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Energy-Optimal Wireless Transmission Schemes

When it comes to optimal transmission strategies for wireless devices in a single or multiuser environment, the worldview many of us are familiar with can be summarized: given a particular transmission scheme, find the minimum average power (or optimal power and bit-rate) required to transmit at a given probability-of-bit-error (P_e). Here, three papers from a slightly different culture are presented, which try to solve for a similar goal, minimum average power (or energy), and find results that are familiar, but using a higher level of system control.

Three aspects of a wireless communications scheme are considered. The first paper considers autonomous transmitters who must choose their transmit power levels given information on the nature of the channel and the level of interference at the receiver. The second paper analyzes simple protocols for correcting packet errors. Finally, the third paper considers basic multiple access protocols from an energy-optimal standpoint.

Mobile Power Management

First, in (1), the authors find the optimal level of transmit power given a set of quality-of-service constraints (in this case, minimum rate), the functional form of P_e as some function of signal to interference ratio (which might take fading into account), and the level of interference in the channel. It is assumed that the interference is independent of the transmit power of the transmitter, and that an infinite stream of data is waiting to be transferred. An implicit assumption is made that the transmitter somehow is given information regarding the level of interference at the receiver. For a transmission scheme in which $P_e = 1 / (\gamma + 1)$ –similar to NC-FSK in fading – the optimal transmitter power is derived:

$$p(i) = \begin{cases} \sqrt{3Iri} - i, & \text{if} \quad r \le \frac{1}{3} \quad \text{and} \quad i \le 3Ir \\ 0 & \text{if} \quad r \le \frac{1}{3} \quad \text{and} \quad i > 3Ir \\ \frac{2\sqrt{Ii}}{3(1-r)}, & \text{if} \quad r > \frac{1}{3} \end{cases}$$

where *r* is the required data rate and *I* is the maximum interference level. It is pointed out that this result is independent of the distribution of the interference process (a somewhat interesting point that makes sense as a result of the implicit assumption made above; if the state of the

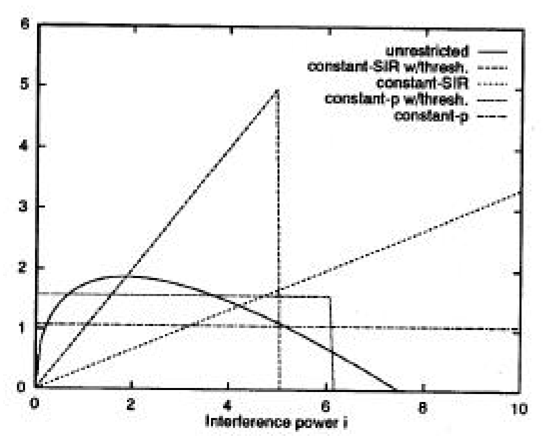

Figure 1: Transmitter power using various forms of power management. ((1), fig. 4)

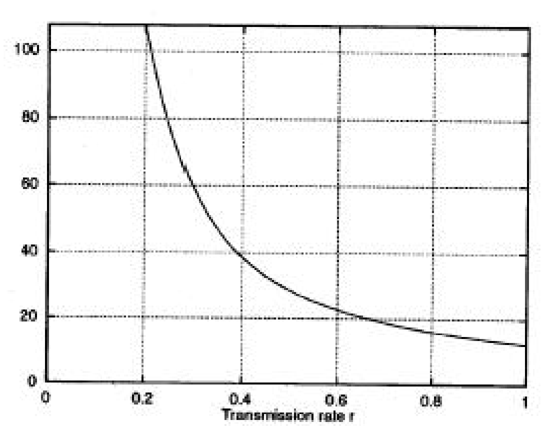

Figure 2: Percent increase in useful battery life using unrestricted power management versus best-case constant-SIR operation. ((1), fig. 3)

channel was known, but with some delay, it would seem that the distribution of the interference process would be important). Because of the relative complexity of the optimal result, a comparison is made to two simpler power control functions (each with an optional threshold level for transmission), constant-power and "constant-SIR" (e.g., transmit power linear with interference level). Figure 1 shows the variation of transmit power for the different methods. The adjacent Figure 2 shows that as the user's desired rate increases, the increased efficiency due to optimal power control versus constant-SIR-with-threshold decreases.

Before moving on, it is educational to pause to consider the form of the optimal power control function. Notice that (for rates below a certain level), there is a maximum interference power above which transmission is simply not attempted. This result will be very familiar to readers of the typical literatures, in which a similar concept is referred to as the "cutoff" level.

The second half of the paper deals with the case in which there are multiple users each following a power control algorithm, and thus creating a situation in which the interference level is directly related to the power control algorithm. A dynamic power control algorithm is presented that essentially modifies the optimal power control result to predict the relative level of interference in the channel. The performance of this algorithm is simulated given a model which assumes that bits arrive at each user's transmitter with probability *a*, and that each user experiences as interference the sum of the other user's transmit powers and additive uniform noise. The resulting performance in terms of average power and average delay is depicted in a series of plots, one of which is replicated in Figure 3.

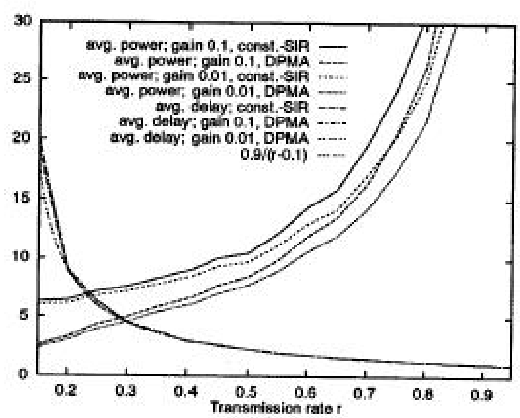

Figure 3: Average power and delay for various DPMA schemes compared with constant-SIR for 5 users with a = 0.1. ((1), fig. 11)

Energy-Constrained Error Control

Moving to a slightly higher level analysis, in (2), the energy consumption of a classic automatic repeat request error-correcting protocol (ARQ) is compared with a more novel protocol that takes the memory of a wireless fading channel into account. The metric used for comparison (described by the authors as "new") is energy efficiency, or the ratio of the total amount of data transferred to the amount of energy consumed. The classic protocol, "Go-Back-N" (GBN), involves the receiver negative-acknowledging every packet following an errant one until the transmitter has successfully retransmitted the errant packet. In the alternative protocol proposed in the paper, "Probing" protocol, the transmitter has two modes, one normal, in which packets are transmitted successively, and a second, in which simple (and thus presumably requiring less energy than normal) "probe" packets are transmitted periodically, but at a lower rate than necessary. The transmitter switches from the normal to the probing mode when it detects a transmission error (i.e., that the channel may be becoming poorer), and then switches back when it detects that the receiver has been able to receive a probe packet. This algorithm highlights one of the uniting principles of these three papers, that wireless fading channels are often well modeled as having memory.

A basic Markov channel model is presented, as are the results of simulations based on it. Figures 4 and 5 show the energy efficiency of the GBN protocol and that of the probing protocol. The probing protocol clearly outperforms the GBN in a slow fading environment (in which the assumption of channel memory is appropriate), but actually performs worse in a fast fading

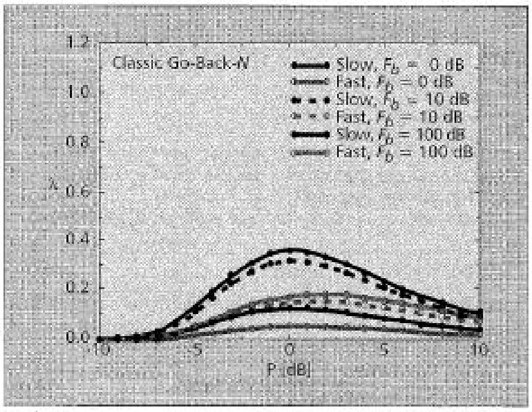

Figure 4: Energy efficiency vs. normalized output power for GBN protocol with slow ($f_DT = 0.02$) and fast ($f_DT=1$) Rayleigh fading. ((2), fig. 1)

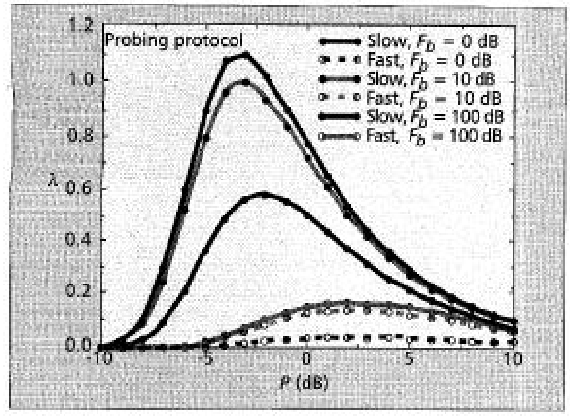

Figure 5: Energy efficiency vs. normalized output power for probing protocol with slow ($f_DT = 0.02$) and fast ($f_DT=1$) Rayleigh fading. ((2), fig. 2)

environment. This makes intuitive sense: in fast fading, the probability of a packet error becomes less predictable, and time spent transmitting non-data packets may forgo good channel states. It is noted that the assumption that probe packets are more energy efficient than regular ones is critical to these results.

Energy Consumption Performance of Access Protocols

Finally, in (3), the energy consumption of three types of wireless access control protocols is compared using the same metric as developed in the previous work. The same Markovian channel model is also used. The "basic" of the three protocols "can be viewed as a hybrid protocol employing the slotted ALOHA and reservation concepts." To summarize, header packets are transmitted on a contention basis, and then the receiver reserves time for the rest of the data from the transmitter whose header is successfully received. The two modifications of this protocol are presented. In the "error detect" protocol, if the receiver detects an errant packet, it orders the transmitter to stop transmitting, allowing for another transmitter with a potentially better channel state to try to use the rest of the time slot. In the third, or "retransmission protocol, if an error is detected, rather than having the link cancelled (as in the error detect protocol) or simply passing the error on to the next higher networking level (as in the basic protocol), the receiver will request the retransmission of errant packets.

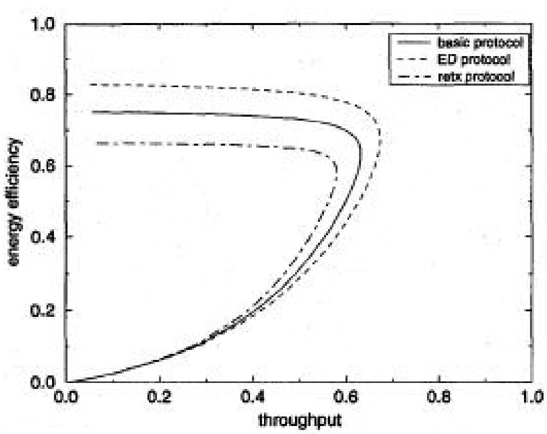

Figure 6: Energy efficiency vs. throughput for various protocols in slow fading, i.e., $f_DT = 0.02$, N = 10. ((3), fig. 1)

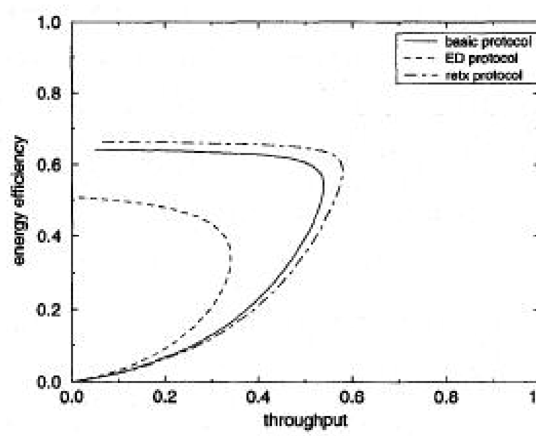

Figure 7: Energy efficiency vs. throughput for various protocols in fast fading, i.e., $f_DT = 0.64$, N = 10. ((3), fig. 2)

The results shown in Figures 6 and 7 are somewhat familiar. When fading is slow (as in Figure 6), the error detection protocol, which is similar to transmitting up to a threshold interference level, is optimal. When fading is faster (and thus becomes less correlated in time), the optimal approach becomes a retransmission scheme. Note that moving clockwise along the curves represents increasing the rate at which data arrives at the transmitter from zero. Thus, the optimal point for operating is the "knee" of the curves.

Conclusion

These three papers repeat what is a familiar result, that the performance of a wireless system can, in general, often be improved by not transmitting in channel states that are particularly poor. The different authors arrive at this same conclusion by considering several different mechanisms, however: ranging from simple autonomous transmission decisions to more complicated protocol design.

An interesting point of these analyses deals with packet errors. The "typical" literature seems to assume that some higher-level system can process data with somewhat low bit-error rates to recover an arbitrarily low BER. From the latter two papers, however, it seems that the common error-recovery system is often the retransmission of an entire high-level data packet. Thus, their results are useful, in the sense that these schemes will clearly become more efficient as they consider the effect of memory in a wireless channel (also reference (4), in which various forms of the TCP protocol is analyzed in a similar method).

There are several aspects of the results that merit further thought. First, as physical-layer designers, we do well to consider how the higher level system functions impact overall performance. Second, another commonality of the three papers is that they assume perfect feedback information from the receiver to the transmitter. Because this is a clearly impossible assumption, it would be interesting to know how relaxing it would affect the results, especially those which depend on estimation of the channel state transition model. Finally, perhaps its useful to try to remain aware of work done on wireless networks on many levels.

Bibliography

(1) J. M. Rulnick and N. Bambos, "Mobile Power Management for Maximum Battery Life in Wireless Communication Networks," *Proc. IEEE INFOCOM '96*, 1996, vol. 2, pp. 443-450.
(2) M. Zorzi and R. Rao, "Energy-Constrained Error Control for Wireless Channels," *IEEE Personal Communications*, Dec. 1997, pp. 27-33.
(3) A. Chockalingham and M. Zorzi, "Energy Consumption Performance of a Class of Access Protocols for Mobile Data Networks," *Proc. IEEE Vehicular Technology Conference*, 1998, vol. 2, pp. 820-824.
(4) M. Zorzi and R. Rao, "Is TCP Energy Efficient?" *Proc. IEEE International Workshop on Mobile Multimedia Communications*, 1999, pp. 198-201.