Provision of Maximum Delay Guarantee at Low Energy in a Multi-user Environment

Muhammad Majid Butt, Kimmo Kansanen, Ralf R. Müller
Institute of Electronics and Telecommunications
Norwegian University of Science and Technology
Trondheim, Norway
Email: majid.butt@iet.ntnu.no

***Abstract*— In this work a simple scheduling scheme is proposed for wireless sensor networks in presence of a *maximum tolerable delay constraint*. The scheduler performs the dual task of scheduling the users experiencing high channel gains to minimize the energy consumption while at the same time, it takes into account the maximum allowed buffer length of each user to provide an upper bound on the maximum tolerable delay. The idea of a threshold depending on the buffer occupancy is proposed to schedule the users opportunistically unless the deadline for transmission is reached. A maximum delay guarantee is provided in the proposed scheme in addition to average delay guarantee at almost no additional energy cost. The results show that *multilevel recursive optimization* can minimize energy subject to maximum bounded delay for schedulers that *empty the buffer*.**

I. INTRODUCTION

Energy saving and delay constraints are one of the most demanding requirements for the state of the art wireless communication networks. Specifically, wireless sensor networks (WSN) put an emphasis on the energy saving aspect of the system. WSN consists of a large number of nodes with the sensing, computation and communication capabilities merged together. One of the fundamental and most important tasks in designing protocols for WSN is minimization of energy expenditure to increase the life time of the network. Sensor nodes can save the measured data locally for some duration and wait in *sleep mode* before transmitting it to the data collecting node, called fusion node. When they find good channel conditions, they *wake up* and empty the buffer by transmitting the whole data. Some applications explicitly require the transmission of sensed data before a hard deadline and therefore, often an upper delay bound for each node needs to be provided. This work deals with the dual task of minimizing the energy of the system while providing an upper delay bound for each node.

The work in [1] deals with maximization of the information capacity by scheduling the users having the instantaneous channel quality near the peaks. This form of diversity in which different users experience independent channels at the same time is called *multiuser diversity*. In wireless systems, channel fading has been treated as a source of uncertainty but in the context of multiuser diversity, it can be considered as randomness that can be exploited by scheduling the users experiencing a good channel. Reference [2] discusses a scheme to increase the random fading in a slow fading environment by using multiple antennas on the transmitter side of the downlink. The larger the number of the users in the multiuser environment, the greater is the chance that some of the users will be experiencing channel near the peaks. In [2] an opportunistic scheduling scheme called proportional fair scheduling (PFS) is proposed to provide the fairness guarantees to all users. Reference [3] deals with the tradeoffs between average delay and average power.

In [4], a scheduling policy has been proposed to maximize the expected data throughput by using dynamic programming. Similar work in [5] considers a scheduling policy without a centralized scheduler and discusses the energy delay trade off with full and partial shared information about the queue lengths of all the users. In [6], an exact solution for the average packet delay under the optimal offline scheduler has been presented. The results of [3] have been extended to the multiuser context in [7] and the result yields that to achieve an average power within the $O(1/L)$ of the minimum power required for the network stability, there must be an average queuing delay greater or equal to $\Omega(\sqrt{L})$. The work in [8] proposes an iterative algorithm for finding optimal offline scheduler. Also an energy saving on line scheduler is discussed which adapts both to the channel fading and backlog.

Most of the work has been in the direction of finding minimum energy solution for the average system delay. As mentioned earlier, some applications in WSN explicitly require maximum delay guarantees for individual nodes in addition to average delay. In this work, multi-user scheduling is performed by extending the idea of a single user scheduling in the large system limit. We have used the new modalities provided by the physical layer for opportunistic communication and the scheduling parameters at MAC layer are tuned according to the channel distributions at the physical layer. This tuning of parameters across different layers can be regarded as vertical calibration in a cross layer design approach [9].

The rest of the paper has been organized as follows. Section II describes the system model used for evaluating the results. Section III presents the detailed discussion of the Deadline Dependent Opportunistic Scheduling (DDOS) scheme proposed in this work. In section IV, numerical results have been described to evaluate the DDOS scheduling scheme and section V concludes the contribution of this paper.

978-1-4244-2204-3/08/$25.00 ©2008 IEEE

II. SYSTEM MODEL

We consider a multi access system with K users placed uniformly at random in a cell. Each user requires a certain fraction of the data rate provided in the system. The required average rate R for each user is $\frac{\Gamma}{K}$ where Γ denotes the spectral efficiency of the system. We consider a time slotted system while arrival rate is constant for all the users. Arrivals are queued in a finite buffer of length τ^{max} before transmission. In each time slot $\frac{\Gamma}{K}$ bits arrive in the buffer of each use and we consider an uplink case but results can be generalized for down link in a straightforward manner.

The fading environment of the multi-access system is described as follows. Each user k experiences a channel gain $d_k(t)$ in slot t. The channel gain $d_k(t)$ is the product of path loss $s_k(t)$ and short term fading $f_k(t)$ i.e. $d_k(t) = s_k f_k(t)$. The path loss and short term fading are assumed independent. The path loss is a function of distance between the transmitter and the receiver and we assume a constant path loss from slot to slot for a specific user. Short term fading depends on the scattering environment and depicts the situation when coherence time of the channel is much less than the delay requirement of the application. Short term fading changes from slot to slot for every user and is i.i.d across both users and slots but remains constant within a block. This model is referred to as block fading. $E_k^R(t)$ and $E_k(t)$ represent the received and the transmitted energy for each user k such that $E_k^R(t) = d_k(t)E_k(t)$. It can be observed that distribution of $d_k(t)$is not symmetric across the users. Let N_0 denote the noise power spectral density.

Using superposition coding, the transmit energy E_{π_k} of the scheduled user π_k is given by [10],

$$E_{\pi_k} = \frac{N_0}{d_{\pi_k}}[\exp(\sum_{i\leq k} R_{\pi_i}) - \exp(\sum_{i<k} R_{\pi_i})]. \tag{1}$$

where π is the permutation of the users which sorts the channel gains in increasing order and results in minimum transmit energy for the scheduled users. Collisions between the simultaneous transmissions are avoided because in a multi user environment, superposition coding and successive decoding ensures that data from multiple users is coded in increasing order of channel gains on the transmitter side and decoded successfully without error on the receiver side.

III. DEADLINE DEPENDENT OPPORTUNISTIC SCHEDULING

Opportunistic Superposition Coding (OSPC) has been proposed to exploit the channel diversities of the users in [11]. This scheme provides the desired throughput for all the users and average delay guarantees for each user. We have extended the approach of OSPC and proposed Deadline Dependent Opportunistic Scheduling (DDOS) in this work.

In DDOS, individual queues of the users are observed in addition to the short term fading $f_k(t)$ for the scheduling purpose. The proposed scheme schedules a set of users experiencing high short term fading gains. If backlog of a user is equal to the maximum delay parameter, the user is scheduled and channel is assigned regardless of its instantaneous fading state. We are using the approach of emptying the queue to keep the scheduling operation simple. DDOS switches between two modes. First mode provides the energy efficient solution by scheduling the users experiencing high short term fading gains as compared to an opportunistic threshold and this mode is referred as *opportunistic mode*. The scheduler performs scheduling in this mode as long as the backlog of the user is less than the maximum tolerable delay, called deadline. The scheduler shifts from the opportunistic mode to the *deadline mode* when the maximum buffer length is reached and provides the required data rate to the user by emptying the queue, regardless of its fading state. Users are scheduled in an energy efficient way in the opportunistic mode while scheduling in deadline mode has adverse effects on the energy efficiency. Pseudo code for DDOS has been shown below.

```
Algorithm III.1: DDOS($Backlog, Deadline$)

  comment: User $k$ knows Backlog and Deadline
  $i \leftarrow Backlog$
  $n \leftarrow Deadline$
  comment: Current Buffer contains $i\frac{\Gamma}{K}$ data
  $Buffer \leftarrow i\frac{\Gamma}{K}$
  comment: Rate $R$ is provided by the scheduler
  if $(f_k > \kappa_i)$ or $(i = n)$
    then $\begin{cases} R \leftarrow Buffer \\ i \leftarrow 1 \end{cases}$
    else
    then $\begin{cases} R \leftarrow 0 \\ i \leftarrow i + 1 \end{cases}$
```

We consider the evolution of the buffer of a single user. The state transition diagram for the single user has been shown in Fig. 1. We denote the probability of the user scheduled in buffer state one as P_1 and probability of the user not scheduled in buffer state one and moving in the next state as $\bar{P}_1$. The variable f denotes the short term fading state of the user while $\vec{\kappa}$, represents the vector of buffer state dependent opportunistic thresholds such that, $\vec{\kappa} = (\kappa_1, \kappa_2, ...\kappa_n)^T$.

State 1:

$$P_1 = P(f > \kappa_1) \sum_{i=1}^{n} \alpha_{i1}\pi_i \tag{2}$$

$$\bar{P}_1 = P(f \leq \kappa_1) \sum_{i=1}^{n} \alpha_{i1}\pi_i \tag{3}$$

where π_i is the limiting probability of entering in state i and α_{i1} is the transition probability of moving into state 1 from state i.

For the buffer state 2, the probabilities of the users being scheduled and entering in next state are denoted by P_2 and

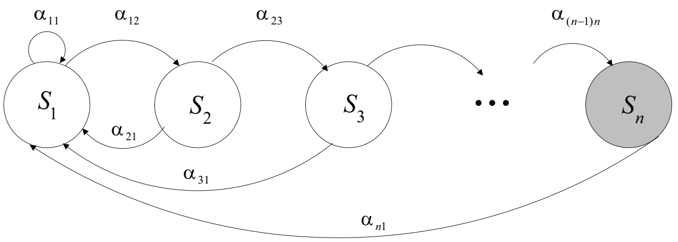

Fig. 1. State diagram for the transition states of a single user for DDOS. Due to constant arrival rate, user moves into next state if not scheduled

---

$\bar{P}_2$ respectively and given by:

$$P_2 = P(f > \kappa_2)\bar{P}_1 \tag{4}$$

$$\bar{P}_2 = P(f \leq \kappa_2)\bar{P}_1 \tag{5}$$

Similarly, for the buffer state i, the probabilities of users being scheduled and entering in next state are given by,

$$P_i = P(f > \kappa_i)\prod_{j=1}^{i-1}\bar{P}_j \tag{6}$$

$$\bar{P}_i = P(f \leq \kappa_i)\prod_{j=1}^{i-1}\bar{P}_j \tag{7}$$

Buffer state n is the last state where users are scheduled in deadline mode. All the users entering in this state are scheduled with probability one and the probability of a user being scheduled is given by:

$$P_n = \prod_{j=1}^{n-1}\bar{P}_j \tag{8}$$

In the asymptotic case when K approaches to infinity, these probabilities are equal to the fraction of the users in each buffer state and we can formulate the following optimization problem. We want to compute the vector $\vec{\kappa}$, the buffer state dependent opportunistic threshold, which minimizes the system sum energy while fulfilling the deadline requirements for all the users. This parameter is dependent upon the channel statistics. Suppose the buffer can be in one of the n states where each state i represents the buffer occupancy of the user. $\vec{\Upsilon}$ represents the vector of possible buffer occupancy states for K users in one scheduling operation and τ_k denotes the possible buffer occupancy state for a user k from a set of n possible buffer occupancy states.

$$\vec{\Upsilon} = (\tau_1, \tau_2 ..., \tau_K)^T. \tag{9}$$

We want to compute $\vec{\Upsilon}_{opt}$, the optimal vector of buffer states for all the users, that minimizes the cost function,

$$C = \sum_K E(\tau_k). \tag{10}$$

Energy is computed using Eq. (1). Energy required for transmitting the users depends on user buffer state and buffer state is a function of opportunistic threshold κ_i. Let S be the set of all possible buffer states. The optimization problem is to find opportunistic threshold such that overall system energy is minimized.

$$\vec{\kappa}_{opt} = \arg\min_{\kappa_i} \mathrm{E}\Big[\sum_S \sum_{k \epsilon S_i} E(\kappa_i)\Big] \tag{11}$$

We compute the solution of Eq. (11) for small values of spectral efficiency and large number of users because results are close to asymptotic results in this region [11]. We optimize, κ_i regardless of the data in the buffer state i by considering the users being scheduled in opportunistic mode and deadline mode simultaneously. Using Eq. (8), Eq. (11) can be written as,

$$\vec{\kappa}_{opt} = \arg\min_{\kappa_i} \mathrm{E}\Big[\sum_S \sum_{i=1}^{n-1} E(\kappa_i)P_i + E(\kappa_n)\prod_{i=1}^{n-1}\bar{P}_i\Big] \tag{12}$$

where P_r, κ_r and κ_n is the probability of the user being scheduled in state r, opportunistic threshold in state r and deadline threshold in the last deadline buffer state respectively. For $n > 2$, Eq. (12) can be written as,

$$\vec{\kappa}_{opt} = \arg\min_{\kappa_i} \sum_S \prod_{i=1}^{n-2}\bar{P}_i\big[\mathrm{E}\big(E(\kappa_{n-1})P_{n-1} + E(\kappa_n)\bar{P}_{n-1}\big)\big] \tag{13}$$

Through simulations, the solution of this equation is computed recursively as the terms outside are constant. The optimal value of threshold is computed for the base case of $n = 2$ when first scheduling operation is performed in the opportunistic mode and second one in deadline mode. For $n = 3$, $E(\kappa_n)$ is replaced with the optimized total energy for $n = 2$. The already computed threshold value κ_2 is used as a threshold between S_2 and S_3 now and the optimization process is repeated for computing the threshold value κ_1 between S_1 and S_2. The base case solution is used to compute threshold values $\kappa_{\{2,3,4...\}}$ for $\tau^{max} = \{3, 4, 5...\}$ recursively. It has been numerically verified that opportunistic thresholds optimized for the lower state space remains optimized for the higher state space though the corresponding rate allocation is not exactly equal for the same states.

Table I shows the recursively computed threshold values for each backlog state for different values of maximum buffer length. The optimal threshold decreases with an increase in backlog and the probability of the transmission of data increases. When maximum buffer length is reached, this threshold is set to zero requiring the user to transmit data in

TABLE I

RECURSIVE THRESHOLD COMPUTATION

τ^{max}	κ_1	κ_2	κ_3	$\kappa_{Deadline}$
2	**2.2**	NA	NA	0
3	**2.6**	2.2	NA	0
4	**3**	2.6	2.2	0

TABLE II

COMPARISON OF THE SCHEDULING SCHEMES

Scheme	Opportunistic Mode	Deadline Mode	Deadline Rate Allocation
OSPC	κ	NA	NA
DDOS	κ_i	0	Full Buffer
MDDOS	κ_i	κ_{n-1}	Full Buffer if $f_k > \kappa_{n-1}$ $\frac{\Gamma}{K}$ if $f_k \leq \kappa_{n-1}$

the deadline mode. By using the parameter maximum buffer length τ^{max}, we can control the energy-delay tradeoff. A higher value of τ^{max} means that the application is highly delay tolerant and this scheme will provide the energy solution close to the solution provided by the schemes which empty the buffer on scheduling without providing maximum delay guarantees.

A. Modified Deadline Dependent Opportunistic Scheduling (MDDOS)

Instead of emptying the buffer on reaching maximum buffer length, a more sophisticated approach would be to transmit only the data that has reached the deadline and this scheme is referred as Modified Deadline Dependent Opportunistic Scheduling (MDDOS). The queue is emptied at the deadline only if short term fading gain f_k of the user is greater than the opportunistic threshold in the time slot before the deadline i.e. κ_{n-1} for the case of $\tau^{max} = n$. This scheme schedules the user opportunistically even in deadline state and transmits *the oldest data unit* $\frac{\Gamma}{K}$ if deadline is reached but $f_k < \kappa_{n-1}$, resulting in further energy saving. The comparison of the characteristics of OSPC, DDOS and MDDOS has been summarized in table II.

B. Implementation Consideration

Two scheduling schemes proposed in this work solve the optimization problem offline by using the channel statistics. The offline optimization task is performed by a central scheduler but the online scheduling decisions of the users are local. The threshold vector $\vec{\kappa}$ is optimal for a given set of channel statistics and can be used by the network nodes which have similar fading statistics. The threshold $\vec{\kappa}$ is transmitted to all the sensor nodes in the network. No future channel state information is required at the nodes. The nodes perform simple comparison of the instantaneous short term fading with the state dependent threshold and decide to transmit or wait for the next time slot. The users scheduled for the simultaneous transmission are provided with the required rate and power information and they transmit data without interfering with each other. The complexity at the sensor node is minimum and very small energy is required for making scheduling decisions. This feature makes DDOS and MDDOS ideal for sensor nodes.

IV. NUMERICAL RESULTS

We have considered a multi-access channel with M bands and it is assumed that fading on these channels is statically independent. It implies that every user senses M channels instead of a single channel and selects its best channel as a candidate channel for the transmission scheduling. Therefore, the scheduler schedules a specific user in the opportunistic mode if its *best* channel is greater than the opportunistic scheduling threshold. This is the optimal multi-band allocation for the asymptotic case [10]. We consider a system where users are placed uniformly at random in a cell except for a forbidden region around the access point of radius $\delta = 0.01$. The path loss is exponential with exponent 2. All users experience fast fading with exponential distribution with mean one on each of the M channels. The details of path loss model can be found in [10]. We consider $M = 10$ in our numerical results. The spectral efficiency values used in the results are divided by M to get spectral efficiency/channel. All the numerical results have been obtained by simulating a multiuser environment where 5000 users have simultaneous access to the 10 channels. For each operation, 100 path loss environments have been simulated to remove the effect of variation in path loss on the system energy. For a single path loss environment, 200 scheduling operations have been performed for the convergence of the sum energy of the system. We consider the constant arrivals for all the users.

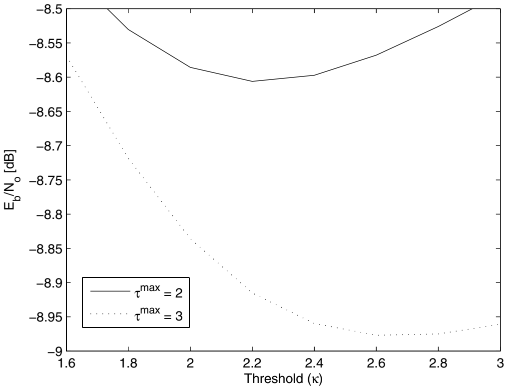

Fig. 2. The figure shows the recursive computation of balance point for $\tau^{max} = 2$ and $\tau^{max} = 3$.

In Fig. 2 energy is plotted against different values of threshold for a fixed spectral efficiency. The aim is to find the threshold value for scheduling the users that correspond to minimum sum energy for the system. We set the value of spectral efficiency per channel equal to 0.5 and the minimum value of the threshold κ_1 is found to be 2.2 for the case when the users with backlog one perform opportunistic scheduling and the users with backlog 2 are in deadline mode. For the case of $\tau^{max} = 3$, the dotted line is plotted by using $\kappa_2 = 2.2$ (found in previous case) as threshold for the buffer state 2 and optimizing κ_1 for the buffer state 1. The Fig. 3 shows the comparison of system energy for different values of maximum

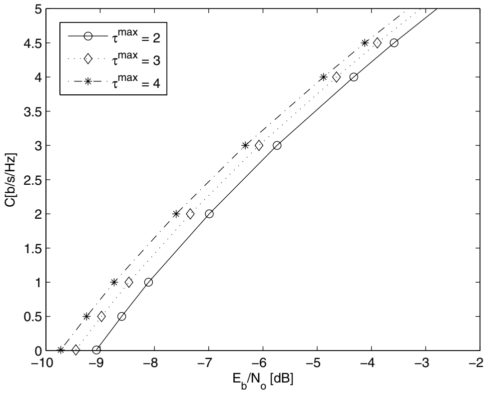

Fig. 3. Comparison of DDOS scheme for different values of τ^{max}

buffer length. It is observed that an increase in maximum buffer length constraint results in an energy efficient system.

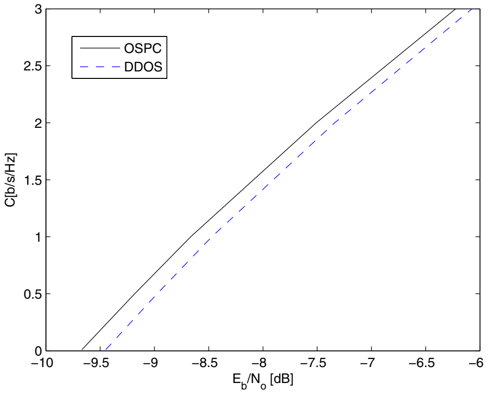

Fig. 4. Comparison of OSPC and DDOS for $\tau^{max} = 3$ and same average delay

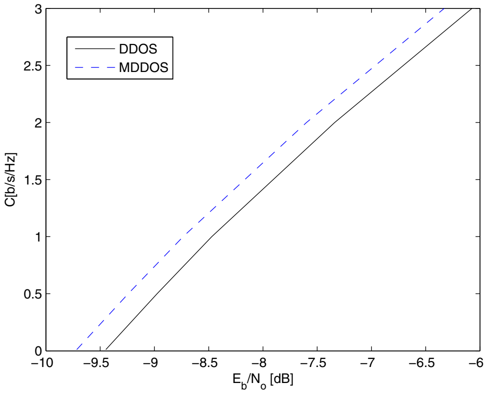

Fig. 5. Energy efficiency of DDOS and MDDOS for $\tau^{max} = 3$

Fig. 4 demonstrates the comparison of OSPC with DDOS for the maximum delay $\tau^{max} = 3$. For a fair comparison, same threshold value is set for OSPC scheduling scheme which guarantees long term average delay for all the users but does not provide any maximum delay guarantee. DDOS provide the same average delay in this setting but provides the additional maximum delay guarantee. A small loss in system energy is observed for DDOS by providing the additional maximum delay guarantee to the users. Fig. 5 shows the comparison of energy efficiency between DDOS and MDDOS schemes for $\tau^{max} = 3$. As described in Sec (III-A), MDDOS behaves similarly in the opportunistic mode but operation is modified in deadline mode. This modification results in further improvement in energy efficiency while fulfilling the same maximum tolerable delay constraint as shown in Fig. 5.

V. CONCLUSION

In this work, a multi-user scheduling scheme is presented which specifically suits to wireless sensor networks due to their deadline delay constraints. The sensor nodes are scheduled opportunistically and coded by superposition coding to save the energy as long as the buffer occupancy of the user is less than the deadline. A simple scheduler is presented that uses the channel distribution to optimize the transmission threshold for an energy efficient solution and performs online scheduling operation. The main contribution of the work is the proposal of opportunistic scheduling scheme with the hard deadline constraints. Maximum tolerable delay is proposed as a system parameter that can be used by the designers to control the tradeoff between maximum delay in data transmission and the energy efficiency of the system. The proposed scheduling schemes provide the maximum delay guarantee in addition to average system delay guarantee at the cost of marginal additional energy.

REFERENCES

[1] R. Knopp and P. Humblet, "Information capacity and power control in single cell multiuser communications," in *IEEE, Int. Computer conf, Seattle, WA*, June 1995.

[2] P. Viswanath, D. N. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inform. Theory*, vol. 46, no. 6, pp. 1277–1294, June 2002.

[3] R. A. Berry and R. G. Gallager, "Communication over fading channels with delay constraints," *IEEE Trans. Inform. Theory*, vol. 48, no. 5, pp. 1135–1149, May 2002.

[4] A. Fu, E. Modiano, and J. Tsitstiklis, "Optimal energy allocation for delay constraint data transmission over a time varrying channel," in *IEEE Infocom*, 2003.

[5] T. P. Coleman and M. Medard, "A distributed scheme for achieving energy-delay tradeoffs with multiple service classes over a dynamically varying channel," *IEEE journal on selected areas in communications*, vol. 22, no. 5, pp. 929–941, june 2004.

[6] W. Chan, M. J. Neely, and U. Mitra, "Energy efficient scheduling with individual packet delay constraints: offline and online results," in *IEEE Infocom*, June 2007.

[7] M. J. Neely, "Optimal energy and delay tradeoffs for multiuser wireless downlinks," *IEEE Trans. Inform. Theory*, vol. 53, no. 9, pp. 3095–3113, September 2007.

[8] E. U. Biyikoglu and A. E. Gamle, "On adaptive transmission for energy efficeincy in wireless data networks," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3081–3094, December 2004.

[9] V. Srivastava and M. Motani, "Cross layer design: A survey and the road ahead," *IEEE communication magazine*, pp. 112–119, December 2005.

[10] G. Caire, R. Müller, and R. Knopp, "Hard fairness versus proportional fairness in wireless communications: The single-cell case," *IEEE Trans. Inform. Theory*, vol. 53, no. 4, pp. 1366–1385, April 2007.

[11] P. Chaporkar, K. Kansanen, and R. R. Müller, "Channel and multiuser diversites in wireless systems: Delay-energy tradeoff," in *RAWNET, Limassal,Cyprus*, April 2007.