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An Economic Model of Subscriber Offloading Between Mobile Network Operators and WLAN Operators

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Abstract—**With increasing mobile data demand there is a push towards heterogeneous networks. Small-scale operators (SSOs) of WLANs are becoming more prevalent, while Mobile Network Operators (MNOs) seek an outlet for their customers' data usage. These conditions prompt the need for an effective relationship between the two parties for the purpose of offloading cellular data traffic to WLANs in a way that is economically beneficial to all involved. This paper presents a model of such a relationship, in which the SSO sets a strategic offloading price per subscriber and the MNO chooses how many subscribers it wants to offload in order to minimize its costs. The application of this model is simulated in a real-world WLAN deployment in Oulu, Finland. Our findings can be used by both MNOs and SSOs to make informed network deployment decisions, even before engaging in an offloading relationship.**

I. INTRODUCTION

The continued rapid growth of mobile broadband data traffic [1] places significant monetary burdens on a Mobile Network Operator (MNO). The MNO is driven to invest in additional infrastructure in order to increase its network capacity but it encounters two significant economic obstacles. The first obstacle is encountered when the MNO uses smaller cell sites to take advantage of frequency reuse, a common strategy in densely populated areas. Though the standalone cost of an individual Micro Base Station (BS) is lower than that of a Macro BS, the cost per unit area of coverage is greater if Micro BSs are used [2]. When attempting to increase spatial reuse, there is potentially increased cost per unit area of coverage.

The second and possibly more damaging economic obstacle to network upgrades is a decrease in the MNO's revenue per unit traffic. This effect is explored in [3], in which a Nordic MNO offers unlimited data plans and its average customer continues to consume more data at the same price. This narrower profit margin makes future network upgrades more difficult, thus causing a decline in the average quality of service experienced by customers.

In response to this difficulty, many MNOs (e.g. AT&T Wireless and Verizon Wireless in the United States) have removed their unlimited data plans in an effort to curb their customers' average data use. Another option, which is only beginning to be explored, is to make use of large-scale Wi-Fi deployment. The use of WLAN infrastructure offers significantly lower investment and operational costs than any type of cell site [3]. Widely-deployed WLANs in densely populated areas can decrease the burden on cellular networks while continuing to satisfy large data demands from mobile customers.

In coincidence with the changing mobile data landscape, there have recently been a number of advancements in WLAN connectivity and heterogeneous networks that can be considered part of the aforementioned effort to relieve load on 3G and 4G cellular networks. Offloading large amounts of traffic onto WLANs can boost overall capacity due to increased spatial reuse in WLANs and potential access to additional, underutilized spectrum (such as 802.11a in the 5 GHz ISM band). This endeavor has been the object of much research, with varying opinions as to its viability. The authors of [4] are skeptical of significant offloading benefits due to the practical issue of WLAN deployments being optimized for laptop Wi-Fi devices, rather than the more constrained devices found in mobile phones. Other research, however, presents convincing arguments to the contrary. A dense urban WLAN deployment is studied in [5], which concludes that such a deployment would likely decrease network outage time and increase average user throughput as compared to femtocell deployment or the sole use of macrocells. There is also interest in the more technical aspects, such as the circumstances under which Wi-Fi can be used as a trusted replacement for cellular deployments [6] and methods of targeting specific types of traffic for offloading (such as delay-tolerant traffic in [7] and [8]).

We expect that these continued research efforts, combined with industry advances, will facilitate conditions that allow for easy transitions between cellular and Wi-Fi access. This scenario could benefit from an economic analysis of WLAN offloading. MNOs and WLAN operators would be more likely to engage in economic relationships if they are presented with justified strategies that are effective at securing their interests. We refer to the WLAN operators discussed here as Small Scale Operators (SSOs) due to the relative size and coverage area

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of their networks in comparison to MNO networks. Examples of such SSOs include commercial providers of WLAN connectivity (e.g., Boingo) as well as university campuses and municipalities that have deployed extensive Wi-Fi coverage.

This paper models the relationship between an MNO and an SSO in the context of WLAN offloading, identifying the incentives for each party and determining the equilibrium behavior (including price charged and number of users offloaded). The SSO controls the offloading price in a way that ultimately determines how many users will be offloaded. In choosing a price, the SSO must weigh the revenue it will receive against the quality of service (QoS) strain that the additional users will place on its network.

The results of this paper provide insight into the nature of the relationship between the MNO and the SSO. Our model accounts for the effects of offloading on the QoS experienced by native SSO users, thereby inhibiting excessive offloading. As the revenue obtained by the SSO from subscribers offloaded to its network increases, the SSO is less concerned about the immediate reduction in QoS experienced by its users, as it considers the additional revenue a means to make network upgrades that will boost capacity and improve user experience in the long run. Additionally, when this model is applied to a real-world WLAN deployment we find that the equilibrium price allows a fraction p $(0 < p < 1)$ of the total "offloadable" MNO subscribers (those within range of the SSO's WLAN) to be offloaded. That is, our model does not require more WLAN resources than what is currently viable.

Our model can be used as a basis for network planning. Our results enable both MNOs and SSOs to make informed decisions regarding network deployment based on projected costs/benefits of engaging in an offloading relationship.

II. RELATED WORK

A. WLAN Offloading

The IEEE 802.11u amendment, titled "Interworking with External Networks," provides MAC layer specifications that facilitate seamless interworking, an enabler for large-scale WLAN offloading. Implementation of the new standard in most cases only requires a firmware upgrade, which avoids the infrastructure cost of purchasing new hardware for service providers who want to deploy these capabilities.

The key component of the 802.11u standard is the ability to conduct pre-association communication between an AP and a client device. The AP now includes information regarding interworking and roaming consortia in its beacon frame [9]. This way a mobile device can learn which WLANs support interworking and roaming agreements before association and can prioritize the order of networks with which it tries to authenticate. The subsequent association requests/responses can involve exchanging SIM information for the purpose of authentication with a cellular network.

The Wi-Fi Alliance (WFA), through a task group called Hotspot 2.0, has the objective to streamline the use of this new WLAN standard. Hotspot 2.0 specifications include prioritization of available WLANs based on the user's preferences, authentication of the mobile device to external cellular networks (different methodologies for GSM, CDMA, UMTS, etc.), and appropriate security protocols for relaying this information [10]. Large-scale deployment of these technologies can allow mobile devices to seamlessly transition from a cellular network to a secure Wi-Fi network with no input from the user. Roaming consortia between MNOs and SSOs can be established to deliver the best quality of service to the end user.

B. Economic Offloading Models

The idea of a network operator boosting its own subscribers' performance by leveraging a separate network's resources has been explored in other offloading models. The authors of [11] present a model of femtocell offloading with the same idea of the roles of large-scale and small-scale operators. This work considers the relationship between the price charged for accepting a foreign user and the resources set aside for accepting foreign users. Similarly, [12] explores the challenges of overlapping WiMAX and Wi-Fi coverage, where the two radio access technologies are part of separate networks run by separate operators. The author used a genetic algorithm for the two operators to determine each other's bandwidth demand in order to set a price. Both of these models are related to the one presented in this paper, in which one operator considers the user demand and cost structure of the other operator's network in order to set an offloading price that will maximize the utility of both parties.

The key difference between these models and the one presented here is the party making the decision. In the model presented in this paper, the MNO decides for itself how many of its subscribers it wants to offload rather than allowing its subscribers to choose for themselves. In the traditional case of free access to a Wi-Fi network, a user naturally has the ability to choose which medium they want to use. However, in an effort to motivate a new cooperation model, we examine the case in which a user does not have free access to existing Wi-Fi networks and must instead rely on their MNO to form roaming agreements with these private SSOs. When confronted with a per-user price for offloading (as the model presented in this paper entails), the MNO has a vested interest in controlling the number of subscribers it allows to be offloaded.

The authors of [13] present a model much more similar to ours in that the MNO makes its own offloading decisions, though the transaction process differs as it calls for a third party "broker" to relay a ceiling price offered by the MNO to the APs of several owners which may not be aggregated into a single network. Another model in which the offloading decision is transparent to the mobile subscriber is presented in [14]. This model shares with ours the concept of MNOs engaging in incentive-based relationships directly with Wi-Fi AP operators, but once again differs in that the MNOs are the parties initiating the price.

III. MODEL

In this paper we identify the incentives for both MNOs and SSOs when they establish a partnership. Operators of both types of networks need to take into account their immediate monetary incentives as well as the responsibility they hold to their paying customers to provide an acceptable quality of service.

Let n_{mno} be the total number of customers that an MNO has to service at a given time and W be the number of offloadable MNO users. We assume that each user requires the same average bandwidth. Our model analyzes a single snapshot in time to determine the equilibrium price to be charged by the SSO and the resulting number of MNO subscribers that get offloaded onto the SSO's network.

We first discuss the MNO's cost function $\psi(n)$, the total cost to operate its network. This is a function of the number of users n currently being serviced by the MNO's native network, and we want it to account for the monetary cost of building and operating the network as well as the less tangible cost of dissatisfied customers when the network is congested. Due to fixed infrastructure costs, the MNO can service up to a threshold n_T users at a constant cost of ψ_0. Upon surpassing this threshold, however, the cost increases for a variety of reasons. In addition to higher operating expenses to service more traffic, the cost function is indicative of the need for network upgrades and the "penalty" for the increased risk of losing customers. Acquiring new customers represents a large cost for MNOs, so it is expensive to lose a customer. For ease of analysis, we use a continuous function for ψ and a continuous domain n, despite the fact that in a real-world scenario we would only observe discrete values of n. We examine two separate types of cost functions in this paper: The first type (seen in Figure 1) has a linear cost increase after the threshold number of users n_T, while the second (seen in Figure 2) has a strictly convex increase after the threshold.

Given these considerations, we have defined the MNO's utility function as the negative of the total cost incurred to service its n_{mno} users. The first term in the utility function is the cost incurred solely as a result of servicing users on its native network, while the second term is the price paid to an SSO for offloaded users:

$$U_{mno} = -\left[\psi(n_{mno} - n_{off}) + n_{off}\chi\right], \tag{1}$$

where:

- χ is the price set by the SSO to offload a single user, and
- n_{off} is the number of users offloaded, and therefore currently being serviced by the SSO's network.

The SSO's utility function considers the revenue it receives as a result of servicing offloaded users and the additional strain that these new users place on its network:

$$U_{sso} = n_{off}\chi + d_1 n_{sso} \log\left(\frac{B}{n_{sso} + n_{off}}\right), \tag{2}$$

where:

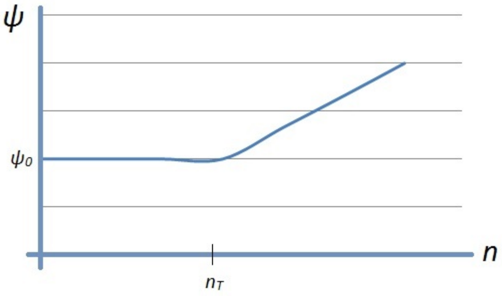

Fig. 1. MNO cost function with a linear increase after surpassing a threshold number of users.

- n_{sso} is the number of native (non-offloaded) users on the SSO's network,
- B is the SSO's total bandwidth, and
- d_1 is a scaling factor to establish an appropriate relationship that defines the tradeoff between the revenue due to the offloaded users and the strain that those users place on the SSO's network.

Though it is difficult to obtain real-world information on the utility structure of any telecom operator, we consider that the log term captures a property that we know to be important: Diminishing marginal utility with an increase of users. As the SSO continues to accept more offloaded users onto its network it incurs the cost of dissatisfaction among its customers. The expression $\frac{B}{n_{sso}+n_{off}}$ represents the bandwidth per user on the SSO's network.

A key parameter of both of these utility functions is the price χ that the SSO sets to offload a user. This price will determine the number of users offloaded, as the MNO will only offload a subscriber if the cost to do so is less than or equal to the cost of servicing that user on its native network. In the "indifferent" case in which the two costs are the same we assume that the MNO will choose to offload. We set out to find the equilibrium offloading price that the SSO will charge.

IV. LINEAR COST FUNCTION

The MNO's piecewise linear cost function is depicted in Figure 1. In this case, we denote by c_{mno} the slope of the cost function for $n > n_T$, corresponding to the MNO's marginal cost of servicing one additional customer. Formally:

$$\psi(n) = \begin{cases} \psi_0 & n \leq n_T \\ c_{mno}(n - n_T) + \psi_0 & n > n_T \end{cases}. \tag{3}$$

Once the SSO sets an offloading price, the MNO chooses whether or not to offload users based on the value of χ. In the context of a linear increase of ψ, the MNO's cost to service each additional subscriber (past n_T) on its native network is fixed at c_{mno}. If the SSO sets $\chi > c_{mno}$, the MNO will choose to retain all of its subscribers on its native network. However, if the SSO instead sets $\chi \leq c_{mno}$, the MNO will choose to offload exactly the number of users $(n_{mno} - n_T)$ by which it is exceeding its threshold n_T (unless they are constrained by W, the total number of offloadable users).

In anticipation of the MNO's strategy, the SSO will maximize its utility by setting $\chi = c_{mno}$, on the condition that its utility would be lower for having zero offloaded users than it would be for having $n_{mno}-n_T$ offloaded users. This condition can be expressed mathematically:

$$\chi(n_{mno}-n_T) \geq d_1 n_{sso} \log\left(\frac{n_{sso}+n_{mno}-n_T}{n_{sso}}\right).$$

When the above inequality holds, at equilibrium we find:

$$\chi^* = c_{mno}.$$

The MNO then makes the decision to offload as many users past the threshold n_T as it can:

$$n^*_{off} = \min\left[(n_{mno}-n_T), W\right].$$

This mathematical analysis implicitly assumes that the SSO has complete information, including access to the total number of active MNO customers, n_{mno}, as well as to the MNO's cost function. Given that ours is a snapshot model, there can be no iterative learning process by either party. In our future work, we will investigate time-varying pricing by the SSO based on the variations in demand that both operators are expected to encounter.

V. CONVEX COST FUNCTION

A. *Simplified SSO Utility*

A less trivial scenario would be if the MNO's cost function ψ, upon surpassing n_T users, is strictly convex. This implies that the *rate* of the cost increase is also increasing, as seen in Figure 2. The justification for this is that getting slightly better overall network performance is generally very costly for an MNO when infrastructure is currently in place. When the MNO is over capacity, their cost function should represent the need to acquire more spectrum or perhaps redeploy cell sites in a denser arrangement. Furthermore, a customer's satisfaction and trust of an MNO's performance are the primary reasons for loyalty to that MNO [15] [16]. Given this information, the MNO's burden of servicing a new user should be an *increasing* cost corresponding to an increasing need for network upgrades and a greater risk of causing customer dissatisfaction.

We will begin this analysis with a simplified version of the SSO's utility function that only includes the term that accounts for revenue as a result of accepting offloaded users. We call this simplified utility function G:

$$G = n_{off}\chi. \tag{4}$$

Given that the MNO's cost function is slowly increasing (only slightly convex), we consider the marginal cost to the MNO of servicing the i^{th} additional user (for $i > n_T$) on its own network to be approximately $\psi'(i)$. As before, we denote the number of users that the MNO chooses to offload as n_{off}. Let:

$$n_{mno} - n_{off} = n_b \geq n_T.$$

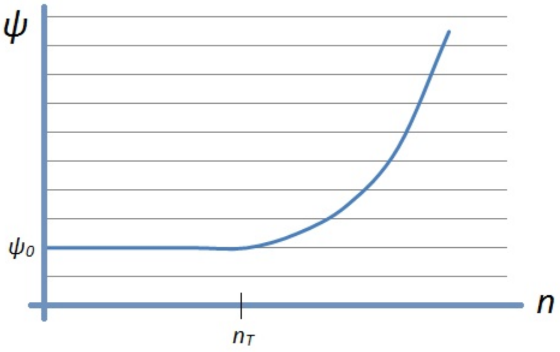

Fig. 2. MNO cost function with a strictly convex increase after surpassing a threshold number of users.

In this equation n_b is the number of users that the MNO will service on its native network. This number is dependent on the price χ, and it will be equal to the lowest value of n for which $\chi \leq \psi'(n)$. That is, the MNO will offload a customer only if the cost to do so is not more than the cost to service the customer on the cellular network. Therefore, once the SSO has set its price and the MNO has chosen the number of users it wants to offload, we will find, as a close approximation, that the equilibrium price $\chi^*_G = \psi'(n_b)$. After we explicitly define $G(\chi)$ we can obtain a closed-form expression for the value of n_b (and therefore also for n_{off}) that maximizes the MNO's utility. We simply need to optimize G with respect to χ in order to determine the equilibrium price that the SSO will charge to maximize its utility in anticipation of the MNO's decision.

The example we chose to explore in this paper for the MNO's cost function involves a quadratic increase after the threshold n_T:

$$\psi(n) = \begin{cases} \psi_0 & n \leq n_T \\ \alpha(n-n_T)^2 + \psi_0 & n > n_T \end{cases}. \tag{5}$$

Since the MNO will only offload a user when its total n_{mno} is in excess of n_T, we need only consider the quadratic portion of its cost function:

$$\begin{aligned} \chi^*_G &= \psi'(n_b) \\ &= 2\alpha(n_b - n_T). \end{aligned}$$

$$n_b = \frac{\chi^*_G}{2\alpha} + n_T.$$

We know that $n_{off} = n_{mno} - n_b$. Consequently we derive the number of users that the MNO will choose to offload as a function of the offloading price set by the SSO:

$$n_{off}(\chi^*_G) = n_{mno} - \left(\frac{\chi^*_G}{2\alpha} + n_T\right). \tag{6}$$

Now we can express the SSO's revenue function explicitly and then optimize it by setting its derivative equal to zero:

$$\begin{aligned} G(\chi_G^*) &= n_{off}(\chi_G^*) \cdot \chi_G^* \\ G(\chi_G^*) &= (\chi_G^*)^2 \left(\frac{-1}{2\alpha}\right) + \chi_G^*(n_{mno} - n_T) \\ G'(\chi_G^*) &= -\frac{1}{\alpha}\chi_G^* + n_{mno} - n_T = 0 \end{aligned}$$

Solving for this value of χ_G^* will give us the equilibrium price. Naturally, to formally express this solution, we must also consider the case in which the SSO knows in advance that the MNO will be limited by the number of offloadable users. In this case the SSO wants to set its price high enough that the MNO finds it economically beneficial to offload exactly W users. Formally:

$$\chi_G^* = \min\{\alpha(n_{mno} - n_T), 2\alpha(n_{mno} - W - n_T)\}$$

Given the relationship in equation (6), we can also find the equilibrium number n_G^* of users offloaded at the equilibrium price χ_G^*. Once again, we consider the case where the number of offloadable MNO subscribers, W, limits the result:

$$n_G^* = \begin{cases} \min\left\{\frac{1}{2}(n_{mno} - n_T), W\right\} & n_{mno} > n_T \\ 0 & n_{mno} \leq n_T \end{cases}.$$

The piecewise-quadratic MNO cost function defined in this section provides intuitive results for our model, and the same analysis can be performed for different convex cost functions.

B. Full Utility Analysis

While the case of revenue-based utility for the SSO is helpful in providing intuitive results for the basic relationship between MNO and SSO, it does not in fact address the complete scenario in which the SSO has a vested interest in maintaining good quality of service (QoS) for its customers. This consideration is part of the motivation for the log term in the SSO's utility function, which in fact diminishes marginal utility.

Recall our previous result in equation (6):

$$n_{off} = A - \frac{\chi^*}{2\alpha},$$

where $A = n_{mno} - n_T$.

Similar to the case with the revenue function G, the most important factor in our analysis is the price that the SSO charges the MNO to accept an offloaded user, as this affects the MNO's offloading decision. In order to find the equilibrium price χ_U^* and corresponding number of offloaded users n_U^* (when the SSO is attempting to maximize its full utility function), we follow the same method as our revenue analysis. The first step is to express U_{sso} as a function of χ:

$$\begin{aligned} U_{sso}(\chi) &= \left(A - \frac{\chi}{2\alpha}\right)\chi + d_1 n_{sso} \log\left(\frac{B}{n_{sso} + A - \frac{\chi}{2\alpha}}\right) \\ &= -\frac{\chi^2}{2\alpha} + A\chi + d_1 n_{sso} \log\left(\frac{B}{n_{sso} + A - \frac{\chi}{2\alpha}}\right). \end{aligned}$$

From here the problem of finding the equilibrium price when the SSO is maximizing its own utility becomes a simple non-linear optimization problem with respect to χ:

$$U'_{sso}(\chi) = A - \frac{\chi}{\alpha} + \left(\frac{d_1 n_{sso}}{2\alpha(n_{sso} + A) - \chi}\right) = 0$$

$$\chi^2\left(\frac{1}{\alpha}\right) + \chi(-A - 2(n_{sso} + A)) + (2\alpha A(n_{sso} + A) + d_1 n_{sso}) = 0.$$

This is a familiar quadratic form for which we can derive the optimizing solution, χ_U^*:

$$\chi_U^* = \frac{\alpha}{2}\left[(3A + 2n_{sso}) - \sqrt{(3A + 2n_{sso})^2 - \frac{4}{\alpha}(2\alpha A(n_{sso} + A) + d_1 n_{sso})}\right]. \tag{7}$$

To find the equilibrium number of offloaded users, we once again use the relationship in equation (6):

$$n_U^* = A - \frac{\chi_U^*}{2\alpha}, \tag{8}$$

Naturally these results are not mathematically applicable for all values of the constituent parameters. The parameters that cause expression (7) to produce a complex number indicate situations where the SSO would maximize its utility by setting the offloading price high enough that no users are offloaded. This can be observed by calculating the SSO's utility for many values of χ through an exhaustive search method, which can also be used to verify the accuracy of expressions (7) and (8) under conditions that do not produce a complex number solution.

VI. CASE STUDY - OULU, FINLAND

A. Methodology

We apply our model in a simulation using information from a real municipal WLAN environment. The city of Oulu, Finland operates a widely-deployed WLAN (called "panoulu") in select areas throughout the city. We examined an area in downtown Oulu that is the busiest commercial area of the city (Figure 3). It is this type of region that is most likely to benefit from an offloading relationship like the one we are describing.

We have access to information on access point placement in the panoulu network throughout the city of Oulu.[1] We use this information that we collected while varying certain MNO network parameters (including cost function parameters and average number of active subscribers) within a range that encompasses reasonable real-world conditions. This allows us to assess the performance of a functioning WLAN deployment in conjunction with realistic MNO conditions in order to determine the applicability of our model.

[1] Panoulu AP location information accessible online at http://www.panoulu.net/panoulu-wlan

Fig. 3. Area in downtown Oulu, Finland observed in this case study. We assessed the WLAN coverage within this area and determined the achievable offloading benefit when our model is applied.

The panoulu APs target certain indoor *and* outdoor areas (The panoulu web site indicates that certain APs are designated for outdoor coverage.). We used this information as a basis for determining the total proportion of outdoor area covered within the observed zone, assuming a 50m outdoor propagation radius. The other APs listed were assumed to mostly cover indoor areas. If a sole AP was listed at a location we considered it to cover a circular indoor area with radius 20m. On the other hand, locations that listed multiple APs were considered to cover a certain fraction of the 100m by 100m square block area according to a rule that 12 APs would cover the full square block. Using these criteria we were able to determine the overall proportion of indoor area covered (ρ_{in}) as well as the proportion of outdoor area covered (ρ_{out}) within the section of the city observed for this study.

We classify a certain fraction c of the n_{mno} subscribers as indoor users and the rest as outdoor users. The total number of MNO subscribers within range of WLAN coverage can then be expressed by the following linear function of c:

$$W = c\rho_{in}n_{mno} + (1-c)\rho_{out}n_{mno}. \tag{9}$$

The rest of the simulation parameters are outlined in Table I. Using these conditions, we independently performed two experiments, each varying a different parameter. First, we assumed a constant $n_{sso} = 30$ and varied n_{mno} between 200 and 300 to observe how this affected the equilibrium number of users offloaded, both for the simplified SSO utility G and the full utility U_{sso}. We observed the effect that the number of offloadable users had on the SSO's and MNO's decisions. Cisco reports that nearly 80 percent of mobile data users are "either indoor or nomadic, rather than truly mobile" [17]. In light of this, we considered c to range from 0.5 to 0.9. For "worst case scenario" comparison purposes, we chose to compute the *minimum* number of offloadable users for each value of n_{mno} between 200 and 300. Since $\rho_{in} < \rho_{out}$ (as seen in Table I), equation (9) is a decreasing function of c. Therefore the minimum value of W for any n_{mno} corresponds to the maximum value of c. For this reason we set $c = 0.9$, the highest value of our acceptable range.

n_T	α	ψ_0	d_1	B	ρ_{in}	ρ_{out}
200	0.001	100	0.08	1000	0.19	0.36

TABLE I
SIMULATION PARAMETERS

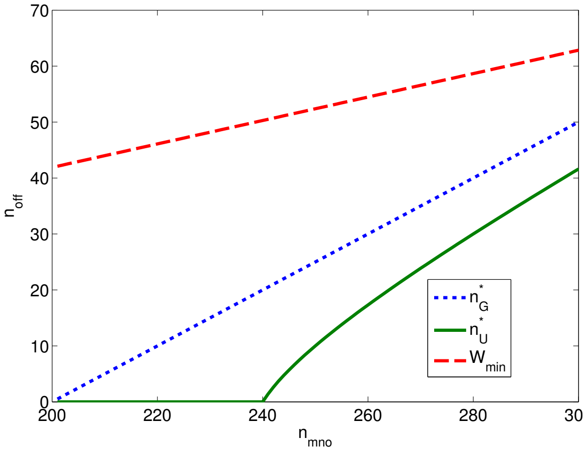

Fig. 4. Equilibrium number of MNO users offloaded from the cellular network to the SSO's WLAN, as the total number of active MNO users (n_{mno}) varies. n_G^* is the number of offloaded users when the SSO is acting on its revenue function alone, and n_U^* is the number when the SSO acts on its full utility function. W_{min} is the minimum number of offloadable users.

The second experiment assumed a constant $n_{mno} = 300$ and instead varied n_{sso} with the intent of observing its relationship to n_U^*.

B. Results

This simulation offers insight into the applicability of our model. First of all, Figure 4 shows that the minimum number of offloadable MNO subscribers is never lower than the number of users that the SSO would accept for offloading. This means that, for the WLAN deployment currently in place in Oulu and with our simulated MNO network conditions, neither the MNO nor the SSO will find that their actions are limited by the number of users that are within range of the WLAN. We believe that this supports the applicability of our model in scenarios outside of Oulu as well.

Figure 4 also shows us that n_U^* is consistently lower than n_G^*, which is a direct result of χ_U^* being consistently higher than χ_G^*, as seen in Figure 5 (χ_U^* is arbitrarily high initially, just to ensure that the MNO does not offload any users for the given network conditions). Similarly, we find that as the number of native users n_{sso} on the SSO's network increases, n_U^* decreases (seen in Figure 6). When n_{sso} is large, the log term in the utility forces the SSO to raise its offloading price and accept fewer additional users onto its network than

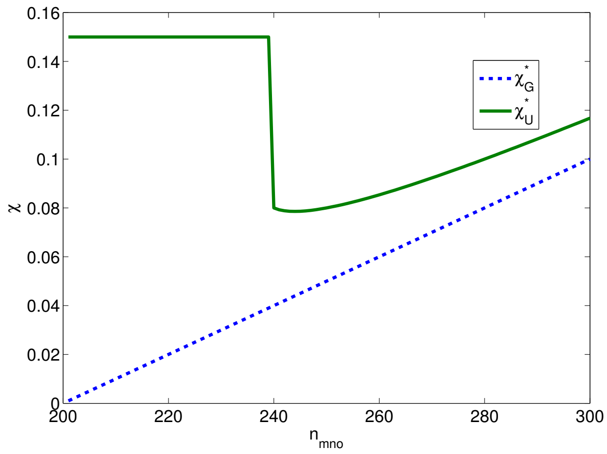

Fig. 5. Equilibrium offloading price per user, set by the SSO, as the total number of active MNO users (n_{mno}) varies. χ_G^* is the price when the SSO is acting on its revenue alone, and χ_U^* is the price when the SSO acts on its full utility function.

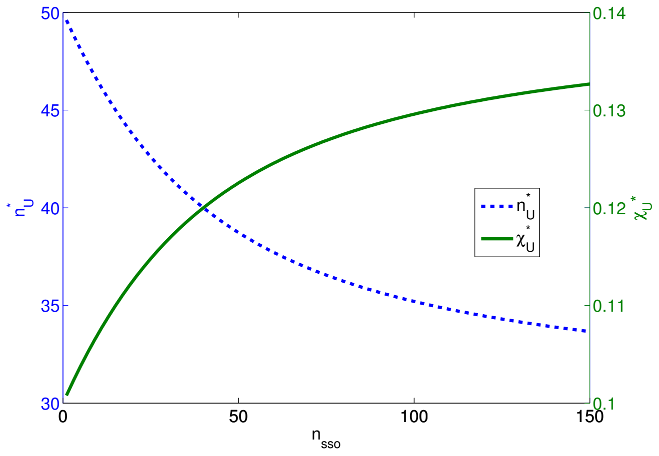

Fig. 6. Equilibrium number of MNO users offloaded n_U^* and price χ_U^* per offloaded user, as the number of native SSO customers (n_{sso}) varies.

it otherwise would. This is in keeping with the idea that preserving quality of service (by limiting the number of users) is an important incentive.

An interesting effect visible in Figure 4 that is not immediately intuitive is that the gap between n_G^* and n_U^* diminishes as n_{mno} increases. This can be explained by considering revenue and QoS as a direct tradeoff. As n_{mno} grows, the MNO is willing to pay enough money to offload customers that the SSO feels it is adequately compensated for the QoS strain that it places on its network. In the snapshot that we observe this appears to be detrimental to the user experience of the SSO's prior users. However, the SSO's decision to sacrifice immediate QoS could be justified by its ability to upgrade its network with the additional revenue earned from the MNO. In the long term, the SSO could re-invest its earnings to appease its native customers.

Alternatively, our results allow an SSO to make network deployment decisions based on projected demand, even before engaging in an offloading relationship. If the SSO's network is in an area with heavy cellular usage, it may decide to increase its AP density to provide more users with better connectivity, or perhaps it would install fewer mesh nodes to prevent routing bottlenecks. The MNO has an even larger decision space, as it can weigh the long-term cost of offloading users to the SSO's network against the immediate cost of deploying its own WLAN infrastructure or even additional cell sites. If the MNO has limited capital that would prevent significant infrastructure investments, it could easily decide that utilizing existing WLAN deployments owned by other operators is more economically beneficial.

VII. CONCLUSIONS

In this paper we have presented a model for the economic relationship between an MNO and an SSO in which the MNO offloads its customers' traffic onto the SSO's WLAN in order to alleviate its own network's congestion. We define incentives for both parties and derive appropriate utility functions which model the entities' preferences. We believe that our model can be applied in many scenarios where there is a high population density and a robust WLAN deployment. Additionally, our results enable both MNOs and SSOs to make informed network deployment decisions. Even so, we acknowledge areas in which the model can be enhanced. Using the same basic principles of an MNO cost function and utility functions for both parties, our continued work will aim to incorporate AP-specific pricing based on user demand. Furthermore, we wish to develop a time-evolving model of this same relationship in which neither party has complete information of the other.

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