Mutual Wi-Fi Deployment: A One-to-Many Bargaining Structure

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Abstract – We develop a mobile application to solve the complications faced by the mobile network operator (MNO) and the venue owners (VOs) on the public Wi-Fi deployment. We consider a one-to-many bargaining framework, where the MNO bargains with VOs sequentially to determine where to deploy Wi-Fi and how much to pay. Taking into account the negative externalities among different steps of bargaining, we analyze the following two cases: for the exogenous bargaining sequence case, we compute the optimal bargaining solution on the cooperation decisions and payments under a predetermined bargaining sequence; for the endogenous bargaining sequence case, the MNO decides the bargaining sequence to maximize its payoff. Through exploring the structural property of the optimal bargaining sequence, we design a low-complexity Optimal VO Bargaining Sequencing (OVBS) algorithm to search the optimal sequence. More specifically, we categorize the VOs into three types based on the impact of the Wi-Fi deployment at their venues, and show that it is optimal for the MNO to bargain with these three types of VOs sequentially.

Index Terms – Mobile Network Operator,Payoff,Android, Mobile Communication, Bargain, Endogenic Technique, Exogenic Technique, Venue Owner, MNO, OVBS, Wi-Fi deployment.

1. INTRODUCTION

We investigated the economic interactions among the MNO and VOs in the cooperative Wi-Fi deployment. We analyzed the problem under the one-to-many bargaining framework, with both exogenous and endogenous sequences. For the exogenous case, we applied backward induction to compute the bargaining results in terms of the cooperation decisions and payments for a given bargaining sequence. For the endogenous case, we proposed the OVBS algorithm that searches for the optimal bargaining sequence by leveraging the structural property. Furthermore, we studied the influence of the bargaining sequence on VOs, and found that when VOs are homogenous, the earlier bargaining positions are always no worse for the VOs. Numerical results showed that the optimal bargaining sequence significantly improves the MNO's payoff as compared with the random and worst bargaining sequences. The offloading problem was formulated as a combinatorial auction, and an innovative payment rule was designed to guarantee both individual rationality and truthfulness for realistic scenarios in which only part of the data traffic can be offloaded. In order to solve efficiently (i.e., in polynomial time) the offloading problem for large-scale network scenarios, we also proposed a greedy algorithm, with two alternative versions of the allocation phase, that preserves the truthfulness property. Numerical results demonstrate that the proposed schemes well capture the economical and networking essence of the problem, thus representing a promising solution to implement a trading marketplace for next-generation access networks composed of heterogeneous systems.

2. RELATED WORK

There are a few literatures studying the MNO's Wi-Fi access point deployment problem. Zheng et al. in [1] proposed Wi-Fi access point deployment algorithms, which provide the worst-case guarantee to the interconnection gap for vehicular Internet access. Wang et al. in [2] real user mobility traces and deployed Wi-Fi access points based on the density of users' data access requests. Liao et al. in [3] investigated the Wi-Fi access point deployment problem with the consideration of both the coverage and localization accuracy. Poularakis et al. in [4] studied a joint Wi-Fi access point deployment and Wi-Fi service pricing problem. These works focused on a single MNO's Wi-Fi deployment decision, an did not consider the VOs, who may collaborate with the MNO and compensate the MNO's Wi-Fi deployment cost. Two more brief concepts discussed by other authors are given below:

- Economics of VOs' Wi-Fi Networks
- One-to-Many Bargaining

2.1 Economics of VOs' Wi-Fi Networks

There have been many literatures studying the mobile data offloading market, where the MNOs lease the VOs' (or resident users') Wi-Fi networks to offload the cellular data traffic. For example, Iosifidis et al. in [5] designed an iterative double auction mechanism for an offloading market, where the MNOs compete to lease the VOs' Wi-Fi networks for data offloading. The authors proposed an efficient allocation and payment rule that maximizes the social welfare. References [6], [7], [8] designed reverse auctions for an MNO to motivate the VOs to offload the cellular traffic. Gao et al. in [8] applied a bargaining framework to study a similar Wi-Fi capacity trading problem. Furthermore, Yu et al. in [9] focused on the VOs' optimal Wi-Fi monetization strategies by considering the Wi-Fi advertising technique. However, these works assumed that the Wi-Fi networks have already been deployed and are owned by the VOs. They did not study the VOs' cooperation with the MNO in deploying the Wi-Fi networks.

2.2 One-to-Many Bargaining

In terms of the one-to-many bargaining, the most relevant works are [10], [11]. Both papers studied the one-to-many bargaining under the Nash bargaining theory. However, since they did not consider the cooperation cost, their conclusion was that the bargaining sequence does not affect the buyer 's payoff, and their analysis was limited to the one-to- many bargaining with exogenous sequence. In our work, we take into account the cooperation cost (i.e., Wi-Fi deployment and operation cost), which complicates the one-to-many bargaining with exogenous sequence. Such a consideration also motivates us to study the one-to-many bargaining with endogenous sequence. References [12], [13], [14] studied several one-to-many bargaining problems, where the buyer bargains with multiple sellers on a joint project that requires the cooperation from all the participants. It is different from our problem, as here the MNO may only cooperate with a subset of the VOs on the Wi-Fi deployment.

3. PORPOSED MODELLING

We consider one mobile network operator (MNO), who operates multiple macro cells and bargains with venue owners (VOs) to deploy Wi-Fi access points. For simplicity, we assume that each venue (such as a cafe) has a limited space and hence is covered by only one cellular macro cell. Since deploying Wi-Fi at a particular venue only offloads traffic for the corresponding macro cell under our assumption and does not benefit other macro cells, the MNO can consider the Wi-Fi deployments for different macro cells separately. Without loss of generality, we study the MNO's strategy within one macro cell. From the analysis of complications faced by the MNO's and VO's during the deployment of a public Wi-Fi, we propose a model for an android mobile application that consists of 3 modules, each one for MNO's , VO's and common users respectively. Before discussing about the modules and application, the research concepts are to be explained.

- MNO's Payoff, VO's Payoff, and Social Welfare
- One-to-many bargaining with Exogenous sequence
- One-to-many bargaining with Endogenous sequence
- Android application

3.1 MNO's Payoff, VO's Payoff, and Social Welfare.

We use $b_n \in \{0,1\}$ to denote the bargaining outcome between the MNO and VO n: $b_n = 1$ if they agree on the Wi-Fi deployment at venue n, and $b_n = 0$ otherwise. We use $p_n \in R$ to denote the MNO's payment to VO. The MNO's payoff depends on the offloading benefit, advertising profit, Wi-Fi deployment and operation cost, and its payment to VOs. VO n's payoff depends on the revenue directly brought by Wi-Fi and the MNO's payment. Here Q_n captures the increase in social welfare by deploying Wi-Fi at venue n, excluding the data offloading effect.

TABLE 1: Main Notations

$n, \mathcal{N}$	VO index and its feasible set
t	Time period index
X_n^t	Amount of offloaded traffic at venue n during the t-th time period
Q_n	Net benefit of deploying Wi-Fi at venue n without data offloading effect
$f_t(\cdot)$	MNO's data offloading benefit function for the t-th time period
$\boldsymbol{b}_n$	Bargaining outcomes between the MNO and the first n VOs (*Variables*)
$\boldsymbol{p}_n$	Payments from the MNO to the first n VOs (*Variables*)
$\boldsymbol{\pi}_n$	Payoffs of the first n VOs (*Variables*)
$U(\boldsymbol{b}_N, \boldsymbol{p}_N)$	MNO's payoff function
$V_n(b_n, p_n)$	VO n's payoff function
$\Psi(\boldsymbol{b}_N)$	Social welfare function
U_n^0, V_n^0	MNO's and VO n's disagreement points at step n
U_n^1, V_n^1	MNO's and VO n's payoffs at step n under bargaining result (b_n, π_n)
$B_m^s(\boldsymbol{b}_s)$	Outcomes of the first m steps when the MNO reaches $\boldsymbol{b}_s$ in the first s steps
$b_k^*(\boldsymbol{b}_{k-1})$	Outcome of step k when the MNO reaches $\boldsymbol{b}_{k-1}$ in the first $k-1$ steps
$\pi_k^*(\boldsymbol{b}_{k-1})$	VO k's payoff when the MNO reaches $\boldsymbol{b}_{k-1}$ in the first $k-1$ steps
$\hat{\boldsymbol{b}}_N, \hat{\boldsymbol{\pi}}_N$	NBS of all the N steps
U_0	MNO's eventual payoff after bargaining

To simplify the description, we use venue n to refer to VO n's venue. Different from Xn , we aggregate the extra revenues obtained by VO n during different time periods into a single parameter Rn . The reason is that VO n's payoff is linear in Rn , as we will discuss in this Section. Hence, considering the total value leads to the same result as considering different values in different time periods. Similar explanations apply for the definitions of parameters Cn and An. In practice, some VOs undertake the backhaul cost for the MNO. This can be easily incorporated into our analysis by properly redefining Rn and Cn .Sometimes VOs promote their products via Wi-Fi, and we include the corresponding advertising profit in Rn .In practice, the MNO and VOs can estimate these parameters. For example, parameter Xn can be estimated by combining the results, which studied the spatial temporal distribution of cellular traffic and the percentage of offloaded cellular traffic, respectively. Parameters Rn and An are mainly determined by the statistics like the number of customers and the customers' average sojourn time, which can be estimated by the method proposed in [15]. Parameter Cn can be estimated based on [16], which showed the Wi-Fi hotspots' detailed capital expenditures (e.g., equipment fees) and operating expenses (e.g., backhaul costs, power costs, and maintenance fees).

We allow pn to be negative, in which case VO n pays the MNO. This will be the case when deploying Wi-Fi is more beneficial to VO than to the MNO.

3.2 One-to-many bargaining with Exogenous sequence.

In this section, we study the case where the MNO bargains with N VOs sequentially under a fixed sequence. We illustrate the bargaining protocol in Figure At each step, the MNO bargains with one VO n ∈ N on (bn , pn).

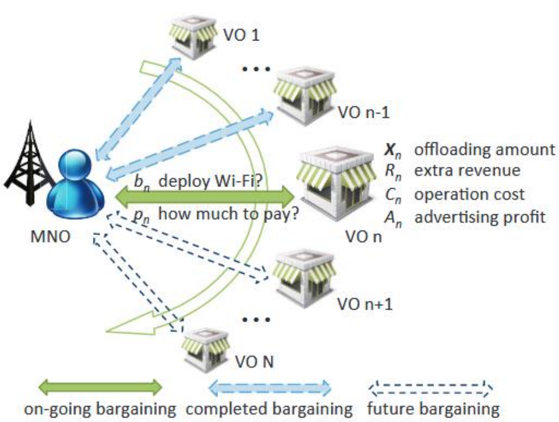

Fig. 1: Bargaining Protocol

At step n ∈ N , the MNO bargains with VO n. We define U 0 and V 0 as the MNO's and VO n's disagreement points, respectively. Furthermore, when the MNO and VO n agree on (bn , πn), we define their payoffs by U 1 and V 1 , respectively. Because VO n has a zero disagreement point if not reaching an agreement with the MNO, we have V 0 = 0. Moreover, based on the definition of πn , we have V 1 = πn .

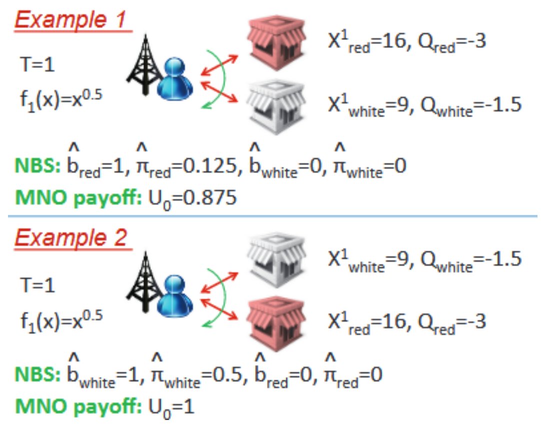

Fig. 2: Influence of Bargaining Sequence on Heterogeneous VOs' Payoffs.

First, we find that the NBS of a particular step depends on the Wi-Fi deployment decisions of all the prior bargaining steps. This is because the more Wi-Fi networks the MNO has already deployed, the less motivation it has to deploy a new Wi-Fi network. On the other hand, since such a negative externality is not related to the payments among the MNO and VOs, the NBS of a particular step is independent of the payments of all the prior bargaining steps.

3.3 One-to-many bargaining with Endogenous sequence.

In this section, we study the one-to-many bargaining with endogenous sequence, where the bargaining sequence is selected by the MNO to maximize its payoff. We illustrate the influence of the bargaining sequence on the MNO's payoff through two examples. We formulate the MNO's optimal bargaining sequencing problem. We solve the problem through an Optimal VO Bargaining Sequencing (OVBS) algorithm. We study two special cases, where we can explicitly determine the optimal bargaining sequence without running OVBS.

For type 1 VO n, its cooperation with the MNO does not decrease the social welfare, i.e., Ψ (b1 , . . . , bn−1 , 1, bn+1 , . . . , bN) ≥ Ψ (b1 , . . . , bn−1 , 0, bn+1 , . . . , bN) for all (b1 , . . . ,bn−1 , bn+1 , . . . , bN);

For type 2 VO n, its cooperation with the MNO may or may not decrease the social welfare, which depends on other VOs' parameters and bargaining positions;

For type 3 VO n, its cooperation with the MNO decreases the social welfare, i.e., Ψ (b1 , . .

$., b_{n-1}, 1, b_{n+1}, \ldots, b_N) < \Psi(b_1, \ldots, b_{n-1}, 0, b_{n+1}, \ldots, b_N)$ for all $(b_1, \ldots, b_{n-1}, b_{n+1}, \ldots, b_N)$.

Proposition 1.The MNO will always cooperate with a type 1VO, regardless of such a VO's position in the bargaining sequence.

Proposition 2.The MNO will never cooperate with a type 3 VO, regardless of such a VO's position in the bargaining sequence.

Proposition 3.If the bargaining sequence follows 1, 2, . . . , N , and VO k belongs to type 1, where k ∈ {2, 3, . . . , N }, the MNO's payoff does not decrease after exchanging VOs k – 1 and k's bargaining positions.

Proposition 4. If the bargaining sequence follows 1, 2, . . . , N , and VO k belongs to type 3, where k ∈ {2, 3, . . . , N }, the MNO's payoff does not change after exchanging VOs k k's bargaining positions.

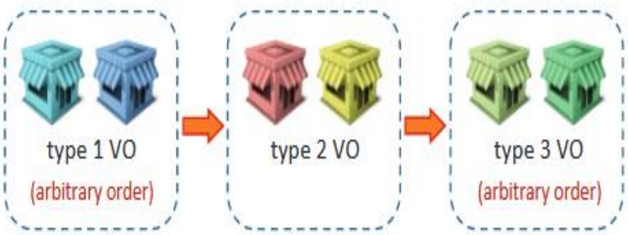

Fig. 3: Structure of the Optimal Bargaining Sequence under OVBS.

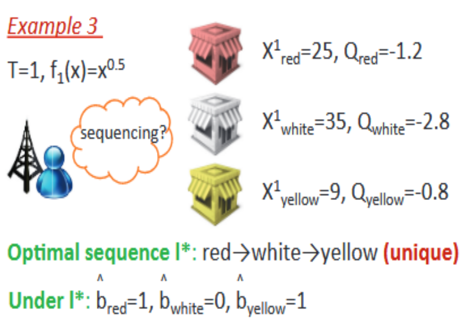

Fig. 4: Counter-Intuitive Sequencing for Type 2 VOs

3.4 Android application

The application consists of 3 major modules for MNOs, VOs and common users each.

The VO module deals with login and lets the Venue owner to update the venue details along with other details such as area and profit due to the Wi-Fi deployment. This module also deals with the bargaining data received from the MNOs that are interested to collaborate with a specific VO. The VO can accept or reject an offer.

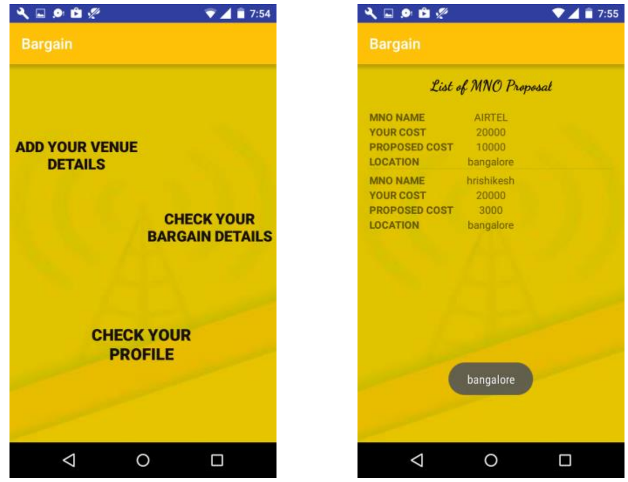

Fig. 5: Screenshots of VO module.

The MNO module consists of login along with a home page that lets them to approach VOs in two different methods such as Exogenous and Endogenous methods.

The base price set by the VO is displayed for which the MNO can provide a counter price, therefore bargaining happens in a secured manner. The MNO has the option to select the Venue type as explained in the One-to-many

Endogenous sequence section.

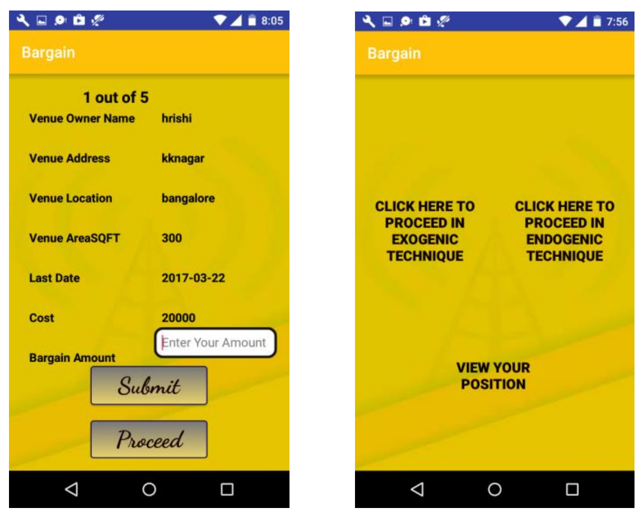

Fig. 6: Screenshots of MNO module.

The user module displays the deployed Wi-Fi spots which can be improved in such a way that the nearest venues can be displayed by getting the user's geo location and the respective Venues can advertise their products in the application, so that it eventually becomes a consumer pulling process.

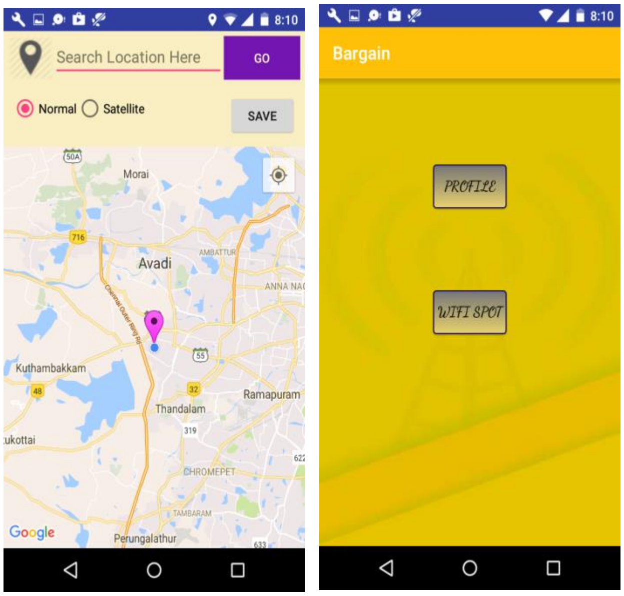

Fig. 7: Screenshots of User module.

4. NUMERICAL RESULT

First we define the criteria for evaluating the performance gap between different sequencing strategies. For a set N of VOs and the corresponding set **L** of bargaining sequences, we define the MNO's maximum, minimum, and average payoff . We define the normalized maximum gap (NMG) and the normalized maximum deviation (NMD): NMG and NMD capture the performance improvement of the optimal sequence over the worst sequence and the random sequence, respectively.

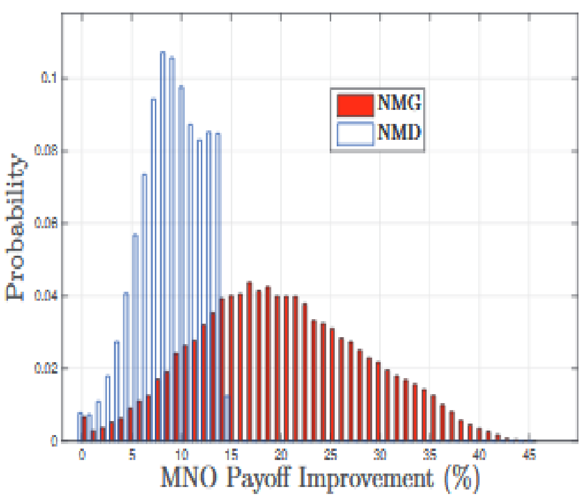

Fig. 8: Distributions of NMG and NMD (Truncated Normal Distribution).

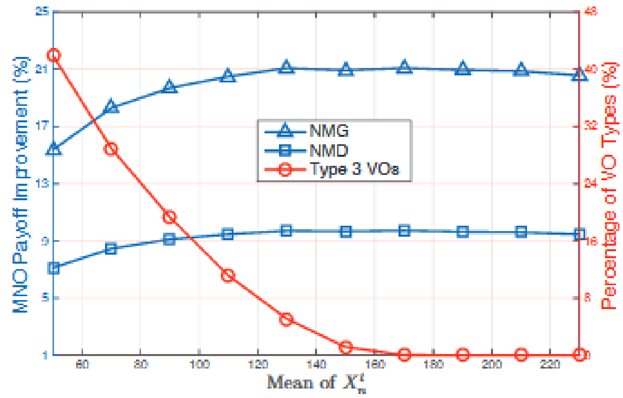

Fig. 9: Influence of E (X(t)) on NMG and NMD.

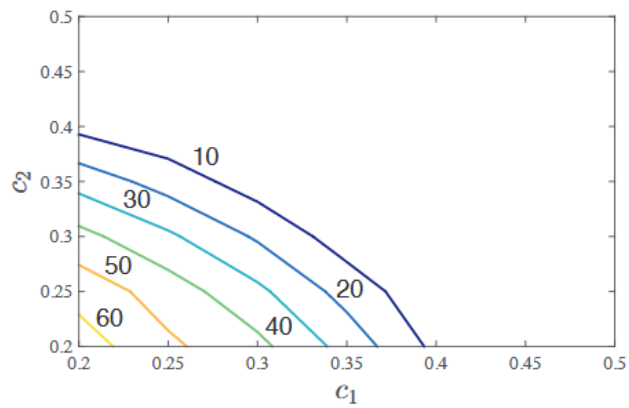

Fig. 11: Percentage of Type 3 VOs under Different ft (•)(%).

5. CONCLUSION

Numerical results showed that the optimal bargaining sequence significantly improves the MNO's payoff as compared with the random and worst bargaining sequences. We illustrated that the optimal sequencing is most beneficial when the offloading benefit functions have medium concavities. In our future work, we will further consider the incomplete information scenario, where the MNO and the VO have limited information of the remaining VOs for each step of the bargaining. Moreover, we are interested in studying the MNO competition, where multiple MNOs compete for the VOs' cooperation.

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