

Energy Efficiency and Delay Quality-of-Service in Wireless Networks

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Abstract—The energy-delay tradeoffs in wireless networks are studied using a game-theoretic framework. A multi-class multiple-access network is considered in which users choose their transmit powers, and possibly transmission rates, in a distributed manner to maximize their own utilities while satisfying their delay quality-of-service (QoS) requirements. The utility function considered here measures the number of reliable bits transmitted per Joule of energy consumed and is particularly useful for energy-constrained networks. The Nash equilibrium solution for the proposed non-cooperative game is presented and closed-form expressions for the users' utilities at equilibrium are obtained. Based on this, the losses in energy efficiency and network capacity due to presence of delay-sensitive users are quantified. The analysis is extended to the scenario where the QoS requirements include both the average source rate and a bound on the average total delay (including queuing delay). It is shown that the incoming traffic rate and the delay constraint of a user translate into a “size” for the user, which is an indication of the amount of resources consumed by the user. Using this framework, the tradeoffs among throughput, delay, network capacity and energy efficiency are also quantified.

I. INTRODUCTION

Future wireless networks are expected to support a variety of services with diverse quality of service (QoS) requirements. For example, a mixture of delay-sensitive and delay-tolerant users could exist in the same network. At the same time, most of the user terminals in a wireless network are battery-powered. As a result, energy efficiency is also crucial in design of wireless networks. Therefore, the objective is to use the radio resources (e.g., power and bandwidth) as efficiently as possible and at the same time satisfy the QoS requirements of the users in the network.

In this work, we study the tradeoffs between energy efficiency and delay QoS using a game-theoretic framework. We consider a multiple-access network in which each user seeks to locally choose its transmit power, and possibly its transmission rate, in order to maximize its own utility (in bits per Joule) and at the same time satisfy its delay QoS requirements. The strategy chosen by each user affects the other users through multiple-access interference. The study of the tradeoffs between energy efficiency and delay has recently attracted considerable attention (see for example [1]–[6]). Our non-cooperative game-theoretic approach allows us to study the energy efficiency-delay tradeoffs in a multiuser competitive setting. Using this framework, we quantify the loss in energy efficiency due to the presence of delay-sensitive users in the network and analyze the tradeoffs among throughput, delay, network capacity and energy

efficiency.

The remainder of the paper is organized as follows. In Section II, we present the system model and define the user utility function. The delay model for the infinite backlog case is given in Section III. The proposed delay-constrained power control game and its Nash equilibrium solution are presented in Section IV. In Section V, we give explicit expressions for the utilities achieved at Nash equilibrium for a multi-class network. The delay model for the finite backlog case is given in Section VI. In Section VII, we propose a delay-constrained power and rate control game and give its Nash equilibrium solution. Numerical results and conclusions are given in Sections VIII and IX, respectively.

II. SYSTEM MODEL

We consider a synchronous direct-sequence code-division-multiple-access (DS-CDMA) network with K users and processing gain N (defined as the ratio of symbol duration to chip duration). We assume that all K user terminals transmit to a receiver at a common concentration point. The received signal at the access point sampled at the chip rate over one symbol duration can be expressed as

$$\mathbf{r} = \sum_{k=1}^K \sqrt{p_k} h_k b_k \mathbf{s}_k + \mathbf{w}, \quad (1)$$

where p_k , h_k , b_k and \mathbf{s}_k are the transmit power, channel gain, transmitted bit and spreading sequence of the k^{th} user, respectively, and \mathbf{w} is the noise vector which is assumed to be Gaussian with mean $\mathbf{0}$ and covariance $\sigma^2 \mathbf{I}$. We assume random spreading sequences for all users.

We assume that data arrives at the user terminal in the form of M -bit packets. The user transmits the arriving packets at a rate R_k (bps) and with a transmit power equal to p_k Watts. We consider an automatic-repeat-request (ARQ) mechanism in which the user keeps retransmitting a packet until the packet is received at the access point without any errors. Let us define the utility function of a user to be the ratio of its goodput to its transmit power, i.e.,

$$u_k = \frac{T_k}{p_k}. \quad (2)$$

Goodput is the net number of information bits that are transmitted without error per unit time and is expressed as

$$T_k = R_k f(\gamma_k) \quad (3)$$

where γ_k is the output SIR for user k and $f(\gamma_k)$ is the “efficiency function” which represents the packet success rate (PSR). We assume $f(\gamma)$ to be continuous, increasing and S-shaped¹ (sigmoidal) with $f(\infty) = 1$. This is a valid assumption for many practical scenarios as long as the packet size is reasonably large (e.g., $M = 100$ bits). We also require that $f(0) = 0$ to ensure that $u_k = 0$ when $p_k = 0$. In general, the efficiency function depends on the modulation, coding and packet size. A more detailed discussion of the efficiency function can be found in [7]. Based on (2) and (3), the utility function for user k can be written as

$$u_k = R_k \frac{f(\gamma_k)}{p_k}. \quad (4)$$

This utility function, which has units of *bits/Joule*, captures very well the tradeoff between throughput and battery life, and is particularly suitable for energy-constrained networks.

III. DELAY MODEL FOR THE INFINITE BACKLOG CASE

Let us for now focus on the case in which there are infinitely many packets to be transmitted by each user. For this case, we concentrate on the transmission delay. Let X represent the (random) number of transmissions required for a packet to be received without any errors. The assumption is that if a packet has one or more errors, it will be retransmitted. We also assume that retransmissions are independent from each other. It is clear that the transmission delay for a packet is directly proportional to X . Since the packet success rate is given by the efficiency function $f(\gamma)$, the probability that exactly m transmissions are required for the successful transmission of a packet is given by

$$\Pr\{X = m\} = f(\gamma) (1 - f(\gamma))^{m-1}. \quad (5)$$

We model the delay requirements of a particular as a pair (L, β) , where

$$\Pr\{X \leq L\} \geq \beta. \quad (6)$$

In other words, we would like the number of transmissions to be at most L with a probability larger than or equal to β . Note that (6) can equivalently be represented as an upper bound on the delay outage probability. Based on (5), it can be shown that the delay constraint in (6) is equivalent to

$$f(\gamma) \geq \tilde{\eta}(L, \beta), \quad (7)$$

where

$$\tilde{\eta}(L, \beta) = 1 - (1 - \beta)^{\frac{1}{L}}. \quad (8)$$

Since $f(\gamma)$ is an increasing function of γ , we can equivalently express (7) as

$$\gamma \geq \tilde{\gamma} \quad (9)$$

where $\tilde{\gamma} = f^{-1}(\tilde{\eta}(L, \beta))$. Therefore, the delay constraint in (6) translates into a lower bound on the output SIR. Since different users could have different delay requirements, $\tilde{\gamma}$ is user dependent. We make this explicit by writing

$$\tilde{\gamma}_k = f^{-1}(\tilde{\eta}_k) \quad (10)$$

where $\tilde{\eta}_k = 1 - (1 - \beta_k)^{\frac{1}{L_k}}$. A more stringent delay requirement, i.e., a smaller L and/or a larger β , will result in a higher value for $\tilde{\gamma}$.

¹An increasing function is S-shaped if there is a point above which the function is concave, and below which the function is convex.

IV. POWER CONTROL GAME WITH DELAY CONSTRAINTS

Consider the non-cooperative power control game (PCG) $\tilde{G} = [\mathcal{K}, \{\tilde{A}_k\}, \{u_k\}]$ where $\mathcal{K} = \{1, \dots, K\}$, and $\tilde{A}_k = [0, P_{max}]$, which is the strategy set for the k^{th} user and u_k is the utility function given by (4). Here, P_{max} is the maximum allowed power for transmission. Each user chooses its transmit power in order to maximize its own utility and at the same time satisfy its delay requirements. We have shown in Section III that the delay requirements of a user translate into a lower bound on the user’s output SIR. Hence, the resulting delay-constrained power control game can be expressed as

$$\max_{p_k} u_k \quad \text{s.t.} \quad \gamma_k \geq \tilde{\gamma}_k \quad \text{for } k = 1, \dots, K. \quad (11)$$

We assume that only those users whose delay requirements can be met are admitted into the network. For example, for the conventional matched filter, this translates into having $\sum_{k=1}^K \frac{1}{1 + \tilde{\gamma}_k} < 1$. This assumption makes sense because admitting a user that cannot meet its delay requirement only causes unnecessary interference for other users. The Nash equilibrium for the proposed game is a set strategies (power levels) for which no user can unilaterally improve its own (delay-constrained) utility function. We now state the following proposition.

Proposition 1: The Nash equilibrium for the proposed delay-constrained power control game is given by $\tilde{p}_k^* = \min\{p_k^*, P_{max}\}$, for $k = 1, \dots, K$, where p_k^* is the transmit power that results in an output SIR equal to $\tilde{\gamma}_k^*$ with $\tilde{\gamma}_k^* = \max\{\tilde{\gamma}_k, \gamma^*\}$. Here, $\tilde{\gamma}_k$ is given by (10) and γ^* is the (positive) solution of $f(\gamma) = \gamma f'(\gamma)$. Furthermore, this equilibrium is unique.

Proof: See [8] for the proof. ■

The above proposition suggests that at Nash equilibrium, the output SIR for user k is $\tilde{\gamma}_k^*$, where $\tilde{\gamma}_k^*$ depends on the efficiency function through γ^* as well as user k ’s delay constraint through $\tilde{\gamma}_k$. Note that this result does not depend on the choice of the receiver and is valid for all linear receivers.

V. MULTI-CLASS NETWORKS

Let us now consider a network with C classes of users. The assumption is that all the users in the same class have the same delay requirements characterized by the corresponding L and β . Based on Proposition 1, at Nash equilibrium, all the users in class c will have the same output SIR, $\tilde{\gamma}^{*(c)} = \max\{\tilde{\gamma}^{(c)}, \gamma^*\}$, where $\tilde{\gamma}^{(c)} = f^{-1}(\tilde{\eta}^{(c)})$. The goal is to quantify the effect of delay constraints on the energy efficiency of the network or equivalently on the users’ utilities.

In order to obtain explicit expressions for the utilities achieved at equilibrium, we use a large-system analysis. We consider the asymptotic case in which $K, N \rightarrow \infty$ and $\frac{K}{N} \rightarrow \alpha < \infty$. This allows us to write SIR expressions that are independent of the spreading sequences of the users. Let $K^{(c)}$ be the number of users in class c , and define $\alpha^{(c)} = \lim_{K, N \rightarrow \infty} \frac{K^{(c)}}{N}$. Therefore, we have $\sum_{c=1}^C \alpha^{(c)} = \alpha$. It can be shown that [8] for the matched filter, the decorrelator, and the linear minimum-mean-square-error (MMSE) detector, the utilities achieved at the

Nash equilibrium are given by

$$u_k^{MF} = \frac{R_k h_k^2}{\sigma^2} \left(1 - \sum_{c=1}^C \alpha^{(c)} \tilde{\gamma}^{*(c)} \right) \frac{f(\tilde{\gamma}^{*(c)})}{\tilde{\gamma}^{*(c)}} \quad \text{for } \sum_{c=1}^C \alpha^{(c)} \tilde{\gamma}^{*(c)} < 1, \quad (12)$$

$$u_k^{DE} = \frac{R_k h_k^2}{\sigma^2} \left(1 - \sum_{c=1}^C \alpha^{(c)} \right) \frac{f(\tilde{\gamma}^{*(c)})}{\tilde{\gamma}^{*(c)}} \quad \text{for } \sum_{c=1}^C \alpha^{(c)} < 1, \quad (13)$$

and

$$u_k^{MMSE} = \frac{R_k h_k^2}{\sigma^2} \left(1 - \sum_{c=1}^C \alpha^{(c)} \frac{\tilde{\gamma}^{*(c)}}{1 + \tilde{\gamma}^{*(c)}} \right) \frac{f(\tilde{\gamma}^{*(c)})}{\tilde{\gamma}^{*(c)}} \quad \text{for } \sum_{c=1}^C \alpha^{(c)} \frac{\tilde{\gamma}^{*(c)}}{1 + \tilde{\gamma}^{*(c)}} < 1. \quad (14)$$

Note that, based on the above equations, we have $u_k^{MMSE} > u_k^{DE} > u_k^{MF}$. This means that the MMSE receiver achieves the highest utility as compared to the decorrelator and the matched filter. Also, the network capacity (i.e., the number of users that can be admitted into the network) is the highest when the MMSE detector is used. For the specific case of no delay constraints, $\tilde{\gamma}^{*(c)} = \gamma^*$ for all c .

We can observe from (12)–(14) that the presence of users with stringent delay requirements results in a reduction in the utility of all the users in the network. A stringent delay requirement results in an increase in the user's target SIR (remember $\tilde{\gamma}_k^* = \max\{\tilde{\gamma}_k, \gamma^*\}$). Since $\frac{f(\gamma)}{\gamma}$ is maximal when $\gamma = \gamma^*$, a target SIR larger than γ^* results in a reduction in the utility of the corresponding user. In addition, because of the higher target SIR for this user, other users in the network experience a higher level of interference and hence are forced to transmit at a higher power which in turn results in a reduction in their utilities (except for the decorrelator, in which case the multiple-access interference is completely removed). Also, since $\tilde{\gamma}_k^* \geq \gamma^*$ and $\sum_{c=1}^C \alpha^{(c)} = \alpha$, the presence of delay-constrained users causes a reduction in the system capacity (again, except for the decorrelator). We will demonstrate these losses in Section VIII using numerical results.

VI. DELAY MODEL FOR THE FINITE BACKLOG CASE

So far, we have assumed that there are infinitely many packets for transmission at each user terminal. Hence, we have focused on the transmission delay. Now, we extend the analysis to consider the case in which the packet arrival rate is finite. For this case, we take into account the queuing delay as well. We specify the QoS constraints of user k by (r_k, D_k) where r_k is the average source rate and D_k is the upper bound on average delay. The delay in this case includes both queuing and transmission delays. The incoming traffic is assumed to have a Poisson distribution with parameter λ_k which represents the average packet arrival rate. Since each packet consists of M bits, the source rate r_k (in bit per second) is given by

$$r_k = M\lambda_k. \quad (15)$$

As before, we assume that the user keeps retransmitting a packet until the packet is received at the access point without any

errors. The retransmissions are assumed to be independent. The incoming packets are assumed to be stored in a queue and transmitted in a first-in-first-out (FIFO) fashion. The packet transmission time for user k is defined as

$$\tau_k = \frac{M}{R_k}. \quad (16)$$

We can represent the combination of user k 's queue and wireless link as an M/G/1 queue where the traffic is Poisson with parameter λ_k (in packets per second) and the service time, S_k , has the following probability mass function (PMF):

$$\Pr\{S_k = m\tau_k\} = f(\gamma_k) (1 - f(\gamma_k))^{m-1} \quad \text{for } m = 1, 2, \dots \quad (17)$$

As a result, the service rate, μ_k , is given by

$$\mu_k = \frac{1}{\mathbb{E}\{S_k\}} = \frac{f(\gamma_k)}{\tau_k}, \quad (18)$$

and the load factor $\rho_k = \frac{\lambda_k}{\mu_k} = \frac{\lambda_k \tau_k}{f(\gamma_k)}$.

To keep the queue of user k stable, we must have $\rho_k < 1$ or $f(\gamma_k) > \lambda_k \tau_k$. Now, let W_k be a random variable representing the total packet delay for user k . This delay includes the time the packet spends in the queue as well as the service time. It can be shown that, for the M/G/1 queue considered here, the average wait time (including the queuing and service time) for user k is given by (see [9])

$$\bar{W}_k = \tau_k \left(\frac{1 - \frac{\lambda_k \tau_k}{2}}{f(\gamma_k) - \lambda_k \tau_k} \right) \quad \text{with } f(\gamma_k) > \lambda_k \tau_k. \quad (19)$$

We require the average delay for user k 's packets to be less than or equal to D_k , i.e.,

$$\bar{W}_k \leq D_k. \quad (20)$$

Note that D_k cannot be smaller than the transmission time τ_k . It can be shown again that the delay constraint in (20) translates into a lower bound on the output SIR, i.e.,

$$\gamma \geq \hat{\gamma}_k \quad (21)$$

where

$$\hat{\gamma}_k = f^{-1}(\hat{\eta}_k) \quad (22)$$

with $\hat{\eta}_k = \lambda_k \tau_k + \frac{\tau_k}{D_k} - \frac{\lambda_k \tau_k^2}{2D_k}$ (again, see [9]).

VII. POWER AND RATE CONTROL GAME WITH DELAY CONSTRAINTS

Consider the non-cooperative joint power and rate control game (PRCG) $\hat{G} = [\mathcal{K}, \{\hat{A}_k\}, \{u_k\}]$ where $\mathcal{K} = \{1, 2, \dots, K\}$ is the set of users, $\hat{A}_k = [0, P_{max}] \times [0, B]$ is the strategy set for user k with a strategy corresponding to a choice of transmit power and transmit rate, and u_k is the utility function for user k given by (4). Here, B is the system bandwidth. Each user chooses its transmit power and rate in order to maximize its own utility while satisfying its delay QoS requirements. The resulting delay-constrained power and rate control game can be expressed as

$$\max_{p_k, R_k} u_k \quad \text{s.t.} \quad \gamma_k \geq \hat{\gamma}_k \quad \text{and} \quad \frac{r_k}{R_k} < \frac{\frac{D_k R_k}{M} - 1}{\frac{D_k R_k}{M} - \frac{1}{2}} \quad (23)$$

for $k = 1, \dots, K$ where $\hat{\gamma}_k = f^{-1}(\hat{\eta}_k)$ and

$$\hat{\eta}_k = \frac{r_k}{R_k} + \frac{M}{D_k R_k} - \frac{M r_k}{2 D_k R_k^2}. \quad (24)$$

The second constraint in (23) is to make sure that $\hat{\eta}_k < 1$. Note that the output SIR γ_k depends on both p_k and R_k .

Let us define

$$\Omega_k^* = \left(\frac{M}{D_k} \right) \frac{1 + D_k \lambda_k + \sqrt{1 + D_k^2 \lambda_k^2 + 2(1 - f^*) D_k \lambda_k}}{2 f^*}. \quad (25)$$

where $f^* = f(\gamma^*)$ with γ^* being the (positive) solution of $f(\gamma) = \gamma f'(\gamma)$. We now state the following proposition.

Proposition 2: If $\sum_{k=1}^K \frac{1}{1 + \Omega_k^* \gamma^*} < 1$, then the proposed delay-constrained power and rate control game has at least one Nash equilibrium given by (p_k^*, R_k^*) , for $k = 1, \dots, K$, where $R_k^* = \Omega_k^*$ and p_k^* is the transmit power that results in an output SIR equal to γ^* . Furthermore, when there are more than one Nash equilibrium, (p_k^*, Ω_k^*) is the most *efficient* one.

Proof: See [9] for the proof. ■

We now define the “size” of user k as

$$\Phi_k^* = \frac{1}{1 + \frac{B}{\Omega_k^* \gamma^*}}. \quad (26)$$

Therefore, the feasibility condition in Proposition 2 can be written as

$$\sum_{k=1}^K \Phi_k^* < 1. \quad (27)$$

The size of a user is basically an indication of the amount of network resources consumed by that user. Note that the QoS requirements of user k (i.e., its source rate r_k and delay constraint D_k) uniquely determine Ω_k^* through (25) and, in turn, determine the size of the user (i.e., Φ_k^*) through (26). A larger source rate or a tighter delay constraint for a user increases the size of the user. The network can accommodate a set of users if and only if their total size is less than 1. In Section VIII, we use this framework to study the tradeoffs among throughput, delay, network capacity and energy efficiency.

VIII. NUMERICAL RESULTS

Let us first consider the infinite backlog case as discussed in Sections III–V. Let us consider a DS-CDMA system with processing gain 100. We assume that each packet contains 100 bits (i.e., $M = 100$). The transmission rate, R , is 100kbps. A useful example for the efficiency function is $f(\gamma) = (1 - e^{-\gamma})^M$. This serves as an approximation to the packet success rate that is very reasonable for moderate to large values of M . We use this efficiency function for our simulations. Using this, with $M = 100$, we have $\gamma^* = 6.48 = 8.1\text{dB}$.

We consider a network where the users can be divided into two classes: delay sensitive (class A) and delay tolerant (class B). For users in class A, we choose $L_A = 1$ and $\beta_A = 0.99$ (i.e., delay sensitive). For users in class B, we let $L_B = 3$ and $\beta_B = 0.90$ (i.e., delay tolerant). Based on these choices, $\tilde{\gamma}_A^* = 9.6\text{dB}$ and $\tilde{\gamma}_B^* = \gamma^* = 8.1\text{dB}$. Without loss of generality and to keep the comparison fair, we also assume that all the users are the same distance from the access point. The system load is α (i.e., $\frac{K}{N} = \alpha$) and we let α_A and α_B represent the load

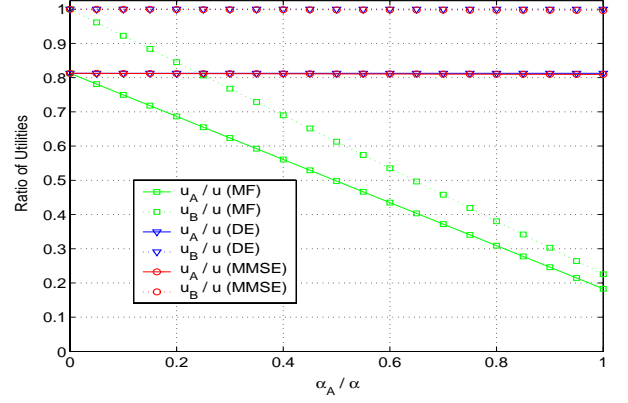


Fig. 1. Loss in utility due to presence of users with stringent delay requirements ($\alpha = 0.1$).

corresponding to class A and class B users, respectively, with $\alpha_A + \alpha_B = \alpha$. We first consider a lightly loaded network with $\alpha = 0.1$ (see Fig. 1). To demonstrate the performance loss due to the presence of users with stringent delay requirements (i.e., class A), we plot u_A/u and u_B/u as a function of the fraction of the load corresponding to class A users (i.e., α_A/α). Here, u_A and u_B are the utilities of users in class A and class B, respectively, and u represents the utility of the users if they all had loose delay requirements. Fig. 1 shows the loss in utility for the matched filter, the decorrelator, and the MMSE detector. We observe from the figure that for the matched filter both classes of users suffer significantly due to the presence of delay sensitive traffic. For example, when half of the users are delay-sensitive, the utilities achieved by class A and class B users are, respectively, 50% and 60% of the utilities for the case of no delay constraints. For the decorrelator, only class A users suffer and the reduction in utility is smaller than that of the matched filter. For the MMSE detector, the reduction in utility for class A users is similar to that of the decorrelator, and the reduction in utility for class B is negligible.

We repeat the experiment for a highly loaded network with $\alpha = 0.9$ (see Fig. 2). Since the matched filter cannot handle such a significant load, we have shown the plots for the decorrelator and MMSE detector only. We observe from Fig. 2 that because of the higher system load, the reduction in the utilities is more significant for the MMSE detector compared to the case of $\alpha = 0.1$. It should be noted that for the decorrelator the reduction in utility of class A users is independent of the system load. This is because the decorrelator completely removes the multiple-access interference.

We now present simulation results for the finite backlog case as discussed in Sections VI and VII. Let us consider the uplink of a DS-CDMA system with a total bandwidth of 5MHz (i.e. $B = 5\text{MHz}$). As explained in Section VII, the QoS parameters of a user define a “size” for that user, denoted by Φ_k^* given by (26). Before a user starts transmitting, it must announce its size to the access point. Based on the particular admission policy, the access point decides whether or not to admit the user. Throughout this section, we assume that the admitted users choose the transmit powers and rates that correspond to their efficient Nash equilibrium (see Proposition 2). Fig. 3 shows the size of a user as a function of the user’s source rate and

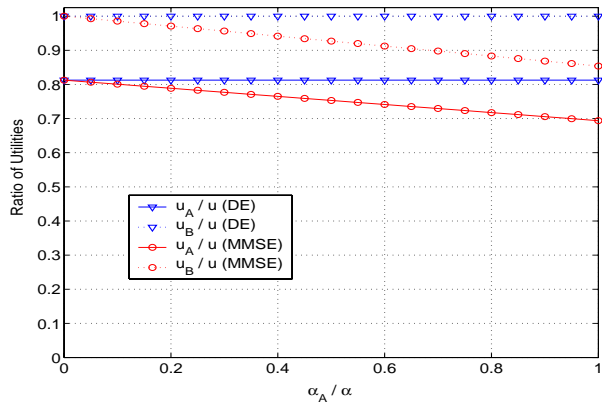


Fig. 2. Loss in utility due to presence of users with stringent ($\alpha = 0.9$).

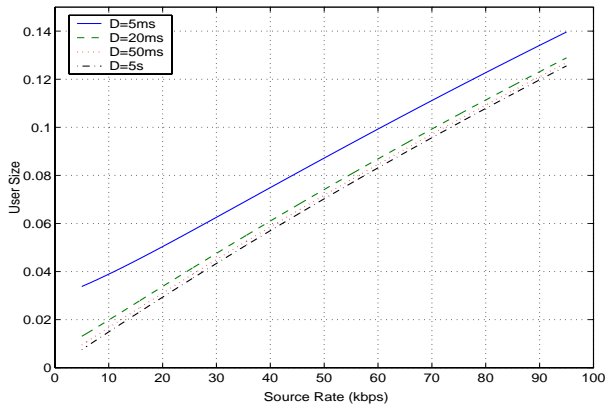


Fig. 3. User size, Φ^* , as a function of source rate for different delay requirements.

for different delay requirements. It is seen that the higher the source rate and the tighter the delay requirement, the larger the size. Now, let us assume that all users in the network have the same QoS requirements, which means that all the users have the same size. Based on (27), we can calculate the maximum number of users whose QoS requirements can be accommodated (i.e., network capacity). Fig. 4 shows the network capacity as a function of the source rate for different delay requirements. As the source rate increases and the delay bound becomes tighter, the number of users that can be accommodate by the network reduces. Eventually, as the source rate becomes very large, only one user can be accommodated by the network. We can also plot the total goodput (i.e., reliable throughput) of the network. Fig. 5 shows the total goodput as a function of the source rate for different delay requirements.

IX. CONCLUSIONS

We have studied the energy-delay tradeoffs using a game-theoretic framework. A non-cooperative game is proposed in which each user chooses its transmit power, and possibly its transmission rate, to maximize its own utility (in bits per Joule) while satisfying its delay QoS requirements. The Nash equilibrium solution for the proposed game is presented. We have shown that the presence of delay-sensitive users results in significant losses in the network utility and capacity, and have quantified the losses. The tradeoffs among throughput, delay, network capacity and energy efficiency have also been analyzed.

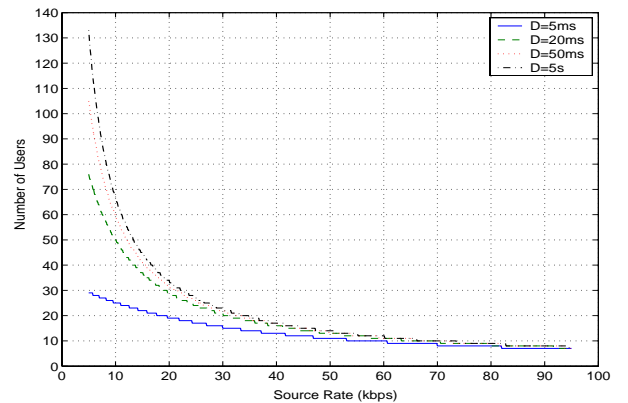


Fig. 4. Network capacity as a function of source rate for different delay requirements.

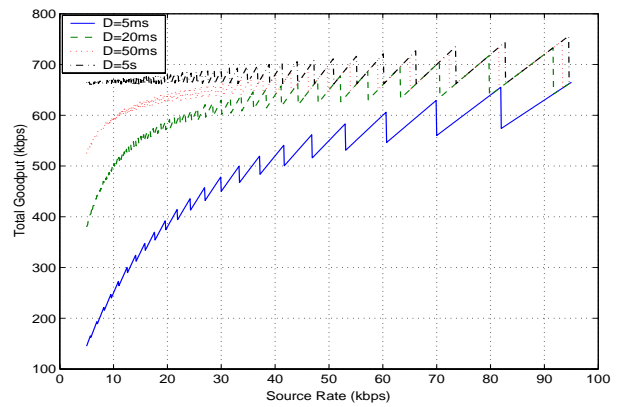


Fig. 5. Total goodput as a function of source rate for different delay requirements.

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