Technology Choices and Pricing Policies in Wireless Networks

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***Abstract*—This paper studies the provision of a wireless network by a monopolistic service provider who may be either benevolent (seeking to maximize social welfare) or selfish (seeking to maximize provider profit). The paper addresses questions that do not seem to have been studied in the engineering literature on wireless networks: Under what circumstances is it feasible for a provider, either benevolent or selfish, to operate a network in such a way as to cover costs? How is the optimal behavior of a benevolent provider different from the optimal behavior of a selfish provider, and how does this difference affect social welfare? And, most importantly, how does the medium access control (MAC) technology influence the answers to these questions? To address these questions, we build a general model, and provide analysis and simulations for simplified but typical scenarios; the focus in these scenarios is on the contrast between the outcomes obtained under carrier-sensing multiple access (CSMA) and outcomes obtained under time-division multiple access (TDMA). Simulation results demonstrate that differences in MAC technology can have a significant effect on social welfare, on provider profit, and even on the (financial) feasibility of a wireless network.**

I. Introduction

There has been much recent debate about the deployment of wireless networks that would allow Internet access in public areas. Central to this debate is the tradeoff between costs and benefits. Surprisingly, this debate seems to have ignored that the costs and benefits of such wireless networks depend crucially on the technology that is or could be employed. The purpose of this paper is to provide a framework for exploring the influence of technology on the costs and benefits of wireless networks and to demonstrate in a simple scenario that the feasibility and desirability of such a network may depend on the technology chosen. We show that the analysis depends crucially on the technology layer, the application layer, and the economic layer, and most crucially of all, on the interactions between these layers.

To see why the analysis depends crucially on the interactions between the three layers, consider a simple scenario that seems typical. There are two classes of (potential) users: *data users*, who are sensitive to throughput but relatively insensitive to delay, and *video users*, who are sensitive to both throughput and delay. In managing the network, the service provider can offer a pricing policy, but the service provider's range of choices depends on the technology – in particular, on the medium access control (MAC) protocol – employed. If time-division multiple access (TDMA) is employed, the service provider will be able to guarantee quality of service (QoS) and monitor the usage of each user in order to charge per bit. Hence, the service provider can use a tiered pricing policy to screen the users into a number of types and offer performance guarantees to those users willing to pay for such guarantees. If carrier-sensing multiple access (CSMA) is employed, the service provider will be unable to guarantee QoS, even if it may employ such technology as enhanced distributed channel access (EDCA). Absent such performance guarantees, users who require higher throughput or less delay may be unwilling to pay more than users who will accept lower throughput and more delay. As we will show, there are large regions within the range of plausible parameters in which employing TDMA rather than CSMA makes possible large improvements in social welfare. Indeed, there are regions in which employing TDMA would be consistent with operating a self-financing public network while employing CSMA would not be.

A. Related Work

Two substantial bodies of work in the engineering literature ask about optimal behavior of the provider of a wireless network. The first considers a benevolent provider whose objective is to maximize social welfare [1]- [5]; the second considers a selfish provider whose objective is to maximize profit [6]- [7]. What we do here is to ask different (although related) questions that do not seem to have been studied at all in this literature: Under what circumstances is it possible for a provider to operate a network in such a way as to cover costs? How is optimal behavior of a benevolent provider different from optimal behavior of a selfish provider and how does the difference affect social welfare? And, perhaps most importantly, how does the MAC protocol influence the answers to these questions?

Among the papers that focus on optimal pricing in networks, Palomar and Chiang [1] and Kelly *et al.* [2] consider a network with one service provider serving multiple users and propose charging in proportion to the flow rates of the users in order to maximize social utility. For cellular networks, Mandayam *et al.* [3] and Alpcan *et al.* [4] propose pricing for power control to reduce interference. Johari and Tsitsiklis

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[5] focus on the efficiency loss under this pricing scheme and its variant with price differentiation. Under the same scenario as in [2], Basar *et al.* [6] propose nonlinear differentiated pricing schemes to control the network usage and maximize the provider's revenue. It should be noted, however, that the prices in the above papers are not actually paid by the users; rather, they are signals used for the purpose of controlling the network congestion or multi-user interference. In Paschalidis and Tsitsiklis [7], which studies a dynamic network with users arriving and leaving the network and derive the optimal pricing strategy and its static approximation, prices are actually paid by users, but – as in [2]- [6] – the technology layer is highly abstracted (as a constraint on the resource allocation). Other papers use different models and have a different focus. Friedman and Parkes [8] study the existence of implementable mechanisms for the users to truthfully announce their arrivals in WiFi networks. Musacchio and Walrand [9] model WiFi pricing as a dynamic game involving one access point and one user, and study the Nash equilibrium (NE) of this game. van der Schaar [10] and Sarkar [11] focus on competition among multiple service providers with simplified user subscription models.

Our work differs from this literature in that we model prices as actually paid by users and collected by the service providers, and we provide a much more detailed description of technology. We make use of both of these differences to study the interaction between technology and pricing and their impacts on performance.[1] In particular, we consider various technologies and pricing policies (closely modeled as those used in the real world by wireless carriers) to study the interactions between technology and pricing.

The remainder of this paper is organized as follows. In Section II we introduce the system model. In Section III we formulate the design problem for the benevolent and selfish providers and the decision process of the users as a two-stage game (with the provider acting in the first stage and the users acting in the second stage). In Section IV, we focus our analysis on a typical scenario to gain insights into this problem, and provide simulation results in this typical scenario. Finally, in Section V we conclude the paper.

II. System Model

We consider a wireless network, created by a service provider to enable Internet connections to potential users in public areas such as parks, libraries, and cafes. We focus on a network with a single access point (AP). We do not consider the scenario with multiple access points, but our future work will consider the possibility for a user to connect to multiple AP's. This is not common nowadays due to the sparsity of the public access points [9]. Keeping in mind that a single access point will typically serve a relatively small number of potential users who may come and go at any moment in time, we build a dynamic continuous-time framework in which a finite number of potential users arrive and depart randomly.

In our framework, the system consists of three layers, namely the *technology layer*, the *application layer*, and the *economic layer*. The technology layer is characterized by the MAC protocol chosen by the service provider; the application layer includes the users' utility functions, arrival rates, and service times; and the economic layer includes the pricing policy offered by the service provider. The usual way to describe a system model is to describe separately and in turn each of the layers. However, in our settings, it is not possible to describe these layers separately because they are interconnected. Instead, we describe the system by the specifications for the service provider and users. In this way, we can better illustrate the interactions among the components in the system and the behaviors of the service provider and users.

Before we begin with the description of the service provider, we first introduce the basic concept of the user type. The *users* are categorized into K types according to their utility functions and arrival and departure processes. There are N_k identical users of type k in total.

A. The Service Provider

The service provider must choose a MAC protocol and a pricing policy. However, before describing these two design parameters, we must note an important *caveat*. A MAC protocol describes which packets of current users will have access to which resources in which way. It would seem that a MAC protocol should allocate resources to packets of current users (or type of users), as a function of the current number of the users of each type in the system. However, the service provider can only use policies that depend on observable characteristics and actions of the users and *the type of a user cannot be observed by the service provider*.[2] In our framework, the relevant observable actions of the users are their choices of pricing plans, so the policies of the service provider should be specified as functions of the choices of pricing plans.

1) The Medium Access Control Protocol: The MAC protocol chosen determines the ways in which users may share the channel resources. In principle, the service provider might be able to choose among many MAC protocols. CSMA and TDMA are the canonical MAC protocols. CSMA is representative of the protocols without a central controller, where the packets contend to get access to the medium. The widely-used IEEE 802.11 standards use CSMA as the basic MAC protocol [13]. TDMA is representative of the protocols with a central controller, where the packets access the medium in non-overlapping periods of time. The IEEE 802.11e standard enables contention-free access control in the Hybrid Control Function (HCF), which can be considered as a generalized TDMA protocol [14]. The key difference between CSMA and TDMA is the capability of QoS guarantee, which potentially

[1] The interplay of technology and pricing policy is discussed by Lehr *et al.* [12], but their paper provides no quantitative analysis. To our best knowledge, no previous work has ever mathematically modeled and explicitly studied this problem.

[2] Leaving aside the point that users might lie about their types in order to obtain more favorable treatment, it might simply be the case that there are more types of users than there are pricing plans, so that different types of users necessarily choose the same pricing plan.

results in different selections of pricing policies. The provider using CSMA may not charge by bit due to the lack of QoS guarantee. We write Θ for the set of possible MAC protocols and $\theta \in \Theta$ for a typical protocol.

2) Pricing Plans and Pricing Policies: A *pricing plan* is a schedule of charges to (potential) users. For simplicity, we assume that charges consist only of a subscription fee (paid once per billing period) p_s and a per-bit surcharge q for usage in excess of some specified threshold number of bits β.[3] Of course, the subscription fee or the surcharge or the threshold might be 0. Thus a pricing plan is a triple

$$\mathbf{p} = (p_s, q, \beta).$$

As noted above, particular MAC protocols may not allow the service provider to observe some of the variables necessary to implement some of these pricing plans; for instance, CSMA does not allow the provider to observe actual data usage. We take account of this by distinguishing the set $\mathcal{P}_\theta$ of pricing plans that can be employed given the MAC protocol θ.

To allow for the possibility that some users choose not to belong to the network at all, let $\phi = (0, 0, 0)$ be the dummy plan that imposes no costs.

A *pricing policy* is a vector of pricing plans; for simplicity, we assume here that each pricing policy is a vector of exactly $L + 1$ pricing plans: $\mathbf{P}_\theta = (\mathbf{p}^0, \mathbf{p}^1, \ldots, \mathbf{p}^L)$; by convention we assume that $\mathbf{p}^0 = \phi$. Write

$$\mathcal{P}_\theta^{L+1} = \{\phi\} \times \underbrace{\mathcal{P}_\theta \times \ldots \times \mathcal{P}_\theta}_{L \text{ times}}$$

for the set of all possible pricing policies given the MAC control protocol θ.

B. Users

As mentioned above, the users are characterized by their utility functions, arrival processes, and service times. Given user characteristics and the technology and the pricing policy adopted by the service provider, each user determines a probability distribution over pricing plans that maximizes its expected utility (which will also depend on the choices of all the other users). At the beginning of time, each user chooses a pricing plan randomly according to the prescribed probability distribution, and reports the chosen plan to the service provider.

1) Choices of Pricing Plans: Users choose pricing plans to maximize their (expected) utility, given the menu of pricing plans, the MAC protocol of the provider and the choices of other users. We allow for the possibility that users *randomize*, so users of type k choose a probability distribution over pricing plans. We write $\pi_{k,\ell}$ for the probability that a user of type k chooses plan ℓ; in particular, $\pi_{k,0}$ is the probability of choosing the dummy plan 0. For each k, the probability of choosing *some* plan is 1:

$$\sum_{\ell=0}^{L} \pi_{k,\ell} = 1.$$

Allowing for randomization guarantees that equilibrium exists. We may interpret randomization literally: users who are indifferent over various plans break their indifference in a random way. Alternatively, we may interpret randomization as simply uncertainty in the minds of the provider and other users.

The randomization is realized at the beginning of time. Upon arrival, each user tells the service provider the pricing plan it chooses, and the provider uses this information for scheduling. Write $\pi_k = (\pi_{k,0}, \ldots, \pi_{k,L})$ for the (random) action of users of type k, $\pi = (\pi_1, \ldots, \pi_K)$ for the vector of actions of all users, and π_{-k} for the actions of users of types other than k.

Represent the result of the randomization by a set of vectors

$$\mathbf{n} = (\mathbf{n}_1, \ldots, \mathbf{n}_K) = ([n_{1,0}, \ldots, n_{1,L}], \ldots, [n_{K,0}, \ldots, n_{K,L}])$$

with $n_{k,\ell}$ being the number of type-k users choosing plan ℓ.

2) System State: The *system state*, or the *true state*, is defined as the number of users of each type choosing each pricing plan. Specifically, the system state X is a $K \times (L+1)$ matrix, with $x_{k,\ell}$ as the element at the kth row and $(\ell + 1)$th column, representing the number of type-k users who choose plan ℓ.

We write $\mathbf{X}(t)$ for the system state at time t; this state depends on arrivals and departures of users and on the admission control policy of the service provider, and thus is random. We assume that the type of a user is a private characteristic, known to the user but generally unobservable by other users and the service provider. As a result, the system state cannot be observed by anyone in the system.

3) Arrival Process and Service Time: For simplicity, we assume the arrival process and service time are exogenously given but not choice variables.[4] We use a continuous-time model (reflecting the fact that users might arrive/depart at any moment); as in [15], we assume that the arrival process of type-k users choosing plan ℓ is Poisson with arrival rate

$$\lambda_{k,\ell}(t) = \lambda_k \cdot (n_{k,\ell} - x_{k,\ell}(t)),$$

where λ_k is the individual arrival rate of a type-k user. We also assume that the service time of one type-k user is exponentially distributed with mean $1/\mu_k$.

4) Billing Period: We fix a *billing period* of length ΔT, which is typically one month. Subscription fees are charged at the beginning of each billing period; other fees are charged at the end of each billing period. This is consistent with the usual billing methods: people pay a subscription fee prospectively and other charges retrospectively. For convenience, we assume that neither the provider nor the users discount payments over the billing period.

[3] There would be no difficulty in allowing connection fees, fees that depend on minutes of usage, fees that depend on time of day, etc. We focus here on a simpler model to make our essential points.

[4] Here, the arrival process characterizes the arrival of users, but not the packets of each user. Similarly, the service time is the duration of users in the system.

5) Expected Utility: The service provider and the users evaluate the social welfare and their satisfaction, respectively, by the *expected utility*, defined as the expectation of the total utility over a billing period when the stochastic process of the system state $\mathbf{X}(t)$ reaches the steady state. Each user's total utility consists of two components: utility of use and disutility of cost. To keep the model simple, we assume that total utility is simply the sum of utility of use and disutility of cost and is linear in cost with marginal utility of cost equal to 1: [16]

$$\text{total utility} \;=\; \text{utility of use} \;-\; \text{cost} \,. \tag{1}$$

First, we denote the expected utility of use of a type-k user by $U_k(\theta, \pi)$, if the MAC protocol is θ and the probability distribution of the choices of all users is π. We can calculate the expected utility of use $U_k(\theta, \pi)$ as follows

$$U_k(\theta, \pi) = \sum_{\ell=1}^{L} \pi_{k,\ell} \cdot \sum_{\mathbf{n}: n_{k,\ell} \geq 1} \Pr(\mathbf{n}) \cdot V_k^{\ell}(\theta, \mathbf{n}), \tag{2}$$

where $\Pr(\mathbf{n})$ is the probability that the randomization results in $\mathbf{n}$, and $V_k^{\ell}(\theta, \mathbf{n})$ is the steady-state utility of use of a type-k user, if the MAC protocol is θ and the result of the randomization is $\mathbf{n}$. We can use basic combinatorics knowledge to calculate the probability $\Pr(\mathbf{n})$, whose expression is shown in [17] and omitted here due to lack of space.

The steady-state utility of use $V_k^{\ell}(\theta, \mathbf{n})$ given $\mathbf{n}$ is

$$\Delta T \cdot \lim_{t \to \infty} \sum_{\mathbf{X}(t) \in \mathcal{X}(\mathbf{n})} \Pr(\mathbf{X}(t)) \frac{x_{k,\ell}(t)}{n_{k,\ell}} u_k(\tau_{k,\ell}^{\theta}(\mathbf{X}(t)), \delta_{k,\ell}^{\theta}(\mathbf{X}(t))),$$

where $\mathcal{X}(\mathbf{n})$ is the set of admissible system states under the choices of pricing plans $\mathbf{n}$, $\Pr(\mathbf{X}(t))$ is the probability that the current system state is $\mathbf{X}(t)$ (calculated in [17]), and $\tau_{k,\ell}^{\theta}(\mathbf{X})$ and $\delta_{k,\ell}^{\theta}(\mathbf{X})$ are the throughput and delay of a type-k user, respectively, if the user is online, the MAC protocol is θ, the system state is $\mathbf{X}$, and the index of the pricing plan it chooses is ℓ. Note that the steady state of the process $\mathbf{X}(t)$ and the limit in the above equation always exist.

Second, we denote the expected cost of a type-k user by $C_k(\theta, \mathbf{P}, \pi)$, if the MAC protocol is θ, the pricing policy is $\mathbf{P}$, and the probability distribution over the choices of pricing plans is π. The expected payment can be calculated as

$$C_k(\theta, \mathbf{P}, \pi) = \sum_{\ell=1}^{L} \pi_{k,\ell} \left(p_s^{\ell} + \sum_{\mathbf{n}: n_{k,\ell} \geq 1} \Pr(\mathbf{n}) \cdot q^{\ell} \cdot \hat{B}_k^{\ell}(\theta, \mathbf{n}) \right) \tag{3}$$

where $\hat{B}_k^{\ell}(\theta, \mathbf{n})$ is the expected amount of excessive data usage consumed by a type-k user choosing plan ℓ over a billing period at the steady state, shown as below

$$\lim_{m \to \infty} \mathbb{E} \left\{ \left(\int_{m\Delta T}^{(m+1)\Delta T} \tau_{k,\ell}^{\theta}(\mathbf{X}(t)) \frac{x_{k,l}(t)}{n_{k,\ell}} dt - \beta^{\ell} \right)^{+} \right\}, \tag{4}$$

where β^{ℓ} is the threshold data usage of plan ℓ.

According to our definition, the expected utility is the expected utility of use minus the expected payment

$$U_k(\theta, \pi) - C_k(\theta, \mathbf{P}, \pi).$$

6) Users' Decision Process: Each user determines the randomizing probability that maximizes its own expected utility. The optimal action for a type-k user satisfies

$$\pi_k = \arg\max_{\pi_k'} \left\{ U_k(\theta, (\pi; \pi_k')) - C_k(\theta, \mathbf{P}, (\pi; \pi_k')) \right\}, \tag{5}$$

where $(\pi; \pi_k')$ is the joint action profile π with one type-k user changing its action from π_k to π_k', and $U_k(\theta, (\pi; \pi_k'))$ and $C_k(\theta, \mathbf{P}, (\pi; \pi_k'))$ are the utility of use and cost of that particular user, respectively. Note that $U_k(\theta, (\pi; \pi_k'))$ and $C_k(\theta, \mathbf{P}, (\pi; \pi_k'))$ are calculated by substituting $\pi_{k,\ell}$ with $\pi_{k,\ell}'$ in (2) and (3), respectively.

Given a pricing policy $\mathbf{P}$, we define the *plan selection game* of the users as

$$\Gamma_{\mathbf{P}} = \left\{ \mathcal{K} = \{1, \ldots, K\}, \{\pi_k\}_{k=1}^{K}, \{U_k - C_k\}_{k=1}^{K} \right\}.$$

The Nash equilibrium is $\pi(\mathbf{P})$, which depends on the pricing policy $\mathbf{P}$.

Proposition 1: There always exists a symmetric Nash equilibrium in the plan selection game $\Gamma_{\mathbf{P}}$.

Proof: The plan selection game $\Gamma_{\mathbf{P}}$ is a finite game; Nash [16], [18] shows that each such game has an equilibrium in which players of the same type choose the same strategies. ■

III. Problem Formulation

In this section, we formulate the design problem of the service provider. The service provider expects that each user will choose the optimal strategy that maximizes its own expected utility, given the pricing policy and the strategies of other users. The design problem of the service provider is therefore to choose a MAC protocol θ and a pricing policy $\mathbf{P}$, so that at the Nash equilibrium of the plan selection game, the social welfare (for the benevolent provider) or the total revenue (for the selfish provider) is maximized, subject to the constraint that costs be covered.

Here we assume that the service provider knows the arrival rates, service times, and utility functions of all types of users (but does not know the type of a particular user), and foresees the behavior of the users. The users in turn must know the behavior of other users. Implicitly, therefore, we view the outcome as involving some learning process that is not modeled here. We intend to address this issue in later work.

Under the assumption of perfect knowledge, we can formulate the design problem of the service provider as follows. For a benevolent service provider aiming at maximizing the social welfare, its design problem (PB) can be written as

$$\begin{aligned}
&(\text{PB}): && \qquad (6)\\
&\max_{\theta, \mathbf{P}} && \sum_{k=1}^{K} \left(U_k(\theta, \pi(\mathbf{P})) - C_k(\theta, \alpha, \mathbf{P}, \pi(\mathbf{P})) \right) \cdot N_k \\
&s.t. && \text{IC}: \pi_k \text{ satisfies (5)}, \quad k = 1, \ldots, K, \\
& && \text{IR}: \sum_{k=1}^{K} C_k(\theta, \alpha, \mathbf{P}, \pi(\mathbf{P})) \cdot N_k \geq C_0,
\end{aligned}$$

where C_0 is the cost of the service provider during a billing period due to the maintenance of the network. The objective

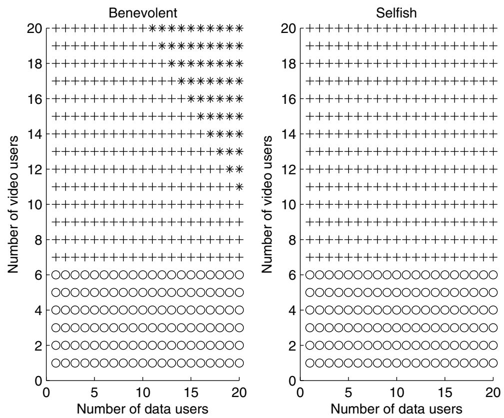

Fig. 1. Phase diagrams on the admission control policy with low-demand ($\lambda_1/\mu_1 = 0.1$) video users and low-demand ($\lambda_2/\mu_2 = 0.1$) data users under CSMA. ('*': video and data users, '+': video users only, '$\times$': data users only, '$\circ$': none.)

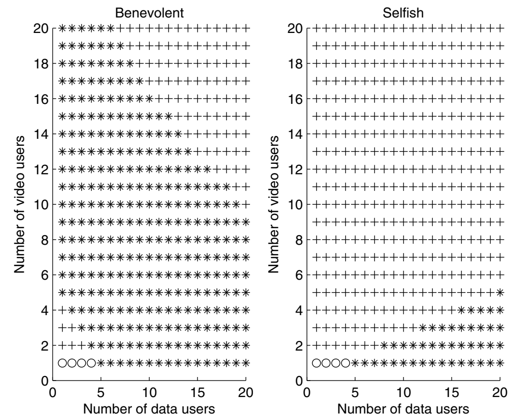

Fig. 2. Phase diagrams on the admission control policy with high-demand ($\lambda_1/\mu_1 = 1$) video users and high-demand ($\lambda_2/\mu_2 = 1$) data users under CSMA. ('*': video and data users, '+': video users only, '$\times$': data users only, '$\circ$': none.)

function is the social welfare defined as the sum utility of all the users. The first constraint is the incentive compatibility (IC) constraint for all the users, saying that the user will not get a higher utility by switching the plan. The second constraint is the individual rationality (IR) constraint for the service provider. The solution $\mathbf{P}^*$ to the above problem provides the users with a set of payment plans to choose from. After each user chooses the strategy that maximizes its own expected utility, the system reaches the maximum social welfare.

The design problem (PS) of a selfish service provider aiming at maximizing its own revenue is similar to(PB) with the objective function as $\sum_{k=1}^{K} C_k(\theta, \alpha, \mathbf{P}, \pi(\mathbf{P})) \cdot N_k$.

Because our focus is the influence of technology on the economic layer and system performance, we will first fix the technology θ and optimize the problems (PB) and (PS) over pricing and admission policies (given the number of users of each type) and then compare the influence of different technologies on the optimal pricing policies and the resulting system performance.

IV. Two Simple Scenarios

In this section, we study two simple scenarios. In each scenario there are two types of users: type-1 users are video users with stringent throughput and delay requirements, while type-2 users are data users, who require low throughput and can tolerate large delay. In the first scenario, the service provider uses CSMA, cannot measure the data usage of a specific user, and can only charge the same subscription fee for all the active users. In the second scenario, the service provider uses TDMA, can measure the data usage of each user, and can charge for a per-bit surcharge in addition to the subscription fee.

In Theorem 1 and 2 of [17], we characterizes the optimal pricing policy employed by the service providers and the resulting operating points for both scenarios. We omit those analysis here for the sake of space and show some simulation

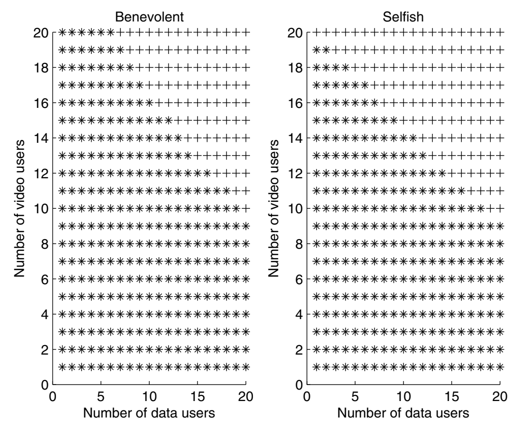

Fig. 3. Phase diagrams on the admission control policy with high-demand ($\lambda_1/\mu_1 = 1$) video users and high-demand ($\lambda_2/\mu_2 = 1$) data users under TDMA. ('*': video and data users, '+': video users only, '$\times$': data users only, '$\circ$': none.)

results for illustration in the following. The key parameters in the simulation are described as follows:

- The service provider uses 802.11a DCF as CSMA protocol and 802.11e HCF as TDMA protocol.
- The pricing policy of the provider using CSMA is

$$\mathbf{P}_{\mathrm{csma}} = \{\phi, (p_s, 0, 0)\}$$

  and that of the provider using TDMA is

$$\mathbf{P}_{\mathrm{tdma}} = \{\phi, (p_s^1, 0, 0), (p_s^2, q, \beta)\}.$$

- The total throughput of the AP is $B = 54\ Mbps$.
- The average service time of type-1 users, the video users, is fixed at $1/\mu_1 = 1$, and their utility is the Peak Signal-to-Noise Ratio (PSNR) of the video sequences. Here we use the *Foreman* video (CIF 15Hz), whose operational utility-rate-delay function can be calculated by experiment in [19].

- The average service time of type-2 users, the data users, is fixed at $1/\mu_2 = 1$, and their utility function is

$$u_2 = 10 \cdot \log(1 + \tau_2). \quad (7)$$

- The billing period is $\Delta T = 360$ hours/month, namely 12 hours/day times 30 days/month.
- The cost of the service provider is $C_0 = 1000$.
- The marginal utility of cost is $w = 1$ for both types.

Now we show some simulation results to illustrate the impact of the provider types and the technology on the system performance.

A. Impact of Provider Types

Here we show the phase diagram on the system operating points under different numbers of users of each type. The points in the phase diagram show which type or types of users choose to stay in the system.

Fig. 1 shows the phase diagram with low-demand video users and low-demand data users. We can see that the benevolent provider sets such a low subscription fee that both types of users can use the network, as long as the numbers of both types of users are large enough to provide sufficient payment to cover the cost. On the contrary, the selfish one sets such a high subscription fee that only the high-utility video users can afford to use the network. In this way, the entire bandwidth is dedicated to the highly profitable video users.

Fig. 2 shows the phase diagram with high-demand video and data users. In this case, the benevolent provider sets a high subscription fee when the number of data users is large, so that only video users can afford the fee. This means that the benevolent provider chooses the high-utility video users, when both users have high demand and large population and the network cannot support both due to congestion. For the selfish provider, it always tends to set a high subscription fee to exclude the data users from the network, so that only video users can afford to stay.

We show in [17] the phase diagrams with different configurations of user demands, which we omit here due to space constraints. In general, the benevolent provider admits more types of users than the selfish one does, whenever it is possible.

B. Impact of MAC Protocols

We show the phase diagram under TDMA protocol with low-demand video and data users in Fig. 3. In contrast with the CSMA case, both providers, even the selfish one, admit both types of users under most configurations of user numbers. TDMA enables both providers to admit both users by setting different plans for different types of users, when the difference between the utility of different users is large. We show more figures with different user demands and provide detailed analysis on each case in [17].

V. Conclusion

In this paper, we studied the provision of a wireless network by a monopolistic (benevolent or selfish) provider. The paper presented a model for the wireless network with three interdependent layers, namely the technology layer, the application layer, and the economic layer. Using the proposed model, we can analyze the influence of technology on the economic layer, and more importantly, the interaction of technology and economic layers that determines the feasibility and desirability of the network. By simulation, we illustrated different behaviors of a benevolent provider and a selfish provider at their optimal operating points. Simulation results also demonstrated that differences in MAC technology can have a significant effect on the system performance.

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