Exploiting Multiuser Diversity in Wireless ALOHA Networks

Xiangping Qin, Randall Berry

Dept. of Electrical and Computer Engineering
Northwestern University
2145 Sheridan Rd., Evanston IL 60208
Email: sandra@ece.nwu.edu, rberry@ece.nwu.edu

In wireless networks, diversity techniques are widely used to compensate for the unstable environment. Multiuser diversity has recently received attention in the literature. The idea of multiuser diversity has its roots in [1], where a centralized power control scheme for maximizing the information theoretic capacity of the uplink of a single cell is studied. The optimal strategy is shown to be to transmit to the user with the best channel at any given time. In this work we also consider a group of users accessing the uplink of a single cell. However we focus on the case where no centralized scheduler is available; specifically we assume each user has knowledge of its own fading level, but no knowledge of the fading levels of the other users in the cell. This precludes an approach as in [1], for each user will not be able to tell at which times its channel gain is the best. We consider a variation of a slotted ALOHA random access technique in which a user's transmission probability in a slot is a function of the user's channel gain. For a simple model of such a system, we show that users can still take advantage of multi-user diversity to improve the overall system capacity.

Consider a model of a slotted ALOHA network with n users. Assume a back-logged system where all n users always have packets to send and transmit independently in each slot with probability p. For such a system, the maximum total throughput, s^*, is given by $\left(1-\frac{1}{n}\right)^{n-1}$, this occurs when $p^*=\frac{1}{n}$. We consider a variation of the above system where each user is transmitting over a channel with flat Rayleigh fading. Specifically, the channel gains of all the users in each slot are independent and identically distributed random variables, with density $f_H(h)=\frac{1}{h_0}e^{-\frac{h}{h_0}}$, where $h_0=\mathbb{E}H$. Suppose that users have perfect channel state information and only transmit when the channel gain is above a threshold H_0. When the threshold, H_0, is chosen so that $p^*=\frac{1}{n}$, we have $H_0=h_0\ln n$. Assume that when a user transmits, it always transmits at a fixed rate and requires a received power of P_r to reliably transmit at this rate, *i.e.* the user "inverts the channel". With these assumptions, the long-term average power, $\bar{P}$, used by a user is given by

$$\bar{P}=\int_{H_0}^{\infty}\frac{1}{h_0}e^{-\frac{h}{h_0}}\frac{P_r}{h}\,dh. \tag{1}$$

As the number of users in the system increases, the threshold H_0 will increase. Thus if each user has an average power constraint of $\bar{P}$, then from (1) the maximum received power per slot P_r can increase. This in turn will enable users to transmit at a higher rate. Assume a user's transmission rate, R as a function of P_r is given by the Shannon capacity of the channel, i.e., $R=W\log(1+P_r/N_oW)$. With this assumption and using (1) the maximum throughput of the system, s^*, in bits/second is given by

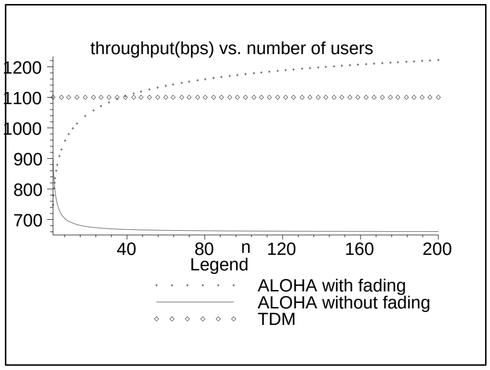

Figure 1: Comparison of throughput versus number of users with peak power constraint ($P_m =$ 5W, $N_0W = 1$, $W = 1000$ and $h_0 = 1$).

$$s^*(n) = W\left(1 - \frac{1}{n}\right)^{n-1} \log\left(1 + \frac{\overline{P}h_0}{N_oW\int_{h_0 ln(n)}^{\infty} e^{-\frac{h}{h_0}}\frac{1}{h}\,dh}\right) \tag{2}$$

This quantity is increasing with n and can be shown to be growing at rate $\Theta(\log(\log n) + \log n)$. There are two factors behind this growth. One is that as more users are added to the system the total average power available increases, the $\log n$ term above can be attributed to this. The other factor is the increase in multiuser diversity with n; the $\log(\log n)$ term can be identified with this effect. In the above system, the peak power each user transmits can be shown to be increasing linearly with n. Suppose each user also has a peak power constraint of P_m. Under a peak power constraint, the throughput can still be shown to be increasing n, however only at rate $\Theta(\log(\log n))$.

Figure 1 shows a comparison of the total throughput as a function of the number of users for three different cases, under a peak power constraint. The case labeled "ALOHA with fading" is the system above. The case "ALOHA without fading" stands for a slotted ALOHA system where there is no fading and each user's channel gain has a constant value of h_0. The total throughput for this case decreases with n and approaches a constant value of $\frac{W}{e}\log\left(1 + \frac{P_m h_0}{N_o W}\right)$ as $n \to \infty$. Clearly for large n the throughput in the non-faded case will be far below the throughput that can be attained when fading is present. Similar comparisons can be shown for a ALOHA system with fading where users do not base their transmissions on the channel state.

Returning to the case where the channel exhibits fading, assume each user is assigned a time slot in a TDM frame. Once again assume that users transmit whenever the channel gain is larger than some value h_{min} and when a user does transmit, it uses a constant rate R. We assume the user can choose h_{min} subject to the peak power constraint to maximize the average throughput. In this case the threshold, h_{min}, will not depend on the number of users and the overall throughput of the system will also not depend on the number of users. The throughput for such a system is shown in Fig. 1. Notice, for small values of n, this approach has a higher throughput than the ALOHA system with transmission probabilities based on the channel gains. However as n grows, the ALOHA approach achieves higher throughputs, despite the fact that collisions occur.

References

[1] R. Knopp, P. Humblet, "Information capacity and power control in single-cell multiuser communications" *Proc. of ICC '95* , vol. 1, pp. 331 -335, 1995.