Analysis of Crowdsourcing Based Multiple Cellular Network: A Game Theory Approach

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Abstract. Multihop cellular network (MCN) is a feasible scheme to help enlarge network coverage and enhance signal strength in the way of deploying heterogeneous network (HetNet). However, it is challenging for mobile network operators (MNOs) to expedite the implementation of MCN. On the one hand, it is prohibitively expensive to deploy and manage a large-scale intermediate nodes which is essential in MCN; on the other hand, traditional intermediate nodes are usually autonomous and self-interested, which has negative effect on the transmission efficiency and reliability. To address this issue, we discuss a new paradigm of MCN based on crowdsourcing-HetNet (CHetNet). In this paradigm, MNOs recruit the third-parties (TPs) to participate in the construction and maintenances of intermediate nodes by means of rational incentive mechanism. In this article, we mainly focus on a two-hop cellular network in CHetNet. A game-theory approach is used to discuss the whole process of crowdsourcing in this two-hop cellular network and detailed proofs of Nash equilibrium and Stackelberg equilibrium is provided. It is concluded that MCN in CHetNet can help MNOs ease the pressure on the deployment of HetNet and further promote development of 5G.

Keywords: Crowdsourcing · Game theory · HetNet

1 Introduction

With mobile devices increasing explosively and various network applications/services emerging endlessly, it has become more and more difficult for 4G networks to bear the load [2]. Naturally, the new vision for 5G which aims to gain at least a thousand times larger capacity per km^2, a hundred times higher data rates and seamless coverage has been a hot pot [8]. However, as the infrastructure gradually becomes ripe and takes shape, it is a big challenge for mobile network operators (MNOs) to proceed with the innovation of 5G.

To realize the vision of 5G, there have emerged many feasible solutions. Among these, heterogeneous network (HetNet) which can greatly enlarge network capacity and make sure seamless coverage by increasing the density of cell sites has been recognized as an effective scheme in communication field [3].

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In HetNet, different kinds of low-power nodes (also called small cell sites) including remote radio heads (RRHs), micro/pico nodes, femto node and relay nodes are expected to distribute around the macro station [4]. Generally speaking, the macro station is mainly in charge of seamless coverage, while low-power nodes have responsibility for some of the network traffic and complementing the coverage holes [1]. What is more, as ubiquitous small cell sites, relay nodes (RNs) play a much important role in the HetNet, because their deployment is fairly flexible and transmission distance is shorter.

However, it is much challenging for MNOs to deploy such large-scale small cell sites. First, it becomes harder for MNOs to gain satisfying profits under heavy operating and capital expenditure (OPEX and CAPEX) [7]. Second, complicated networking topological relation makes it harder to realize seamless coverage and switching among kinds of access ways. For example, seamless coverage from indoor to outdoor areas is still hard to realize. Even the most precise GPS, it has not reached a degree of position in every corner inside buildings. Last but not least, because of regulatory issues, MNOs might face hindrances in obtaining new deployments on existing sites and seeking for new cell sites.

MNOs has been in a dilemma where they have not feasible scheme to proceed the deployment of large-scale small cell sites. Fortunately, a hot concept "Crowdsourcing" appears in recent years which may bring about a favourable turn. Recently, "crowdsourcing" has been widely developed in communication field. Huawei announced a "Crowdsourcing Small Cell" solution at Mobile World Congress 2014. The solution aims to form a new exciting business mode to generate revenue between MNOs and crowdsourcing partners. Partners including facilities owners, building proprietors, network integrators and enterprises can gain rewards which may be money or high-quality service at their locations by participating in the small cell construction and operation. Moreover, MNOs can achieve rapid and large-scale small cells deployment to increase system capacity and energy efficiency (http://pr.huawei.com/en/news/hw-327762-ict.htm#.WZg4BZp96Ul).

In addition, we have witnessed many other practical realization of network deployment based on crowdsourcing. For example, FON (https://fon.com/), a brand about sharing-WiFi routers, aims to build a network where people connect to millions of WiFi hot spots: seamlessly, securely, and everywhere in a crowdsourcing-mode. FON members by using FON devices can choose a voluntary or paid way to provide fractional bandwidth to other FON members. In return, they can enjoy the free WiFi at any corner where there are signals provided by FON members. FON makes good use of crowdsourcing-based mode and has built the world's largest WiFi network, comprised of people sharing their WiFi in recent 10 years. Apart from network deployment, crowdsourcing can also be used for network measurement. GPS tracking unit uploaded by drivers and passengers can be utilized to generate real time traffic statistics [6].

Inspired by these successful examples, allowing the third-parties to participate in the small cell construction and operation may be a significant scheme. In [9], author presents a paradigm called CHetNet which applies crowdsourcing to distributed HetNet deployment. In this paradigm, author discusses roles of crowdsourcer and crowd in the CHetNet in detail and lists four applications scenarios for CHetNet. In this article, we continue the study of CHetNet based on [9]. Our work focuses on multihop cellular networking (MCN), an application scenario presented for CHetNet. We discuss a two-hop cellular network in CHetNet and increase the number of RNs distributed around the mobile networking operator (MNO)-deployed layer. Furthermore, we present an incentive mechanism and build a game-theory model based on Stackelberg game to seek for a win-win situation. The closed solution of Nash equilibrium and proof of Stackelberg Equilibrium are given in detail. At last, we discuss the influence on utility of the Donor evolved nodeB (DeNB) and RNs when increasing greatly the number of RNs and conclude that too many RNs participating in crowdsourcing would not benefit as anticipated.

The rest of this article is organized as follows: we first analyze the specific case about two-hop cellular networks based on crowdsourcing. Following we form a game-theory model to discuss an intelligent incentive mechanism and specifically prove its rationality. Then, we describe the simulation environment and results. Finally, concluding remarks are given.

2 System Model

With low-cost and feasible-deployment of RNs, it is significant to study MCN for crowdsourcing. MCN has attracted a lot of attention as an effective transmission strategy for future cellular networks because it can effectively increase data rate and enhance coverage [5]. However, the RNs in traditional MCN are usually passive and self-interested that delay the implementation of MCN in terms of transmission efficiency and reliability. This hindrance can be addressed in CHetNet by recruiting TPs as the intermediate nodes instead of voluntary RNs. When a multi-hop communication is formed, the DeNB will employ some potential reliable TPs which play the role of RNs to transmit the information to

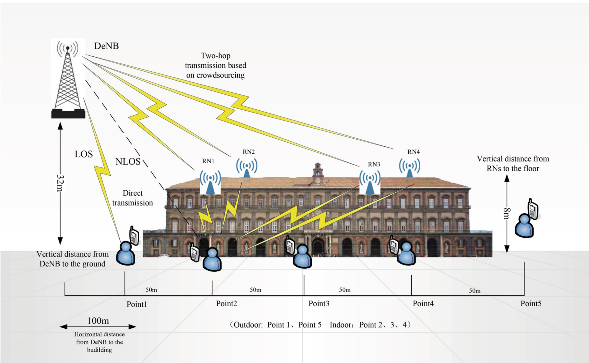

Fig. 1. The model of the two-hop cellular networks

the target UEs. Taking MCN into account, we present a model of two-hop cellular networks in CHetNet using a game-theory approach. The model is composed of an MNO-deployed DeNB, four TP-deployed RNs, and an ordinary user equipment (UE), as shown in Fig. 1. It is evident that the crowdsourcer is the DeNB and crowd is TP-deployed RNs. RNs are deployed on the height of the ceiling in the hall. There are five observation points where the UE walks from outdoor into the hall. When the UE asks for a request, the DeNB has two ways to serve: UE-direct transmission or two-hop transmission, i.e. crowdsourcing way. Note that there is a precondition that only when the task that the DeNB wants to announce is decomposable and sub-tasks are independent, would crowdsourcing scheme proceed [12]. Specifically, when receive a service request from the UE, the DeNB first gathers the network information, including traffic type, channel state information (CSI), potential RNs, resource block (RB), and so on. Depending on these information, orientation process has a decision on a direct transmission way or outsourcing the task to RNs. If outsourcing is determined, the DeNB will start the negotiation with potential partners on the details of the transmission task including transmission parameters, cooperative mode, and the specific incentive mechanism. At last the DeNB and partners reach an agreement in terms of transmission parameters and rewards, and so on. Once an agreement is reached, the DeNB is responsible to transmit traffic data to the recruited RNs in the first time slot, and then these recruited RNs forward the data to the target UE in the second slot [10]. Along with this framework, a general utility function of the DeNB can be written as follows:

$$\begin{aligned} u_{MNO} &= \max\{u_{MNO}^{Direct}, u_{MNO}^{Two-hop}\} \\ u_{MNO}^{Direct} &= \alpha W \log_2\left(1 + SNR^{Direct}\right) \\ u_{MNO}^{Two-hop} &= \frac{1}{2}\alpha W \log_2\left(1 + \sum\nolimits_{i=1}^{N} SNR_i^{Relay}\right) - R \end{aligned} \tag{1}$$

where α is the profit per Mbps of the MNO, and W is the transmission bandwidth assigned to the UE. SNR^{Direct} is the signal-to-noise ratio (SNR) from the DeNB to the UE; N is the number of crowdsourcing RNs, and we assume $N \geq 2$; SNR_n^{Relay} is the received SNR after amplify-and-forward (AF) by RN n; and R is the total reward announced by the MNO. If two-hop transmission is adopted, let p_i denote the transmission power of RN i, the reward allocation can be done using a proportional method, and we can write the reward paid for the i-th RN as

$$r_i = \frac{p_i}{\sum_{j=1}^{N} p_j} \times R \tag{2}$$

Due to the battery-powered form, energy consumption is nonnegligible for RNs to deploy. Let c_i denote the unit power cost of RN i, Accordingly, the cost of RN i participating in the crowdsourcing transmission can be defined as $c_i p_i$, and the utility function of each participating RN can be written as

$$u_i = \frac{p_i}{\sum_{j=1}^{N} p_j} \times R - c_i p_i \tag{3}$$

3 Incentive Mechanism

As MNOs and RNs are the relationship of the employer and employees, an intelligent incentive mechanism is essential to stimulate RNs to participate in crowdsourcing. By means of game-theory model, we can objectively analyze the utility of the two parties and find an optimal scheme for each party and facilitate a win-win situation. In this model, the incentive mechanism of the system using two-hop relay transmission can be modeled as a Stackelberg game. There are one leader and N followers in this game. Obviously, the leader is the DeNB and followers are N relay nodes. Generally speaking, a Stackelberg game can be composed of two stages: In the first stage, the DeNB announces its strategy about the reward R; in the second stage, N relay nodes strategize its transmission power p_i to maximize its own utility and this stage can be considered a non-cooperative game.

In the following parts, we first proves that there exists a unique Nash Equilibrium when R is fixed. On this basis, we further proves that the game between DeNB and recruited RNs has a unique Stackelberg Equilibrium.

3.1 The Determination of Nash Equilibrium

Let a set $\mathcal{U} = \{1, 2, \ldots n\}, n \geq 2$ denote the attached RNs that are interested in participating the transmission task. The strategy of RN i is represented by p_i. The transmission cost of RN i is $c_i p_i$, where $c_i \in \Theta$ is its unit cost. And the set of unit costs is $\Theta = \{\theta_1, \theta_2, \cdots, \theta_l\}$. We assume that the DeNB knows Θ and the distribution of RNs with corresponding unit cost according to the analysis about the historical data. Meanwhile, we assume that RNs with the same unit cost have the same strategy. Based on above descriptions and assumptions, we can transform the utility of RN i (3) to

$$u_i = \frac{p_i}{\sum_{j \in \mathcal{U}} p_j} \times R - c_i p_i \tag{4}$$

The utility of the DeNB is

$$u_0 = g(\widetilde{p}_1, \widetilde{p}_2, \cdots \widetilde{p}_n; n) - R \tag{5}$$

$$g(\widetilde{p}_1, \widetilde{p}_2, \cdots \widetilde{p}_n; n) = \frac{1}{2} \alpha W \log_2 \left(1 + \sum_{i=1}^{n} SNR_i^{Relay} \right) \tag{6}$$

Where $\widetilde{p}_j$ is the transmission power of RNs with unit cost c_j, and $g(\widetilde{p}_1, \widetilde{p}_2, \cdots \widetilde{p}_n; n)$ is the DeNB's valuation function of RNs' transmission power. When $\forall \widetilde{p}_j \leq 0, g(\widetilde{p}_1, \widetilde{p}_2, \cdots \widetilde{p}_n; n) = 0$.

Note that all RNs are willing to provide service for a positive utility, so RN i will not participate in the game when $u_i \leq 0$.

With the strategy of RN i being its own transmission power p_i, we denote $p = (p_1, p_2, \ldots p_n)$ the strategy profile consisting of all RNs strategies. In addition, let p_{-i} denote the strategy profile excluding p_i. Based on it, $p = (p_1, p_2, \ldots p_n)$ can be denoted by $p = (p_i, p_{-i})$.

Definition 1 (Nash Equilibrium). *A set of strategies* $p^{ne} = (p_1^{ne}, p_2^{ne}, \ldots p_n^{ne})$ *is a Nash Equilibrium (NE) if for* $\forall$ *RN* i*,*

$$u_i(p_i^{ne}, p_{-i}^{ne}) \geq u_i(p_i, p_{-i}^{ne})$$

for $\forall p_i \geq 0$*.*

Definition 2 (Best Response Strategy). *Given* p_{-i}*, a strategy of RN* i *is the best response strategy, denoted by* $\beta_i(p_{-i})$*, if it maximizes the utility* $u_i(p_i, p_{-i})$ *of RN* i *for all* $p_i \geq 0$*.*

Based on above definitions, we firstly prove the existence of the Nash Equilibrium according to computing the best response strategy.

Obviously, every RN will play the best response strategy to gain profit in a NE. To study the best response strategy, we firstly compute the derivatives of u_i with respect to p_i:

$$\frac{\partial u_i}{\partial p_i} = \frac{-Rp_i}{(\sum_{j \in \mathcal{U}} p_j)^2} + \frac{R}{\sum_{j \in \mathcal{U}} p_j} - c_i \tag{7}$$

$$\frac{\partial^2 u_i}{\partial p_i^2} = \frac{-2R\sum_{j \in \mathcal{U}} p_j + 2Rp_i}{(\sum_{j \in \mathcal{U}} p_j)^3} = -\frac{2R\sum_{j \in \mathcal{U}_{-i}} p_j}{(\sum_{j \in \mathcal{U}} p_j)^3} < 0 \tag{8}$$

Since the second-order derivative of u_i is negative, the utility u_i is a strictly convex function with respect to p_i. It indicates that RN i can maximize its own utility according to changing its transmission power p_i when other RNs' transmission power p_{-i} is fixed. Note that we should set $\beta_i(p_{-i}) = 0$ when the best response strategy $p_i \leq 0$.

We let the first-order derivative of u_i be zero, we can obtain

$$\frac{-Rp_i}{(\sum_{j \in \mathcal{U}} p_j)^2} + \frac{R}{\sum_{j \in \mathcal{U}} p_j} - c_i = 0 \tag{9}$$

$$p_i = \sqrt{\frac{R\sum_{j \in \mathcal{U}_{-i}} p_j}{c_i}} - \sum\nolimits_{j \in \mathcal{U}_{-i}} p_j \tag{10}$$

when $p_i \leq 0$, $\sqrt{\frac{R\sum_{j \in \mathcal{U}_{-i}} p_j}{c_i}} - \sum_{j \in \mathcal{U}_{-i}} p_j \leq 0$, $R \leq c_i \sum_{j \in \mathcal{U}_{-i}} p_j$, we will set $\beta_i(p_{-i}) = 0$. Hence we can obtain the best response strategy of RN i

$$\beta_i(p_{-i}) = \begin{cases} 0. & if\ R \leq c_i \sum_{j \in \mathcal{U}_{-i}} p_j; \\ \sqrt{\frac{R\sum_{j \in \mathcal{U}_{-i}} p_j}{c_i}} - \sum_{j \in \mathcal{U}_{-i}} p_j & otherwise \end{cases}$$

Since the best response strategy of RN i is solved, we have proved that the existence of a NE. Then, we should prove that the NE is unique according to proving the theorem below. The idea of demonstration about NE is learned from [11].

Theorem 1. *Let $R > 0$ be given. Let $\overline{p} = (\overline{p}_1, \overline{p}_2, \ldots \overline{p}_n)$ be the strategy profile of an NE, and let $\overline{\mathcal{S}} = \{i \in \mathcal{U} | \overline{p}_i > 0\}$, $|\overline{\mathcal{S}}| = n_0$, we have*

1. $|\overline{\mathcal{S}}| > 1$
2. $\overline{p}_i = \begin{cases} 0, & if\ i \notin \overline{\mathcal{S}}; \\ \frac{(n_0-1)R}{\sum_{j\in\overline{\mathcal{S}}} c_j}\left(1 - \frac{(n_0-1)c_i}{\sum_{j\in\overline{\mathcal{S}}} c_j}\right), & otherwise \end{cases}$
3. *if* $c_q \leq \max_{j\in\overline{\mathcal{S}}}\{c_j\}$, *then* $q \in \overline{\mathcal{S}}$
4. *Assume that RNs are ordered in a ascending way such that* $c_1 \leq c_2 \leq c_3 \leq \cdots \leq c_n$. *Let h be the largest integer in $[2, n]$ that meets* $c_h < \frac{\sum_{j=1}^{h} c_j}{h-1}$. *Then* $\overline{\mathcal{S}} = \{1, 2, \ldots h\}$

By means of proving these statements, we can obtain the closed-form solution of $\overline{p}_i$ and then prove the unique NE.

Proof. Firstly we prove $|\overline{\mathcal{S}}| > 1$. We assume $|\overline{\mathcal{S}}| = 0$, obviously it is impossible, as RN 1 can increase its utility by increasing its transmission power. So $|\overline{\mathcal{S}}| > 0$. Then we assume $|\overline{\mathcal{S}}| = 1$, it shows there is only RN $k (k \in \overline{\mathcal{S}})$ participating in the game. However, the first-order derivative of u_k is $-c_k$ and it is unequal to zero. It indicates the strategy of the RN k is not a best response strategy. In other words, it has not reach a NE. It contradicts the NE assumption. So $|\overline{\mathcal{S}}| > 1$.

Then we prove the second one. Based on $|\overline{\mathcal{S}}| > 1$ and (9), we can replace p_i with $\overline{p}_i$ and replace $\mathcal{U}$ with $\overline{\mathcal{S}}$. We can obtain

$$\frac{-R\overline{p}_i}{\left(\sum_{j\in\overline{\mathcal{S}}} \overline{p}_j\right)^2} + \frac{R}{\sum_{j\in\overline{\mathcal{S}}} \overline{p}_j} - c_i = 0, \quad i \in \overline{\mathcal{S}} \tag{11}$$

Summing up (11) over the $|\overline{\mathcal{S}}|$ and we can obtain

$$\frac{-R + n_0 R}{\sum_{j\in\overline{\mathcal{S}}} \overline{p}_j} - \sum_{j\in\overline{\mathcal{S}}} c_j = 0 \tag{12}$$

$$\sum_{j\in\overline{\mathcal{S}}} \overline{p}_j = \frac{(n_0 - 1)R}{\sum_{j\in\overline{\mathcal{S}}} c_j} \tag{13}$$

Then substituting (13) into (11), we can obtain

$$\overline{p}_i = \frac{(n_0 - 1)\,R}{\sum_{j\in\overline{\mathcal{S}}} c_j}\left(1 - \frac{(n_0 - 1)\,c_i}{\sum_{j\in\overline{\mathcal{S}}} c_j}\right) \tag{14}$$

Besides, we set $\overline{p}_i = 0$ when RN i does not belong to $\overline{\mathcal{S}}$. Thus, we can get

$$\overline{p}_i = \begin{cases} 0, & if\ i \notin \overline{\mathcal{S}}; \\ \frac{(n_0-1)R}{\sum_{j\in\overline{\mathcal{S}}} c_j}\left(1 - \frac{(n_0-1)c_i}{\sum_{j\in\overline{\mathcal{S}}} c_j}\right), & otherwise \end{cases} \tag{15}$$

From the above statement, we find that $\overline{p}_i$ only depends on reward R, the set of unit cost Θ and the number n_0 of RNs participating in the game. The reward R is fixed and the set of unit cost Θ can be learned. Thus, only when we confirm the number n_0, would we prove the unique NE. The next work is to find the certain RNs that belongs to $\overline{\mathcal{S}}$.

The third one was proved as follows: Since $\overline{p}_i > 0$ for every RN i belongs to $\overline{\mathcal{S}}$. Then from the (15), we can know $1 - \frac{(n_0-1)c_i}{\sum_{j\in\overline{\mathcal{S}}} c_j} > 0$ which implies $\frac{(n_0-1)c_i}{\sum_{j\in\overline{\mathcal{S}}} c_j} < 1$. Thus we can obtain

$$c_i < \frac{\sum_{j\in\overline{\mathcal{S}}} c_j}{n_0 - 1}, \qquad \forall i \in \overline{\mathcal{S}} \tag{16}$$

And then

$$\max_{i\in\overline{\mathcal{S}}} c_i < \frac{\sum_{j\in\overline{\mathcal{S}}} c_j}{n_0 - 1} \tag{17}$$

We assume that $c_q \le \max_{j\in\overline{\mathcal{S}}}\{c_j\}$, but $q \notin \overline{\mathcal{S}}$. Since $q \notin \overline{\mathcal{S}}$, we know that $\overline{p}_q = 0$. Using the (13), we can obtain the first-order derivative of u_q with respect to p_q when $p = \overline{p}$

$$\frac{\partial u_q}{\partial p_q} = \frac{R}{\sum_{j\in\overline{\mathcal{S}}} \overline{p}_j} - c_q = \frac{\sum_{j\in\overline{\mathcal{S}}} c_j}{n_0 - 1} - c_q > \max_{i\in\overline{\mathcal{S}}}\{c_i\} - c_q \ge 0 \tag{18}$$

It indicates the RN q has not reach a NE and it can increase its utility by increasing its transmission power. It conflicts the previous assumption. So $q \in \overline{\mathcal{S}}$.

Finally the proof of last one was given. Since we have proved that if $c_q \le \max_{j\in\overline{\mathcal{S}}}\{c_j\}$, then $q \in \overline{\mathcal{S}}$, we know that $\overline{\mathcal{S}} = \{1, 2, \cdots, q\}$ for some integer q in $[2, n]$. Because of $c_h < \frac{\sum_{j=1}^{h} c_j}{h-1}$ and (16), we can make sure that $h \ge q$. Firstly we assume $h > q$, so we can find that $c_{q+1} < \frac{\sum_{j=1}^{q+1} c_j}{q}$. Then we have $q \cdot c_{q+1} < \sum_{j=1}^{q} c_j + c_{q+1}$ which implies $c_{q+1} < \frac{\sum_{j=1}^{q} c_j}{q-1}$. In a similar way, we get the first-order derivative of u_{q+1} with respect to p_{q+1} when $p = \overline{p}$ is $\frac{\partial u_{q+1}}{\partial p_{q+1}} = \frac{R}{\sum_{j\in\overline{\mathcal{S}}} \overline{p}_j} - c_{q+1} = \frac{\sum_{j=1}^{q} c_j}{q-1} - c_{q+1} > 0$. It shows the contradiction to the NE assumption which proves that $h = q$.

3.2 Stackelberg Equilibrium of the DeNB

Based on the above analysis, the DeNB that is the leader in the Stackelberg game knows that there exists a unique NE for the RNs when the reward R is announced. Thus the DeNB can strategize its R to maximize its utility. Next we will prove that there must exist a unique Stackelberg.

Theorem 2. *There exists the unique Stackelberg Equilibrium* $(\overline{R}, p^{ne})$ *in the first stage of the Stackelberg game, where* $\overline{R}$ *is the unique maximizer of the utility of the DeNB over* $R \in [0, \infty)$*, and* $p^{ne} = (\widetilde{p}_1, \widetilde{p}_2, \cdots \widetilde{p}_n)$ *which is a set of NE is given in the part A.*

Proof. Let $u_0 = g(X_1R, X_2R, \cdots, X_nR; n) - R$.

And $g(\widetilde{p}_1, \widetilde{p}_2, \cdots \widetilde{p}_n; n) = \frac{1}{2}\alpha W \log_2\left(1 + \sum_{i=1}^{n} SNR_i^{Relay}\right)$. We can get:

$$X_i = \begin{cases} \frac{(n_0-1)}{\sum_{c_j \in \overline{\mathcal{S}}} c_j}\left(1 - \frac{(n_0-1)c_i}{\sum_{c_j \in \overline{\mathcal{S}}} c_j}\right) & i \in \overline{\mathcal{S}}; \\ 0 & i \notin \overline{\mathcal{S}} \end{cases}$$

Besides, we know that $SNR_i^{Relay} = \frac{p_0\gamma_i^1 p_i \gamma_i^2}{1+p_0\gamma_i^1+p_i\gamma_i^2}$ in a two-hop relay transmission system, where p_0 is transmitting power of the DeNB and p_i is RN i's transmitting power. And $\gamma_i^1 = \frac{|h_i^1|^2}{\sigma^2}, \gamma_i^2 = \frac{|h_i^2|^2}{\sigma^2}$ are respectively the SNR from the DeNB to RN i and RN i to the UE, where h_i^1, h_i^2 refers to their channel coefficients and σ^2 is the variance of additive white gaussian noise. Then let $h_i(R) = \frac{p_0\gamma_i^1\gamma_i^2 X_i R}{1+p_0\gamma_i^1+\gamma_i^2 X_i R}, h_i(R) > 0$ thus $u_0 = \frac{1}{2}\alpha W \log_2\left(1 + \sum_{i=1}^{n} h_i(R)\right)$. Then we can obtain:

$$\frac{\partial u_0}{\partial R} = \frac{1}{2}\alpha W \ln 2 \frac{\sum_{i=1}^{n} \frac{\partial h_i(R)}{\partial R}}{1 + \sum_{i=1}^{n} h_i(R)} \tag{19}$$

$$\frac{\partial^2 u_o}{\partial R^2} = \frac{1}{2}\alpha W \ln 2 \frac{(1 + \sum_{i=1}^{n} h_i(R))\sum_{i=1}^{n} \frac{\partial^2 h_i(R)}{\partial R^2}}{(1 + \sum_{i=1}^{n} h_i(R))^2} \tag{20}$$

$$\frac{\partial h_i(R)}{\partial R} = \frac{p_0\gamma_i^1(\gamma_i^2)^2 X_i(1 + p_0\gamma_i^1)}{(1 + p_0\gamma_i^1 + \gamma_i^2 X_i R)^2} \tag{21}$$

According to (21), it is evident that $\frac{\partial^2 h_i(R)}{\partial R^2} < 0$, and we know $h_i(R) > 0$, so $\frac{\partial^2 u_o}{\partial R^2} < 0$. Thus $u_0 = g(X_1R, X_2R, \cdots, X_nR; n) - R$ is a strictly convex function in variables R when $p^{ne} = (\widetilde{p}_1, \widetilde{p}_2, \cdots \widetilde{p}_n)$ is given. When $R = 0, u_0 = 0$. $R \to \infty, u_0 \to -\infty$. So a unique maximizer $\overline{R}$ must exist. We can find the maximal u_0 and then obtain $\overline{R}$ according to traversing the R in the Matlab.

Based on above analysis, it has been proved that there exists a unique NE of the strategy RNs and a unique Stackelberg equilibrium about the strategy of the DeNB. Thus MNOs can adjust their transmission way based on the maximal utility of direct or relay transmission.

4 Simulation and Results Analysis

In this section, we introduce the environment and results of the simulation about the two-hop cellular networks. The model consists of an MNO-deployed DeNB, four TP-deployed RNs and an ordinary UE. Both the DeNB and RNs are equipped with four uniform linear antenna arrays (ULA-4), and the UE is equipped with ULA-2. We set the transmission power and the profit per Mbps of the DeNB are respectively $p_0 = 1\,\text{W}$ and $\alpha = 20/\text{Mbps}$; Besides, we set the transmission bandwidth $W = 1\,\text{MHz}$; and we set $C = [10, 20, 15, 25]$ that is respectively the unit transmission cost of RNs in order. We use WINNER Phase II channel as the environment and the mode of RNs is amplify-and-forward (AF). Maximal ratio combining (MRC) is adopted when multiple replications are received by the UE. As for

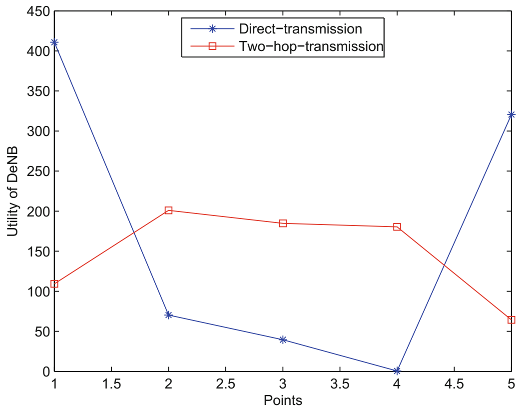

Fig. 2. The utility of the DeNB at different observation

the UE, there are five observation points where points 1 and points 5 are typical urban macrocells with line-of-sight (LOS) condition from the DeNB to the UE. For point 2, 3, 4, the UE moves from outdoor into a large indoor hall and across it. The four RNs are deployed at the four corners of the ceiling. At point 2, 3, 4, transmission from the DeNB to the UE experiences non-LOS (NLOS) outdoor-indoor propagation. As for the two-hop relay transmission, on the first slot, we can consider it LOS macrocell propagation from the DeNB to RNs; and on the second slot, for point 1 and point 5, they are NLOS indoor-outdoor propagation from RNs to the UE, and for the points indoor, they are LOS large-indoor hall propagation from RNs to the UE. Relevant parameters are shown in the Table 1. As unit transmission costs of RNs that plan to receive the transmission task are different, those RNs that have lower unit transmission cost tends to gain higher profits, while RNs which need much more cost would quit the game. In this model, the fourth RN with higher unit cost would not participate in the game because of negative utility. Thus the DeNB and RN $1, 2, 3$ form a cooperative relation to proceed a win-win situation at last.

Table 1. Parameters of layout

Parameter	Value
p_0	1 W
α	20/Mb/s
W	1 MHz
C	10 20 15 25
Height of the DeNB	32 m
Height of RNs	8 m
Height of the UE	1.5 m

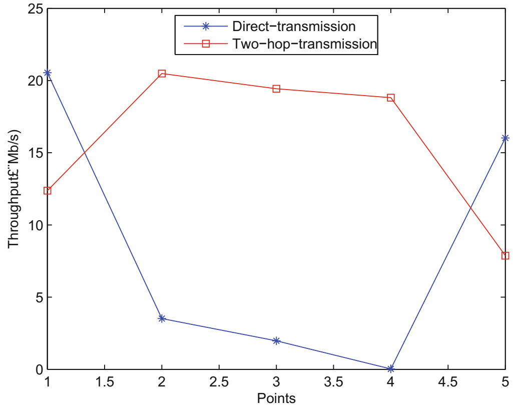

Fig. 3. The throughput of the UE at different observation

Figure 2 shows the variations of utility of the DeNB with different observation points in the way of direct and two-hop transmission. It is evident that when the UE stands at the point 1 or 5, the utility of the DeNB in the direct transmission way is much higher than the two-hop transmission way. However, when the UE enters the mall, the utility of the DeNB in the direct transmission way drops rapidly and even approximates to zero. In this condition, the DeNB will prefer the two-hop transmission way. Figure 3 shows the throughput of the UE, which seems like the trend of graphs about the utility of the DeNB. According to jointly using direct and two-hop transmission, We can find that not only the DeNB can always maintain relatively high utility, but the UE can always experience greater than 15 Mb/s data rate.

Figure 4 shows the relationship between the utility and reward when the UE respectively stands at point 2, point 3 and point 4. The square points labeled on every curve refer to the Stackelberg equilibrium strategy for the DeNB which means the optimal reward offered to RNs. It can be seen that a small amount of reward that is less than 10% of the utility of the DeNB can stimulate the participation of RNs in crowdsourcing task transmission. Thus we can conclude that all participants including the DeNB, RNs and the UE can get what they call for. The DeNB gains more profits and ease the deployment pressure. RNs earn satisfying reward and get higher quality service. And the UE enjoys a better service experience. However, it will not be more profitable when more and more low-cost RNs try to participate in crowdsourcing in a noncooperative competition. We assume all RNs' unit transmission cost is 15/W and gradually increase the number of RNs that are sure to participate in the transmission task one by one when the UE stands at point 3. Figure 5 is the simulation result of utility about the DeNB and RNs and the throughput of the UE in a two-hop transmission way when we add RNs to fourteen. We can find more RNs only make the utility of the DeNB increase little (less than 5%). Meanwhile, the utility of RNs decrease gradually and even approximate to zero as more and

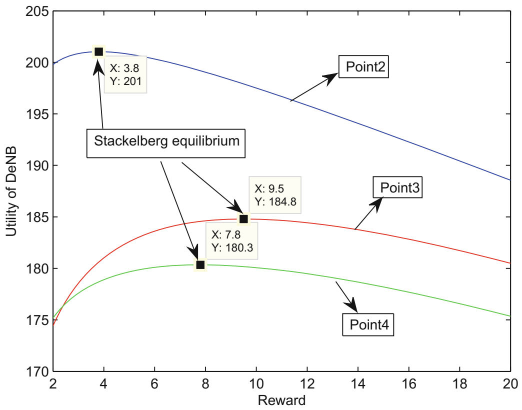

Fig. 4. The utility of the DeNB vs. Reward of RNs.

more competitors take part in the crowdsourcing while the experience data rate of the UE increase barely 2 Mb/s and even improve little at last. Thus, choosing more RNs to participate in a single transmission task benefits little to any party of DeNB, RNs and UEs, it is more worthy to study how to allocate rationally which RNs to which task.

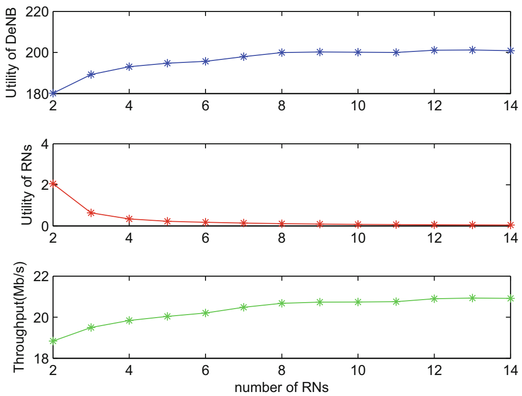

Fig. 5. The utility of the DeNB and RNs, the throughput of the UE

5 Conclusion

In this article, we mainly discuss a two-hop cellular network based on crowdsourcing and its incentive mechanism. By means of a game-theory model, Concrete processes of proof about Nash equilibrium and Stackelberg equilibrium are given to verify the feasibility of the incentive mechanism. The results of simulations verify that the crowdsourcing mode prompts MNOs and TPs to form a win-win situation and helps accelerate deployment of HetNet, and further promote the development of 5G.

However, MCN in CHetNet still faces many challenges in the way of implementation. How to organize and manage a large scale of unplanned TPs in a convincing and legal way is a critical issue to solve. And how to optimize the incentive mechanism and allocate transmission tasks rationally which can ensure equity for TPs needs further research. In addition, security problem becomes particularly important and MNOs should protect the privacy of UEs from revealing through TPs.

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References

1. Cai, S., Che, Y., Duan, L., Wang, J., Zhou, S., Zhang, R.: Green 5G heterogeneous networks through dynamic small-cell operation. IEEE J. Sel. Areas Commun. **34**(5), 1103–1115 (2016)
2. Cisco: Cisco visual networking index: global mobile data traffic forecast update, 2013 to 2018. Technical report, February 2014
3. Ge, X., Tu, S., Mao, G., Wang, C.X., Han, T.: 5G ultra-dense cellular networks. IEEE Wirel. Commun. **23**(1), 72–79 (2015)
4. Ghosh, A., Mangalvedhe, N., Ratasuk, R., Mondal, B., Cudak, M., Visotsky, E., Thomas, T.A., Andrews, J.G., Xia, P., Jo, H.S., et al.: Heterogeneous cellular networks: from theory to practice. IEEE Commun. Mag. **50**(6), 54–64 (2012)
5. Jangsher, S., Li, V.O.K.: Power control in multihop cellular networks with multiple radio access technologies. In: IEEE International Symposium on Personal, Indoor, and Mobile Radio Communication, pp. 1674–1678 (2014)
6. Kanhere, S.S.: Participatory sensing: crowdsourcing data from mobile smartphones in urban spaces. In: Hota, C., Srimani, P.K. (eds.) ICDCIT 2013. LNCS, vol. 7753, pp. 19–26. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-36071-8_2
7. Machuca, C.M.: Expenditures study for network operators. In: International Conference on Transparent Optical Networks, pp. 18–22 (2006)
8. Osseiran, A., Boccardi, F., Braun, V., Kusume, K., Marsch, P., Maternia, M., Queseth, O., Schellmann, M., Schotten, H., Taoka, H.: Scenarios for 5G mobile and wireless communications: the vision of the METIS project. IEEE Commun. Mag. **52**(5), 26–35 (2014)
9. Wang, Y., Lin, X.: CHetNet: crowdsourcing to heterogeneous cellular networks. Netw. IEEE **29**(6), 62–67 (2015)
10. Wang, Y., Lin, X.: User-provided networking for QoE provisioning in mobile networks. Wirel. Commun. IEEE **22**(4), 26–33 (2015)
11. Yang, D., Xue, G., Fang, X., Tang, J.: Incentive mechanisms for crowdsensing: crowdsourcing with smartphones. IEEE/ACM Trans. Netw. **24**(3), 1732–1744 (2016)
12. Zhang, H., Sugiyama, M.: Task selection for bandit-based task assignment in heterogeneous crowdsourcing. In: Technologies and Applications of Artificial Intelligence, pp. 164–171 (2015)