The Wi-Fi Roaming Game

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Abstract. We propose an extensive-form game as a model for pricing roaming charges in 802.11 wireless data networks. We specify utility functions for the three agents involved in the game: the wireless user and the visited and home operators. With realistic assumptions, we use the model to find optimal roaming prices for delay insensitive users.

1 Introduction

In wireless telecommunications, *roaming* refers to the provision of service in a location other than the home location of the service subscriber. The economic aspects of roaming in cellular voice networks have been studied in the literature [1–3]. In such networks, supporting roaming is a static decision which is enforced by a "roaming agreement" between the operators. However, new wireless networks with different properties, such as 802.11, are growing in ubiquity. In 802.11 wireless networks, user accounting and incentives of operators for providing roaming are different from cellular voice networks. In addition to geographical coverage, 802.11 network operators are interested in supporting roaming for better quality of service and load balancing. In these networks, the decision of whether to provide service to a roaming user or not should be made dynamically, especially considering that 802.11 is an open system [4] and users can easily switch between networks.

In this paper, we propose an extensive-form game as a model for users' roaming between multiple 802.11 wireless data networks. we specify the utility functions of the agents involved in the game according to the network properties of the 802.11 protocol. We then examine a specific version of the game to find the behavior of the network operators when charging delay insensitive users for roaming.

In the next section we present the model and specify the utility functions. We will then outline a simplified version of the game in section 3 to gain insight into the properties of the game equilibrium. Finally, section 4 concludes the paper and presents some future work.

2 Modeling

Assume two operators, A and B, have installed infrastructure for wireless mesh [5] networks in an urban area. In some areas their network coverage is exclusive and in other parts, such as heavily crowded malls, their coverage overlaps[1]. Two extensive-form games for roaming users can be envisioned:

1. **User initiated hand-off**: A subscriber to A proposes to connect to an access point belonging to B. B is called the *visited operator* and A is the *home operator*. The visited operator has two choices: *admit* or *reject*. If B decides to admit, the home operator may *agree* or *disagree* with the hand-off[2].
2. **Operator initiated hand-off**: As the home operator, A may instruct a subscriber to *switch* to the other operator. If the subscriber decides to switch, the visited operator may *admit* or *reject* the request. The open nature of 802.11 networks and the limited control of the operators over the users, make the *operator initiated* hand-off scenario impractical.

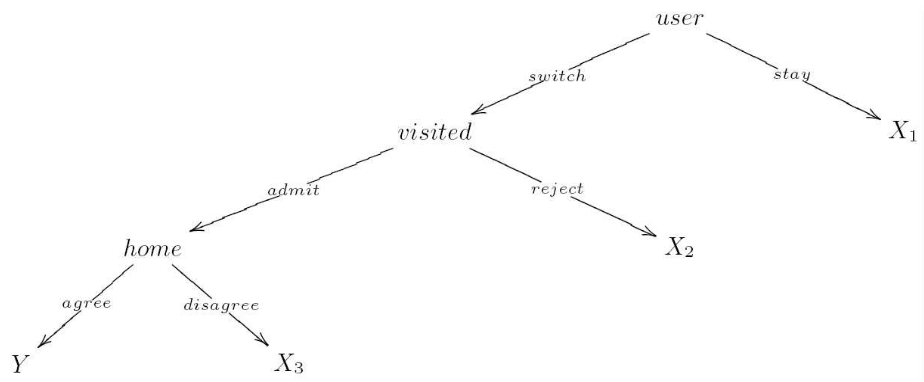

Fig. 1. User-initiated roaming game.

In this paper we will focus on the first scenario because the technical properties of the 802.11 standard [4] suggest that *user initiated* hand-off is more realistic. As demonstrated in Figure 1, the user initiated hand-off is a *perfect information extensive-form game* $G = (N, A, Z, u)$ where:

- The set of agents is $N = \{user, home, visited\}$.
- The set of actions available to agents is $A = \{A_{user}, A_{home}, A_{visited}\}$ where $A_{user} = \{switch, stay\}$, $A_{home} = \{admit, reject\}$ and $A_{visited} = \{agree, disagree\}$.
- The set of terminal choice nodes is $Z = \{X_1, X_2, X_3, Y\}$.
- The utility function, u, of each agent in each terminal node is defined in section 2.1.

[1] Mesh network deployments are not planned, therefore each operator may suffer from bad signal quality in some locations.

[2] The home operator can enforce its decision, if it does not agree, by denying to pay the charges to the visited operator.

2.1 Utility Functions

In this section we introduce the utility functions of the agents participating in the roaming game. Throughout this paper we use the v subscript for the visited operator and the h subscript for the home operator.

Visited Operator Utility Function The visited operator's decision to admit or reject a visitor connection request depends on the cost and benefit of providing the service. The cost consists of the *basic service cost* (C_v) and the cost incurred by the risk of potential congestion in the network ($C_{congestion}$). The benefit to the visited operator is the revenue from the home operator. This revenue may be either fixed for every hand-off instance or dynamic. For simplicity, we consider the fixed revenue and denote it by R_v.

In 802.11 data networks, as a result of contention, if the number of users trying to use an access point crosses some threshold, none of them will be able to utilize the access point effectively. We assume that the operator has decided the maximum possible number of users for an access point, M. If the current number of users of the access point, N_v, plus one exceeds M_v (the maximum possible number of users in the visited access point), the *congestion cost* of admitting the extra roaming user will be too high and admission is effectively impossible.. However, if $N_v + 1 < M_v$ the visited operator will evaluate the congestion cost based on the congestion risk of admitting the visitor to the network. This cost evaluation is similar to *congestion pricing* [6]. Although the user will not be charged based on the congestion cost (this has been proved to be impractical [7]), she will not be admitted if her congestion cost for the visited network is too high.

The congestion cost of the visitor can be modeled by the expected delay incurred by the visitor. We assume adequate resources in the network core, therefore, we only consider delay at an access point based on an $M/M/1$ queueing model [8]:

$$C_{congestion} = k \times \frac{1}{M_v - N_v - 1}$$

where k is the congestion cost coefficient that is determined by the operator. The visited operator would evaluate the following utility function. If the outcome is positive, it would admit the user and otherwise will reject it.

$$U_{visited} = \begin{cases} R_v - C_{congestion} - C_v & \text{if } N_v + 1 < M_v \text{ and } R_v > C_{congestion} + C_v \\ 0 & \text{otherwise} \end{cases}$$

Home Operator Utility Function If hand-off takes place, the home operator charges the user an extra switching cost, S, (i.e. if the normal service charge is R, the use is charged $R + S$). If hand-off does not take place, then the utility of the home operator would be similar to the utility of the visited operator:

$$U_{home} = \begin{cases} R + S - R_v & \text{if hand-off takes place} \\ R - C_{congestion} - C_h & \text{if hand-off does not take place} \end{cases}$$

Where $C_{congestion}$ is evaluated similar to the visited operator.

User Utility Function The user utility depends on the *bandwidth*, B, and *delay*, D, that she experiences [6], plus the service charge. We assume a linear function to evaluate a user's utility:

$$U_{user} = \begin{cases} \alpha B_h - \beta D_h - R & \text{if hand-off does not take place} \\ \alpha B_v - \beta D_v - R - S & \text{if hand-off takes place} \end{cases}$$

where α and β determine the user's sensitivity to bandwidth and delay.

Agent Utilities in Each Game State In 3 of the 4 possible outcomes of the game, no hand-off takes place and the utilities of the agents are as follows:

$$X_1, X_2, X_3 : \begin{cases} U_{user} &= \alpha B_h - \beta D_h - R \\ U_{home} &= R - C_{congestion} - C_h \\ U_{visited} &= 0 \end{cases}$$

If the hand-off takes place (Y) the utility of the agents would be:

$$Y : \begin{cases} U_{user} &= \alpha B_v - \beta D_v - R - S \\ U_{home} &= R + S - R_v \\ U_{visited} &= R_v - C_{congestion} - C_v \end{cases}$$

3 Roaming Prices for Delay Insensitive Users

To find the optimal pricing strategies for roaming charges for delay insensitive users (i.e. $\beta = 0$) we examine the conditions under which the *sub-game perfect equilibrium* for these users is switching. We assume that congestion costs are negligible ($C_{congestion} \approx 0$). This is a valid assumption for any lightly loaded network. With these assumptions the hand-off takes place if:

$$\begin{aligned} \alpha B_v - \alpha B_h &> S \\ R_v - C_h &< S \\ R_v - C_v &> 0 \end{aligned}$$

In the absence of any congestion cost, the last inequality will always hold. That is, the visited operator will always charge more than its cost of service. For now, assume that $R_v - C_h < S$ (we will re-consider this assumption later). The hand-off will take place if:

$$\alpha B_v - \alpha B_h > S$$

The bandwidth available to a user would only be limited by other users in the same access point. We assume that the bandwidth available to any user is a linear function of the number of active users of the same access point, N_h and N_v for the home and the visited operator respectively:

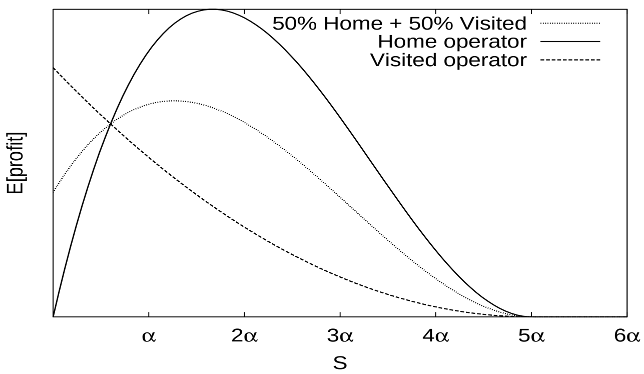

Fig. 2. Expected roaming profit of operators vs. switching cost.

$$B_v(N_v) = (1 - \frac{N_v}{M_v})B_v^m$$
$$B_h(N_h) = (1 - \frac{N_h}{M_h})B_h^m$$

where B_v^m and B_h^m are the maximum available bandwidth of the visited and home access points respectively. Assuming a uniform distribution for users, the probability of hand-off is:

$$Pr(B_v(N_v) - B_h(N_h) > \frac{S}{\alpha}) = \iint_{\text{where } (B_v(N_v)-B_h(N_h))>\frac{S}{\alpha}} \frac{1}{M_v \times M_h}\, dN_v\, dN_h$$
$$= \begin{cases} \frac{2S/\alpha + B_h^m}{2B_v^m} & \text{if } S/\alpha < B_v^m - B_h^m \\ \frac{(B_v^m - S/\alpha)^2}{2B_v^m B_h^m} & \text{if } S/\alpha > B_v^m - B_h^m \text{ and } S/\alpha < B_v^m \\ 0 & \text{if } S/\alpha > B_v^m \end{cases}$$

Figure 2 illustrates the expected value of the roaming profit of each of the operators versus the switching cost. In this figure, the values of S that satisfy $S > R_v - C_h$ are valid. If $R_v < C_h$, then the highest expected value of profit for the visited operator is when $S = 0$. The expected value of profit for the home operator is maximized for a non-zero value of S.

In practice, each operator will play both visited and home roles in the roaming game. If the value of S is the same for both operators in the “roaming agreement,” then the optimal pricing strategy depends on how often each operator will play each of the two roles. In Figure 2, the profit of an operator that plays each role 50% of the time is plotted. In such a scenario the operators can easily agree on the switching cost. But if one operator has a priori knowledge that the other operator will take home role more often, then, as illustrated in Figure 3, the optimal value of S for them will be different. The extreme case of such asymmetry in roles is a Mobile Virtual Network Operator (MVNO) [9]. An MVNO always plays the role of a home operator and can never be visited, because it does not own any infrastructure.

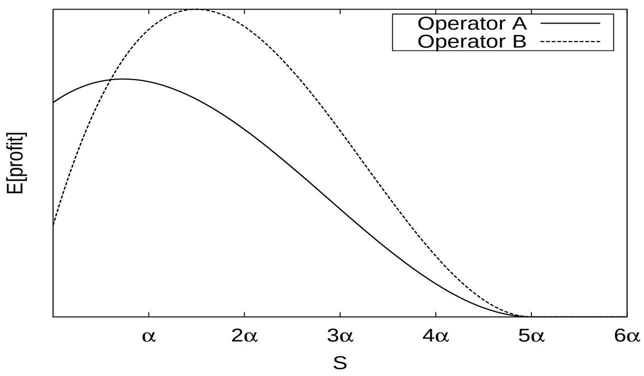

Fig. 3. Expected roaming profit of two operators vs. switching cost. Operator A is 20% of the time visited while operator B is visited 80% of the time.

If the "roaming agreement" has distinct values for the switching cost between operators then each operator would try to set its subscribers' switching cost to the optimal value of itself, as a home operator. At the same time it would try to reduce the switching cost of the other operator's subscribers to get higher revenue as a visited operator.

4 Conclusion and Future Work

In this paper we presented a model for the 802.11 roaming game and constructed the generalized utility functions of the agents involved in the game. The proposed model is rich enough to account for different network aspects of real-world Wi-Fi roaming situations.

To find the optimal pricing strategies of the operators regarding delay insensitive users, we studied the sub-game perfect equilibrium in a congestion-free network and found the optimal value of the switching cost for each of the operators. The results suggest that arbitrarily increasing the roaming charges is not the best strategy for either of the operators.

We believe that Wi-Fi network providers can use the proposed model along with specific field and user behavior information to find optimal pricing strategies. The impact of the relative size of the operators on roaming charges can be studied through service costs. The economic model of mobile virtual network operators (MVNO) [9] for Wi-Fi networks can be studied as a special case of a home operator in the proposed roaming game.

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