced traffic. Cellular networks probably cannot provide the connection service because some of the cells are heavily congested, but at the same time other cells still have available channels. This kind of centralized obstruction makes the system unable to establish successful communication, even though the number of required channels does not reach the maximum capacity of the entire system. Utilizing relaying technologies a mobile host in a congested cell obtains a free channel in another cell and establishes a new call successfully. Wu et al. [8] proposed 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. 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. Wu et al. [8] observed that under a certain delay requirement, the throughput can be greatly improved. Luo et al. [9] proposed a unified cellular and ad hoc network (UCAN) architecture that considers the balanced traffic and network throughput. The UCAN architecture uses relaying technologies to send information to the mobile device if the transmission quality of the channel is poor. Each mobile device in the UCAN model has both a 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. Multihop cellular network is considered as a promising candidate of 4G wireless network for future mobile communications. The complete surveys of technologies advances and economic perspective on the deployment of multihop cellular networks are provided by Li et al. [1] and Manoj et al. [10].

Since forwarding data for others consumes battery energy and delays its own data, providing incentives for mobile nodes to cooperate as relaying entries is necessary. The existing incentive schemes can be classified into detection-based and motivation-based approaches. The detection-based approach finds out the misbehaving nodes and reduces their impact in the networks. Marti et al. [11] developed two methods that find the misbehaving nodes and avoid routing packets through these nodes. Michiardi and Molva [12] proposed a mechanism to enforce cooperation among nodes based on reputation and to prevent denial of service attacks because of selfishness. Buchegger and Le Boudec [13] developed a protocol to detect and isolate misconduct nodes, therefore making it unattractive to deny cooperation.

Instead of discouraging misbehavior by punishing misbehavior node, the motivation-based approach encourages positive cooperation by rewarding incentives for relaying packets. Buttyán and Hubaux [6, 14] developed different approaches to provide incentives to cooperative nodes, therefore simulating packet forwarding. Buttyán and Hubaux [14] did not discuss the reward level, and Buttyán and Hubaux [6] suggested to reward the relaying service based on the number of forwarding packets. Jakobsson et al. [15] developed a micro-payment scheme to encourage collaboration and discourage dishonest behavior in multihop cellular networks. A subject reward level is determined according to the importance of the packet. Lamparter et al. [16] proposed a charging scheme using volume-based pricing. A fixed price per unit of data is rewarded for forwarding traffic in ad hoc stub networks. The rewarding mechanisms mentioned above adopt fixed-rate pricing and do not consider the importance of each mobile node in the routing topology.

Lo and Lin [2] proposed a location-based incentive pricing scheme that adjusts the price of incentives for packet forwarding based on the degree of each mobile nodes contributing to successful hop-by-hop connections. Since the willingness of the mobile node to relay packets has a significant impact on the success of the multihop connections from all nodes in its subtree to the base station, the importance of a mobile node depends on the number of mobile nodes in its subtree. They defined the location index LI_v of a mobile node v as the number of nodes residing in the tree rooted at node v. Let N be the set of intermediate nodes providing relaying services for the mobile nodes that require hop-by-hop connections to the base station, and ALI be the average location index of all nodes in N; the price of the feedback incentives for node v, p_v, is defined as follows [2]:

$$p_v = p_0 + (LI_v - \mathrm{ALI}) \cdot \frac{R_p}{R_{\mathrm{LI}}} \cdot \frac{1}{LI_v}, \tag{2.1}$$

where $R_p = \min\{p_0, P_{\max} - p_0\}$, $R_{\text{LI}} = \max\{\text{ALI} - \min_{v \in N}\{LI_v\}, \max_{v \in N}\{LI_v\} - \text{ALI}\}$, p_0 is the price used in the fixed-rate pricing method, and $P_{\max}$ is the maximum price the network provider can reward to an intermediate mobile node. Equation (2.1) employs p_0 as a basic price and gives a higher incentive price on relaying services for the node with a higher location index. Because some incentive rewards are shifted from the nodes of low importance to the node of high importance, the Lo and Lin [2] pricing scheme results in higher connection availability but does not generate higher relaying costs compared to the fixed-rate pricing scheme. However, their method does not provide an optimal incentive pricing solution that maximizes connection availability of the networks.

3. Proposed Incentive Pricing Model

3.1. Connection Availability Maximization Problem

Pricing is an inducer for suppliers to provide services. Monetary incentives can affect the motivation of mobile nodes providing services and are usually characterized by a supply function that represents the reaction of mobile nodes to the change of the price [17]. In this paper, we assume a linear relationship between the price of incentives and the willingness of forwarding packets [18], that is,

$$S(p_v) = \frac{p_v}{P_{\max}}, \quad 0 \leq p_v \leq P_{\max}, \tag{3.1}$$

where p_v is the incentive price on per unit of relayed data, $P_{\max}$ is the maximum price the network provider can reward to an intermediate mobile node per unit of relayed data, and $S(p_v)$ is the willingness of forwarding packets under the incentive price p_v. $S(p_v)$ is the supply function representing the reaction of mobile nodes to the change in the price of the incentives. $S(p_v = 0) = 0$ means that node v will not relay traffic for others if no feedback is provided for relaying services. The willingness of forwarding packets linearly increases as the incentive price on relaying services increases. $S(p_v = P_{\max}) = 1$ means the maximum price is acceptable for all mobile nodes to provide relaying services.

In multihop cellular networks, data packets must be relayed hop by hop from a given mobile node to a base station; thus the connection availability of node i depends on the willingness of all intermediate mobile nodes on the routing path to forward packets. Let CA_i be the connection availability of node i, that is, the successful connection probability from node i to the base station. CA_i can be expressed as [2]

$$\text{CA}_i = \prod_{v \in M_i} S(p_v), \tag{3.2}$$

where M_i is the set of intermediate nodes in the path from node i to the base station, and all the other variables are the same as defined before.

The connection availability maximization problem in the multihop cellular networks considered in this paper can be formulated as follows:

$$\text{Maximize} \quad \frac{\left(\sum_{i=1}^{w} \mathrm{CA}_i\right)}{w} \tag{3.3}$$

$$\text{subject to} \quad \mathrm{CA}_i = \prod_{v \in M_i} \left(\frac{p_v}{P_{\max}}\right), \quad i = 1, \ldots, w, \tag{3.4}$$

$$\sum_{i=1}^{w} \left(T_i \cdot \sum_{v \in M_i} p_v\right) \le \sum_{i=1}^{w} \left(T_i \cdot \sum_{v \in M_i} P_{\text{fixed}}\right), \tag{3.5}$$

$$0 \le p_v \le P_{\max}, \tag{3.6}$$

where w is the number of nodes requiring hop-by-hop connections to the base station in the networks, T_i is the units of traffic sent by node i, and P_{fixed} is the fixed incentive price on relaying services used by the fixed-rate pricing scheme. The objective function aims to maximize the connection availability of the networks, that is, the average connection availability of all mobile nodes using hop-by-hop connections to the base station. Lo and Lin [2] refers the objective function as service availability. Constraint (3.5) indicates the total relaying costs of the proposed method are not greater than the total relaying costs of the fixed-rate pricing scheme.

3.2. Connection Availability Maximization Problem with QoS Requirements

In the numerical examples, we find the connection availabilities of some mobile nodes are zero by using the proposed model described previously. In order to alleviate the unfairness situation between connection availabilities of individual nodes, this study employs QoS constraints in the original model to guarantee each mobile node with a minimum successful connection probability. The connection availability maximization problem with QoS requirements considered in this study can be formulated as follows:

$$\begin{aligned} &\text{Maximize} && (3.3) \\ &\text{subject to} && (3.4) \sim (3.6), \end{aligned} \tag{3.7}$$

$$\mathrm{CA}_i \ge \mathrm{QoS}_{\mathrm{CA}}, \quad i = 1, \ldots, w, \tag{3.8}$$

$$\mathrm{QoS}_{\mathrm{CA}} = \begin{cases} \operatorname{Min} \mathrm{CA}_{\mathrm{LB}}, & \text{if } \operatorname{Min} \mathrm{CA}_{\mathrm{LB}} > 0, \\ 0.01, & \text{if } \operatorname{Min} \mathrm{CA}_{\mathrm{LB}} = 0, \end{cases} \tag{3.9}$$

where $\operatorname{Min} \mathrm{CA}_{\mathrm{LB}}$ represents the minimal connection availability of all mobile nodes requiring hop-by-hop connections to the base station in the location-based pricing scheme. Constraint (3.8) indicates that the connection availability of each mobile node satisfies the required QoS level ($\mathrm{QoS}_{\mathrm{CA}}$). If the minimal connection availability of all mobile nodes in the location-based pricing scheme is greater than zero, then the required QoS level is set as $\operatorname{Min} \mathrm{CA}_{\mathrm{LB}}$. Otherwise, the required QoS level is set as 0.01.

4. Problem-Solving Approach

Since the problem described in the previous section is an SGP problem, that is, a class of nonconvex programming problems. SGP problems generally possess multiple local optima and experience much more theoretical and computational difficulties. This study uses variable transformations and piecewise linearization techniques to reformulate the problem into a convex MINLP problem that can be globally solved by conventional MINLP methods. Much research has proposed variable transformation techniques to solve optimization problems including signomial functions to global optimality [19–22]. For convexifying positive signomial terms, Lundell and Westerlund [23] proved that the exponential transformation always results in a tighter underestimator than the negative power transformation. This study applies the exponential transformation to convexify a positive signomial function $\prod_{i=1}^{n} x_i^{\alpha_i}$ by the following remark [19, 24].

Remark 4.1. If $\alpha_j > 0$ for some j, $j \notin I$, $I = \{k \mid \alpha_k < 0,\ k = 1, 2, \ldots, n\}$, then we convert $\prod_{i=1}^{n} x_i^{\alpha_i}$ into another function $(\prod_{i\in I} x_i^{\alpha_i}) e^{\sum_{j\notin I} \alpha_j y_j}$, where $y_j = L(\ln x_j)$ and $L(\ln x_j)$, is a piecewise linear function of $\ln x_j$. Then $(\prod_{i\in I} x_i^{\alpha_i}) e^{\sum_{j\notin I} \alpha_j y_j}$ where $x_i > 0$, $i \in I$, $y_j \in \Re$, $j \notin I$ is a convex function.

For convexifying negative signomial terms, we apply the power transformation to reformulate a negative signomial function $-\prod_{i=1}^{n} x_i^{\alpha_i}$ by the following remark [19–22, 24].

Remark 4.2. If $0 \le \alpha_1 \le \alpha_2 \le \cdots \le \alpha_p$, $0 \ge \alpha_{p+1} \ge \alpha_{p+2} \ge \cdots \ge \alpha_n$, and $\sum_{i=1}^{r} \alpha_i < 1$ for some largest integer r, such that $r \le p$, $I = \{k \mid k = 1, 2, \ldots, p\}$, then we convert $-\prod_{i=1}^{n} x_i^{\alpha_i}$ into another function $-\prod_{i\in I} x_i^{\alpha_i} \prod_{j\notin I} y_j^{\beta}$, $\beta = (1 - \sum_{i=1}^{r} \alpha_i)/(n - r)$, where $y_j = L(x_j^{\alpha_j/\beta})$ and $L(x_j^{\alpha_j/\beta})$ is a piecewise linear function of $x_j^{\alpha_j/\beta}$. Then $-\prod_{i\in I} x_i^{\alpha_i} \prod_{j\notin I} y_j^{\beta}$, where $x_i > 0$, $i \in I$, $y_j \in \Re$, $j \notin I$, is a convex function.

Herein the concept of special ordered set of type 2 (SOS-2) constraints can be utilized to formulate the piecewise linear function [25, 26]. This study adopts the piecewise linearization technique introduced by Vielma and Nemhauser [27] that uses a logarithmic number of binary variables and extra constraints. The computational results in [27] show that their piecewise linearization technique outperforms other piecewise linearization formulations. Tsai and Lin [28] applied the piecewise linearization technique developed by Vielma and Nemhauser [27] to efficiently solve posynomial geometric programming problems.

The original model has one nonconvex objective function, one constraint, and n variables, where n is the number of intermediate nodes providing relaying services. The reformulated model has one convex objective function, one constraint, n variables, and several piecewise linear functions. The number of piecewise linear functions depends on convexification process in reformulating the problem. For each piecewise linear function, $\lceil \log_2 m \rceil$ binary variables, $m+1$ continuous variables, and $3+2\lceil \log_2 m \rceil$ constraints are required to express a piecewise linear function with m line segments.

The following example is used to illustrate how the proposed method discussed previously determines the incentive price on relaying services provided by each mobile node.

Example 4.3. Consider an example taken from Lo and Lin [2] with twelve mobile nodes distributed in the multihop cellular networks indicated in Figure 2. Nine nodes (nodes 2, 3, 4, 5, 7, 8, 9, 11, 12) require hop-by-hop connections to reach the central base station.

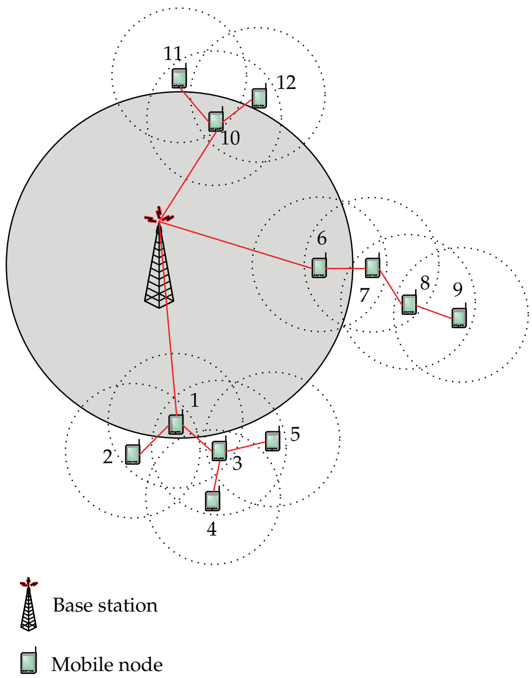

Figure 2: Relaying topology of Example 4.3 [2].

Assume each mobile node has identical traffic load u units, and the fixed-rate pricing scheme uses $0.5P_{\max}$ as the incentive price for relaying per unit of data, that is, $P_{\text{fixed}} = 0.5P_{\max}$. A mathematical programming model can be constructed for the connection availability maximization problem as follows:

$$\begin{aligned}
\text{Maximize} \quad & \frac{(\mathrm{CA}_2 + \mathrm{CA}_3 + \mathrm{CA}_4 + \mathrm{CA}_5 + \mathrm{CA}_7 + \mathrm{CA}_8 + \mathrm{CA}_9 + \mathrm{CA}_{11} + \mathrm{CA}_{12})}{9} \\
\text{subject to} \quad & \mathrm{CA}_2 = \mathrm{CA}_3 = \frac{p_1}{P_{\max}}, \\
& \mathrm{CA}_4 = \mathrm{CA}_5 = \frac{p_1}{P_{\max}} \cdot \frac{p_3}{P_{\max}}, \\
& \mathrm{CA}_7 = \frac{p_6}{P_{\max}}, \\
& \mathrm{CA}_8 = \frac{p_6}{P_{\max}} \cdot \frac{p_7}{P_{\max}}, \\
& \mathrm{CA}_9 = \frac{p_6}{P_{\max}} \cdot \frac{p_7}{P_{\max}} \cdot \frac{p_8}{P_{\max}}, \\
& \mathrm{CA}_{11} = \mathrm{CA}_{12} = \frac{p_{10}}{P_{\max}},
\end{aligned}$$

$$
\begin{aligned}
&2u \cdot p_1 + 2u \cdot (p_1 + p_3) + u \cdot (p_6) + u \cdot (p_6 + p_7) + u \cdot (p_6 + p_7 + p_8) + 2u \cdot (p_{10}) \\
&\qquad \le 2u \cdot (0.5P_{\max}) + 2u \cdot (0.5P_{\max} + 0.5P_{\max}) + u \cdot (0.5P_{\max}) \\
&\qquad\quad + u \cdot (0.5P_{\max} + 0.5P_{\max}) + u \cdot (0.5P_{\max} + 0.5P_{\max} + 0.5P_{\max}) + 2u \cdot (0.5P_{\max}), \\
&0 \le p_i \le P_{\max}, \quad i = 1, 3, 6, 7, 8, 10,
\end{aligned}
\tag{4.1}
$$

where CA_i, $i = 2, 3, 4, 5, 7, 8, 9, 11, 12$, represents the connection availability of mobile node i, and $P_{\max}$ and u are constants. This program is a nonconvex SGP problem. Applying the method mentioned previously, the connection maximization problem of Example 4.3 can be converted into a convex MINLP problem as follows:

$$
\text{Minimize} \quad \left(-2\frac{p_1}{P_{\max}} - 2\frac{y_1^{0.5}}{P_{\max}} \cdot \frac{y_3^{0.5}}{P_{\max}} - \frac{p_6}{P_{\max}} - \frac{y_6^{1/3}}{P_{\max}} \cdot \frac{y_7^{1/3}}{P_{\max}} - \frac{y_6^{1/3}}{P_{\max}} \cdot \frac{y_7^{1/3}}{P_{\max}} \cdot \frac{y_8^{1/3}}{P_{\max}} - 2\frac{p_{10}}{P_{\max}}\right)/9
\tag{4.2}
$$

$$
\begin{aligned}
\text{subject to} \quad &2u \cdot p_1 + 2u \cdot (p_1 + p_3) + u \cdot (p_6) + u \cdot (p_6 + p_7) + u \cdot (p_6 + p_7 + p_8) + 2u \cdot (p_{10}) \\
&\quad \le 7uP_{\max}, \\
&y_1 = L\left(p_1^2\right), \quad y_3 = L\left(p_3^2\right), \quad y_6 = L\left(p_6^3\right), \quad y_7 = L\left(p_7^3\right), \quad y_8 = L\left(p_8^3\right), \\
&0 \le p_i \le P_{\max}, \quad i = 1, 3, 6, 7, 8, 10,
\end{aligned}
\tag{4.3}
$$

where $L(p_1^2)$, $L(p_3^2)$, $L(p_6^3)$, $L(p_7^3)$, and $L(p_8^3)$ are piecewise linear functions of p_1^2, p_3^2, p_6^3, p_7^3, and p_8^3, respectively. By using the efficient piecewise linearization technique introduced by Vielma and Nemhauser [27], this program is reformulated as a convex MINLP problem that can be solved on LINGO [29] to obtain a global solution $(p_1, p_3, p_6, p_7, p_8, p_{10}) = (0.8763P_{\max}, 0.7474P_{\max}, 0, 0, 0, P_{\max})$. Table 1 compares the incentive price on relaying services and connection availability of the networks under different pricing schemes. Herein the fixed-rate pricing scheme rewards each mobile node $0.5P_{\max}$ for relaying per unit of data. From the data listed in Table 1, we find the proposed pricing scheme provides higher connection availability of the networks than the fixed-rate pricing scheme and the location-based pricing scheme do. We also observe that the three methods use approximately the same relaying costs.

From Table 1, we find out that although the proposed method has better connection availability of the networks than the other two methods, the connection availabilities of some mobile nodes (CA_7, CA_8, CA_9) are zero; that is, these nodes cannot connect to the base station. This study adds the QoS constraints $\mathrm{CA}_i \ge 0.026$, $i = 2, 3, 4, 5, 7, 8, 9, 11, 12$, to guarantee each mobile node with a minimum successful connection probability. The required QoS level 0.026 is the minimal individual connection availability obtained from

Table 1: Comparison between the fixed-rate pricing scheme, the location-based pricing scheme, and the proposed pricing scheme of Example 4.3.

	Fixed-rate pricing scheme	Location-based pricing scheme	Proposed pricing scheme
Incentive price on relaying services	$p_1 = p_3 = p_6 = p_7 = p_8 = p_{10} = 0.5P_{\max}$	$p_1 = 0.625P_{\max}$ $p_6 = 0.567P_{\max}$ $p_3 = p_7 = p_{10} = 0.45P_{\max}$ $p_8 = 0.1P_{\max}$	$p_1 = 0.8763P_{\max}$ $p_3 = 0.7474P_{\max}$ $p_6 = p_7 = p_8 = 0$ $p_{10} = P_{\max}$
Connection availability of each node	$CA_2 = CA_3 = S(p_1) = 0.5$ $CA_4 = CA_5 = S(p_1)S(p_3) = 0.25$ $CA_7 = S(p_6) = 0.5$ $CA_8 = S(p_6)S(p_7) = 0.25$ $CA_9 = S(p_6)S(p_7)S(p_8) = 0.125$ $CA_{11} = CA_{12} = S(p_{10}) = 0.5$	$CA_2 = CA_3 = S(p_1) = 0.625$ $CA_4 = CA_5 = S(p_1)S(p_3) = 0.281$ $CA_7 = S(p_6) = 0.567$ $CA_8 = S(p_6)S(p_7) = 0.255$ $CA_9 = S(p_6)S(p_7)S(p_8) = 0.026$ $CA_{11} = CA_{12} = S(p_{10}) = 0.45$	$CA_2 = CA_3 = S(p_1) = 0.8763$ $CA_4 = CA_5 = S(p_1)S(p_3) = 0.6549$ $CA_7 = S(p_6) = 0$ $CA_8 = S(p_6)S(p_7) = 0$ $CA_9 = S(p_6)S(p_7)S(p_8) = 0$ $CA_{11} = CA_{12} = S(p_{10}) = 1$
Connection availability of the networks	$(0.5 + 0.5 + 0.25 + 0.25+$ $0.5 + 0.25 + 0.125 + 0.5+$ $0.5)/9 = 0.375$	$(0.625 + 0.625 + 0.281 + 0.281 + 0.567 + 0.255 + 0.026 + 0.45 + 0.45)/9 = 0.3956$	$(0.8763 + 0.8763 + 0.6549 + 0.6549+0+0+0+1+1)/9 = 0.5625$
Relaying costs	$2u(0.5P_{\max}) + 2u(0.5P_{\max}$ $+0.5P_{\max}) + u(0.5P_{\max})$ $+u(0.5P_{\max} + 0.5P_{\max})$ $+u(0.5P_{\max} + 0.5P_{\max} + 0.5P_{\max})$ $+2u(0.5P_{\max}) = 7uP_{\max}$	$2u(0.625P_{\max}) + 2u(0.625P_{\max}+$ $0.45P_{\max}) + u(0.567P_{\max})+$ $u(0.45P_{\max} + 0.567P_{\max})+$ $u(0.1P_{\max} + 0.45P_{\max}+$ $0.567P_{\max}) + 2u(0.45P_{\max}) =$ $7.001uP_{\max}$	$2u(0.8763P_{\max})+$ $2u(0.8763P_{\max}+$ $0.7474P_{\max}) + 2u(P_{\max}) =$ $7uP_{\max}$

the location-based pricing scheme. The proposed model with QoS requirements becomes as follows:

Minimize (4.2)

subject to (4.3)

$$-\frac{p_1}{P_{\max}} < -0.026, \quad -\frac{y_1^{0.5}}{P_{\max}} \cdot \frac{y_3^{0.5}}{P_{\max}} < -0.026, \quad -\frac{p_6}{P_{\max}} < -0.026,$$
$$-\frac{y_6^{1/3}}{P_{\max}} \cdot \frac{y_7^{1/3}}{P_{\max}} < -0.026, \quad -\frac{y_6^{1/3}}{P_{\max}} \cdot \frac{y_7^{1/3}}{P_{\max}} \cdot \frac{y_8^{1/3}}{P_{\max}} < -0.026, \quad \frac{p_{10}}{P_{\max}} < -0.026. \tag{4.4}$$

Solving this problem can obtain a globally optimal solution $(p_1, p_3, p_6, p_7, p_8, p_{10}) = (0.6539P_{\max}, 0.3085P_{\max}, 0.3165P_{\max}, 0.2313P_{\max}, 0.3550P_{\max}, P_{\max})$. Table 2 shows comparison between the location-based pricing scheme and the proposed pricing scheme with QoS requirements of Example 4.3. We find the minimal individual connection availability from the proposed pricing scheme is equal to that from the location-based pricing scheme, and the

Table 2: Comparison between the location-based pricing scheme and the proposed pricing scheme with QoS requirements of Example 4.3.

	Location-based pricing scheme	Proposed pricing scheme with QoS requirements
Incentive price on relaying services	$p_1 = 0.625P_{\max}$ $p_6 = 0.567P_{\max}$ $p_3 = p_7 = p_{10} = 0.45P_{\max}$ $p_8 = 0.1P_{\max}$	$p_1 = 0.6539P_{\max}$ $p_3 = 0.3085P_{\max}$ $p_6 = 0.3165P_{\max}$ $p_7 = 0.2313P_{\max}$ $p_8 = 0.3550P_{\max}$ $p_{10} = P_{\max}$
Connection availability of each node	$\mathrm{CA}_2 = \mathrm{CA}_3 = S(p_1) = 0.625$ $\mathrm{CA}_4 = \mathrm{CA}_5 = S(p_1)S(p_3) = 0.281$ $\mathrm{CA}_7 = S(p_6) = 0.567$ $\mathrm{CA}_8 = S(p_6)S(p_7) = 0.255$ $\mathrm{CA}_9 = S(p_6)S(p_7)S(p_8) = 0.026$ $\mathrm{CA}_{11} = \mathrm{CA}_{12} = S(p_{10}) = 0.45$	$\mathrm{CA}_2 = \mathrm{CA}_3 = S(p_1) = 0.6539$ $\mathrm{CA}_4 = \mathrm{CA}_5 = S(p_1)S(p_3) = 0.2017$ $\mathrm{CA}_7 = S(p_6) = 0.3165$ $\mathrm{CA}_8 = S(p_6)S(p_7) = 0.0732$ $\mathrm{CA}_9 = S(p_6)S(p_7)S(p_8) = 0.0260$ $\mathrm{CA}_{11} = \mathrm{CA}_{12} = S(p_{10}) = 1$
Connection availability of the networks	$(0.625 + 0.625 + 0.281 + 0.281 + 0.567 + 0.255 + 0.026 + 0.45 + 0.45)/9 = 0.3956$	$(0.6539 + 0.6539 + 0.2017 + 0.2017 + 0.3165+0.0732+0.0260+1+1)/9 = 0.4585$
Relaying costs	$2u(0.625P_{\max}) + 2u(0.625P_{\max}+ 0.45P_{\max}) + u(0.567P_{\max}) + u(0.45P_{\max} +0.567P_{\max}) + u(0.1P_{\max} + 0.45P_{\max}+ 0.567P_{\max}) + 2u(0.45P_{\max}) = 7.001P_{\max}$	$2u(0.6539P_{\max}) + 2u(0.6539P_{\max}+ 0.3085P_{\max}) + u(0.3165P_{\max})+ u(0.3165P_{\max} + 0.2313P_{\max}) + P_{\max}$ $u(0.3165P_{\max} + 0.2313P_{\max}+ 0.3550P_{\max}) + 2u(P_{\max}) = 6.9997u$

connection availability of the networks from the proposed pricing scheme is still higher than that from the location-based pricing scheme.

5. Numerical Experiments

5.1. Fixed-Rate Method versus Location-Based Method versus Proposed Method

This section describes the simulation results for verifying the advantages of the proposed pricing scheme. We design our simulation tests by C++ language. All simulations are run on a Notebook with an Intel CPU P8700 and 4 GB RAM. The simulation environment is a rectangular region of 100 units width and 100 units height with a single base station of 30 units radius located in the central point. The radius of each mobile node is 20 units. In this study, a shortest path tree is built such that each mobile node connects to the base station with a minimum number of hops.

In the experiments 32, 64, and 128, mobile nodes, respectively, are randomly distributed in the rectangular region. 10 simulations are run for each set of parameter settings. Table 3 compares average connection availability of the networks of 10 simulations by different incentive pricing schemes. Figure 3 indicates that the proposed pricing scheme obtains higher average connection availability than the fixed-rate pricing scheme and the

Table 3: Comparison of connection availability of the networks by three methods in the simulation space of (width, height) = (100 units, 100 units).

Number of mobile nodes	CA_{FR}	CA_{LB}	CA_P	$(CA_P - CA_{FR})/CA_{FR}$	$(CA_P - CA_{LB})/CA_{LB}$	Average path length
32	0.47898643	0.48730129	0.53038439	10.82%	8.88%	1.0840542
64	0.48652063	0.49130662	0.51966696	6.87%	5.81%	1.0539176
128	0.49012412	0.49131695	0.51875024	5.88%	5.62%	1.0395036

CA_{FR}: connection availability of the networks from the fixed-rate pricing scheme.
CA_{LB}: connection availability of the networks from the location-based pricing scheme.
CA_P: connection availability of the networks from the proposed pricing scheme.

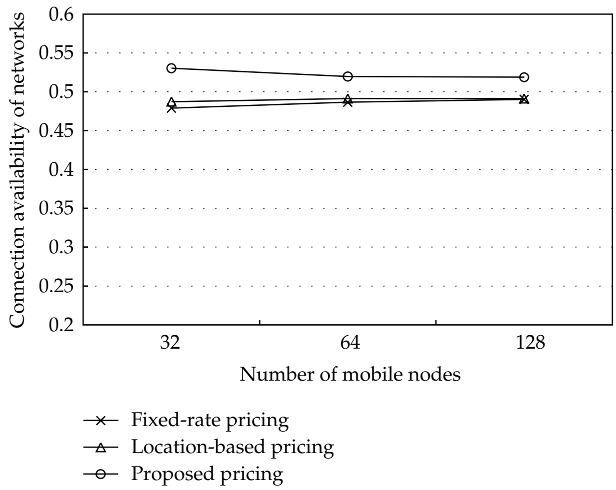

Figure 3: Comparison of connection availability of the networks by three methods in the simulation space of (width, height) = (100 units, 100 units).

location-based pricing scheme under different number of mobile nodes in the simulation environment. As the number of mobile nodes in the networks increases, the mobile nodes are easier to find a shorter hop-by-hop path for connecting to the base station. Therefore the average path length decreases when the number of mobile nodes increases. The effect on improving connection availability of the networks by the proposed method is more significant when the average path is longer.

5.2. Larger Simulation Space

To investigate the advantages of the proposed pricing scheme under a longer path, in this section we change the simulation space to a rectangular region of 200 units width and 200 units height. If the simulation area becomes larger, the path of the hop-by-hop connection to the base station required by a mobile node will be longer. Then the impact of the path length on the performance of the proposed pricing method can be observed. Table 4 shows the average connection availability of the networks of 10 simulations in the rectangular region of 200 units width and 200 units height. The average connection availability of the networks obtained by the proposed pricing scheme is higher than the other two pricing

Table 4: Comparison of connection availability of the networks by three methods in the simulation space of (width, height) = (200 units, 200 units).

Number of mobile nodes	CA_{FR}	CA_{LB}	CA_P	$(CA_P - CA_{FR})/CA_{FR}$	$(CA_P - CA_{LB})/CA_{LB}$	Average path length
32	0.22764841	0.23610142	0.53722796	138.12%	130.04%	2.6502985
64	0.23798218	0.24306587	0.53669912	125.83%	121.06%	2.5031434
128	0.24686002	0.24986204	0.51335212	108.03%	105.54%	2.3962481

CA_{FR}: connection availability of the networks from the fixed-rate pricing scheme.
CA_{LB}: connection availability of the networks from the location-based pricing scheme.
CA_P: connection availability of the networks from the proposed pricing scheme.

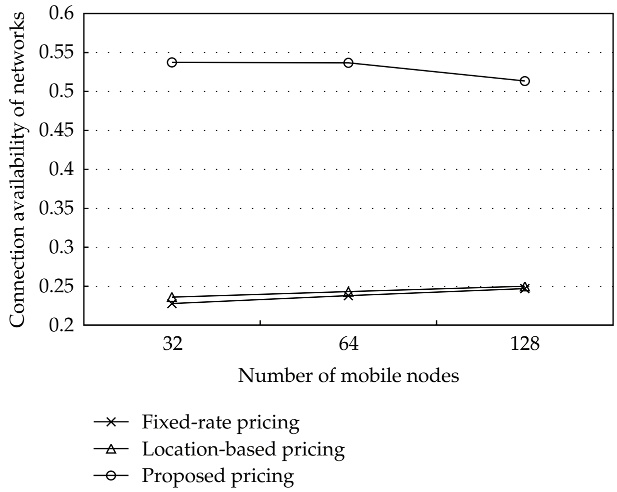

Figure 4: Comparison of connection availability of the networks by three methods in the simulation space of (width, height) = (200 units, 200 units).

models. Figure 4 indicates that in the simulation space of 200 units width and 200 units height, the difference in the connection availability of the networks obtained by the fixed-rate pricing scheme and the location-based pricing scheme is not obvious. However, the connection availability of the networks by the proposed method is much higher than that by the other two methods if a longer path is required to reach the base station.

5.3. Location-Based Method versus Proposed Method with QoS Requirements

Section 4 gives an example that indicates the proposed pricing scheme results in some unfairness, and some of the node's connection availabilities are zero. This section performs several simulations to verify that adding QoS constraints on the connection availability of each mobile node can mitigate the unfairness situation. Each mobile node is guaranteed to obtain the minimum connection availability by taking the minimum connection availability from the location-based pricing scheme. If the minimum connection availability from the location-based pricing scheme is zero, then we move the required level of individual connection availability to 0.01.

Tables 5 and 6 show the average connection availability of the networks of 10 simulations in the simulation space of (width, height) = (100 units, 100 units) and (width,

Table 5: Comparison of connection availability by two methods in the simulation space of (width, height) = (100 units, 100 units).

Number of mobile nodes	CA_{LB}	CA_{P_QoS}	$(CA_{P\_QoS} - CA_{LB})/CA_{LB}$
32	0.48730129	0.49575548	1.74%
64	0.49130662	0.49617013	1.00%
128	0.49131695	0.49246111	0.24%

CA_{LB}: connection availability of the networks from the location-based pricing scheme.
CA_{P_QoS}: connection availability of the networks from the proposed pricing scheme with QoS requirements.

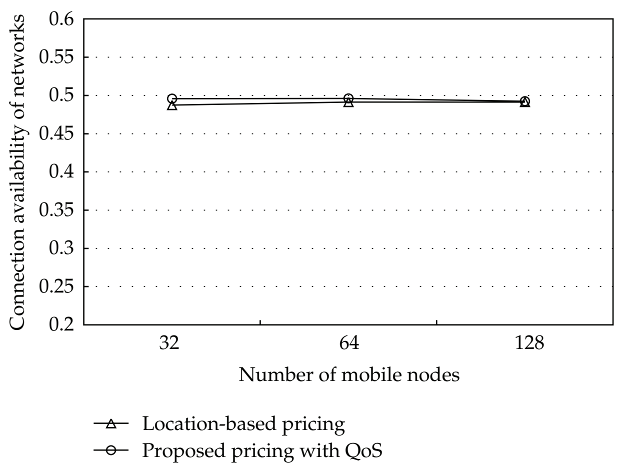

Figure 5: Comparison of connection availability of the networks by two methods in the simulation space of (width, height) = (100 units, 100 units).

height) = (200 units, 200 units), respectively. The comparisons are also indicated in Figures 5 and 6. Compared to the results from the proposed pricing method without QoS constraints in Tables 3 and 4, although the connection availability of the networks decreases, the proposed pricing method with QoS requirements still performs better than the location-based pricing method. Since the minimum individual node's connection availability in the proposed pricing method is greater than or equal to that in the location-based pricing method, adding QoS constraints makes the proposed pricing method consider both connection availability of the networks and fairness between individual node's connection availabilities.

6. Conclusions

Cost savings and connection availability are two crucial issues of a network provider adopting multihop cellular networking technology. This paper determines the optimal incentive price on relaying services for each mobile node by constructing a mathematical programming model that maximizes connection availability without extra relaying costs. A deterministic optimization approach based on variable transformations and piecewise linearization techniques is utilized to solve the formulated problem. Simulation results demonstrate that the proposed pricing model results in higher connection availability than the fixed-rate pricing scheme and the location-based pricing scheme. In addition, a mathematical programming model involving QoS requirements in connection availability of

Table 6: Comparison of connection availability of the networks by two methods in the simulation space of (width, height) = (200 units, 200 units).

Number of mobile nodes	CA_{LB}	CA_{P_QoS}	$(CA_{P\_QoS} - CA_{LB})/CA_{LB}$
32	0.23610142	0.3183623	34.84%
64	0.24306587	0.31280795	28.69%
128	0.24986204	0.29797671	19.26%

CA_{LB}: connection availability of the networks from the location-based pricing scheme.
CA_{P_QoS}: connection availability of the networks from the proposed pricing scheme with QoS requirements.

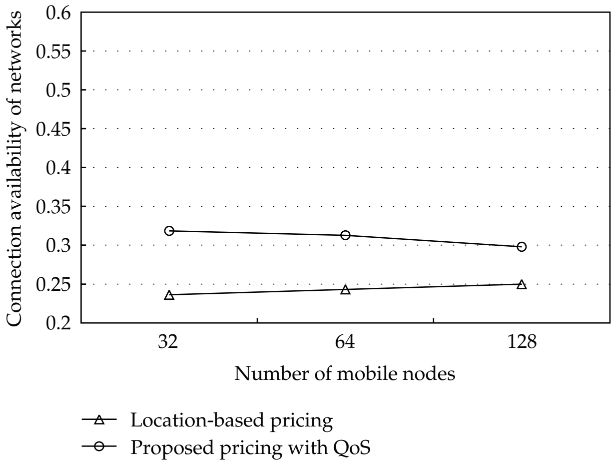

Figure 6: Comparison of connection availability of the networks by two methods in simulation space of (width, height) = (200 units, 200 units).

each individual mobile node is developed to eliminate the unfairness situation in the original model.

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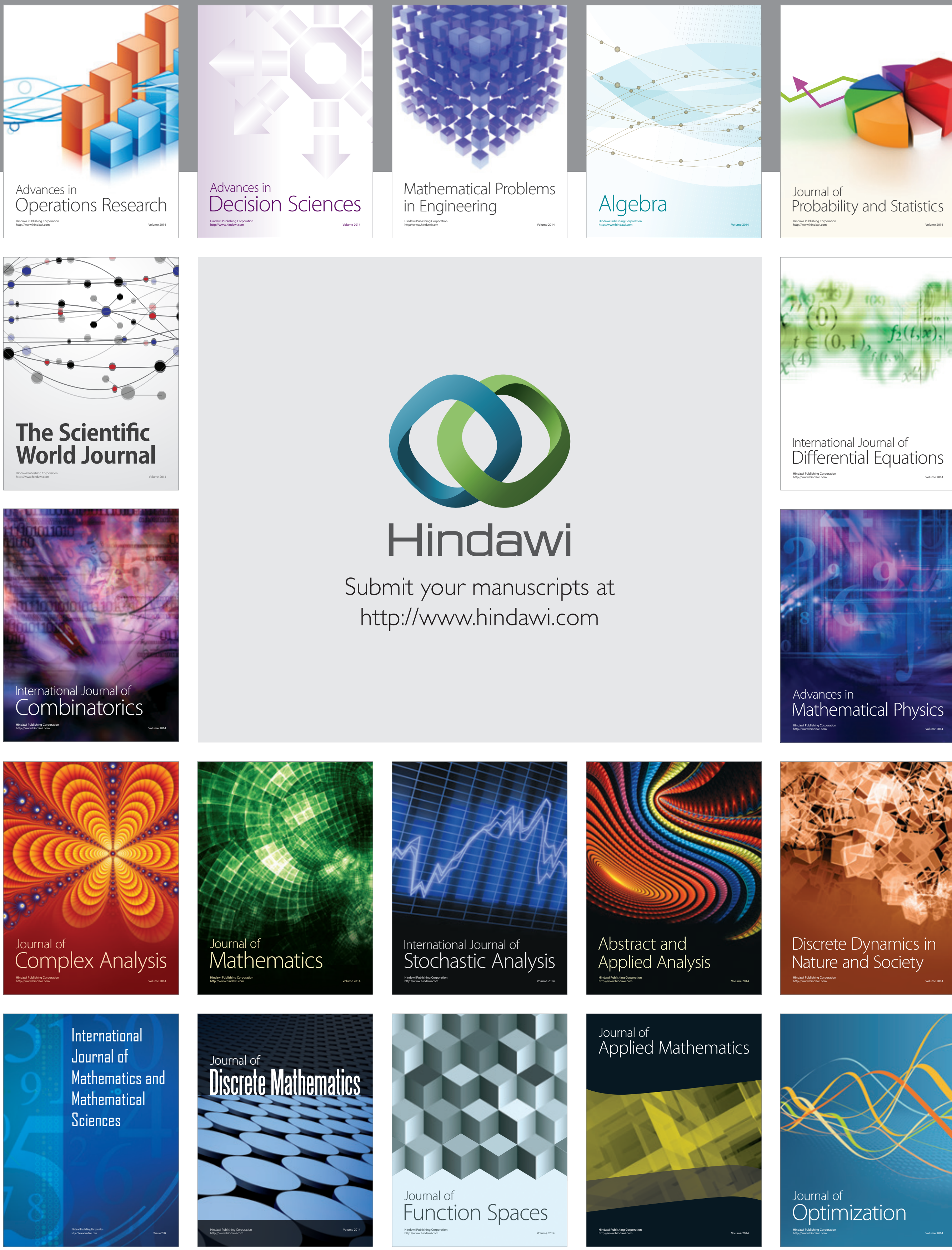
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