

abstract

Diversity in general speech simply means 'variety.' However, in this context, it refers to the technique of creating several independent signal paths between the transmitter and the receiver. Multi-user Diversity is a form of diversity inherited from wireless networks. Its benefits are exploited by tracking each user's channel quality and transmitting to users only when their channel quality is high. In environments with little or no fading, we propose to use multiple transmitting antennas at the base-station to induce large and fast channel fluctuations, so that Multi-user Diversity can still be exploited. This scheme is known as Opportunistic Beamforming and can be achieved when there are a sufficient number of users on the wireless network.

Multiuser diversity and opportunistic beamforming in wireless networks

FARZAD H. ESKAFI

A fundamental characteristic of a wireless network is the fading of the channel due to atmospheric interference. A main cause of poor performance over wireless channels is relaying a single signal path with a high probability of signal fading between the transmitter and the receiver. Fading over wireless networks is a natural phenomenon. Of considerable importance to wireless system designers is not only the depth of the fade but also the duration. It has been observed in the past that deeper fades have shorter durations and occur less frequently. The distance between the transmitter and the receiver also contributes heavily to signal fading. A natural solution to exploit fading and im-

prove the system performance is to create multiple signal paths between the transmitter and the receiver such that each signal path fades independently. In such a scheme, reliable communication is possible as long as one or more of the paths are strong. The basic idea is that more paths make it more likely to have at least one strong path that is not affected by fading. This technique is called Diversity and it can dramatically improve the system performance over fading channels. "Normal" diversity is inherited from traditional wireless systems, which used the technique of individual point-to-point links between the base-station and the users. Recent results have elaborated on another form of diversity named Multi-user Diversity, which tracks the individual channel quality between the transmitter and the receiver and transmits to the receiver with the best channel quality. Multi-user Diversity gain arises from the fact that in a network with many independent users, there is likely to be a user with a very high channel quality. Using this technique, the overall system throughput is proven to be maximized [1].

Traditionally, channel fading has been a source of unreliable communication. In recent systems, fading is used as a source of randomization that can be exploited. By scheduling transmissions to users when the channel quality is high, we increase the Multi-user Diversity gain. However, the gain is limited in two ways: first, there might be a line-of-sight limitation and second, the user might be in an environment with little or no scattering. In such environments, Multi-user Diversity can not be exploited.

In an environment with little or no scattering, we propose to use multiple transmitting antennas at the base-station. Each antenna transmits the same signal with a different phase and magnitude. The phase and magnitude vary independently and can be changed in a controlled fashion. Channel fluctuation and scattering are caused by constructive and destructive interference from each antenna. The overall channel quality of each user is tracked and fed back to the base-station to provide the basis for future scheduling. In a system of many independent users, there is likely to be a user whose channel phase and magnitude matches the phase and magnitude of a transmitting antenna. The transmitting phase and magnitude is randomized and is transmitted to the user whose channel quality is close to the Beamforming configuration. The philosophy in this scheme is to transmit at a high rate when the channel quality is good and transmit at low or no rate when the channel quality is poor.

implementing a multi-user diversity system

As mentioned before, in traditional point-to-point links, fading is a source of unreliability that needs to be mitigated. In the case of Multi-user Diversity, fading is a source of randomization that causes large channel fluctuations over wireless networks. The larger the channel fluctuations, the higher the Multi-user Diversity gain. By looking at Figure

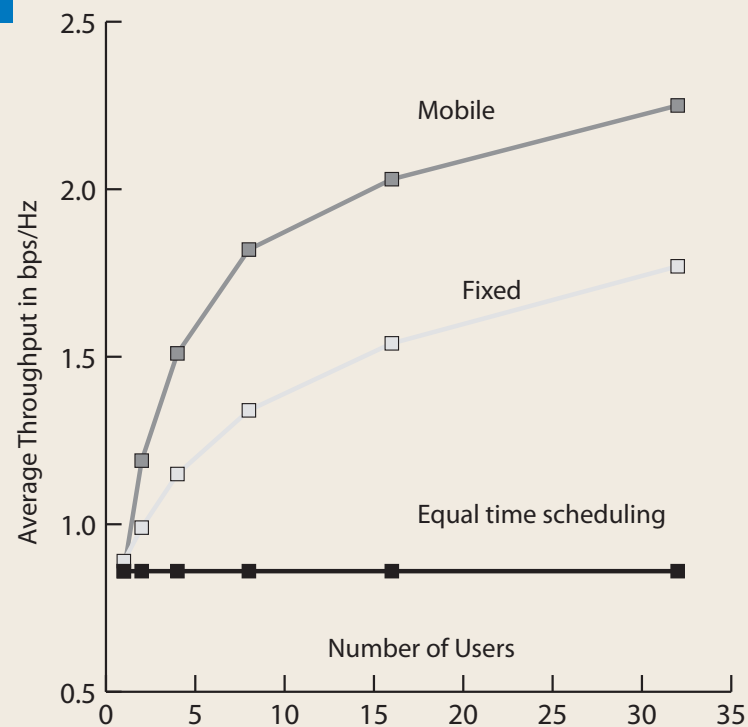


FIGURE 1. Multiuser Diversity gain in fixed vs. mobile environment. Shown in the Figure, as the number of users increase, Multiuser Diversity gain (Average Throughput) is increased, however, the gain is more dramatic when the users are mobile

1, we see that in Multi-user Diversity scheme, as the number of users increase, the average throughput increases as well, however, the increase is more dramatic in mobile environments than in fixed areas. To exploit the benefits of Multi-user Diversity, the system needs to satisfy the following two main requirements:

1. The base station needs to have access to the channel quality of each user. In other words, the user needs to track its own channel quality and feedback the information to the base-station.
2. The base station needs to schedule transmission appropriately among the users and adapt the transmission rate as a function of user's channel quality.

The above features have been implemented in various wireless systems such as 3G systems and IS-856 [1]. In practice, there are several problems that need to be addressed. The two main problems are:

fair scheduling. In implementing the idea of Multi-user Diversity, one is faced with two issues: fairness and delays. In an ideal situation, the strategy of communicating with the best user has the best result. In reality however, users are not all at an ideal position; some users are closer to

wireless

the base-station, some are mobile and some are stationary, some users are in rich scattering environments and some have no fluctuation at all.

slow, limited fluctuations. We have observed that we need channel fluctuation to harness the benefits of Multi-user Diversity. However, the channel fluctuations are limited in environments where there is a line-of-sight with little or no scattering. To resolve this issue, we induce channel fluctuation using multiple transmitting antennas at the base-station and implement the idea of Opportunistic Beamforming described in detail in the next section.

fair scheduling

A simple scheduling algorithm has been designed to specifically address the problems of fairness and delays over wireless networks while at the same time exploiting the idea of Multi-user Diversity. This work has been done in systems like IS-856 [1]. In this system, the channel quality feedback of user k at time n to the base-station is in terms of requested data rate: $R_k[n]$ this is the data rate that the user k can currently support. The scheduling algorithm back on the base-station keeps track of the average throughput of each user. At time n , the scheduling algorithm simply transmits to the user k with the largest

$$(EQ 1) \quad \frac{R_k[n]}{T_k[n]}$$

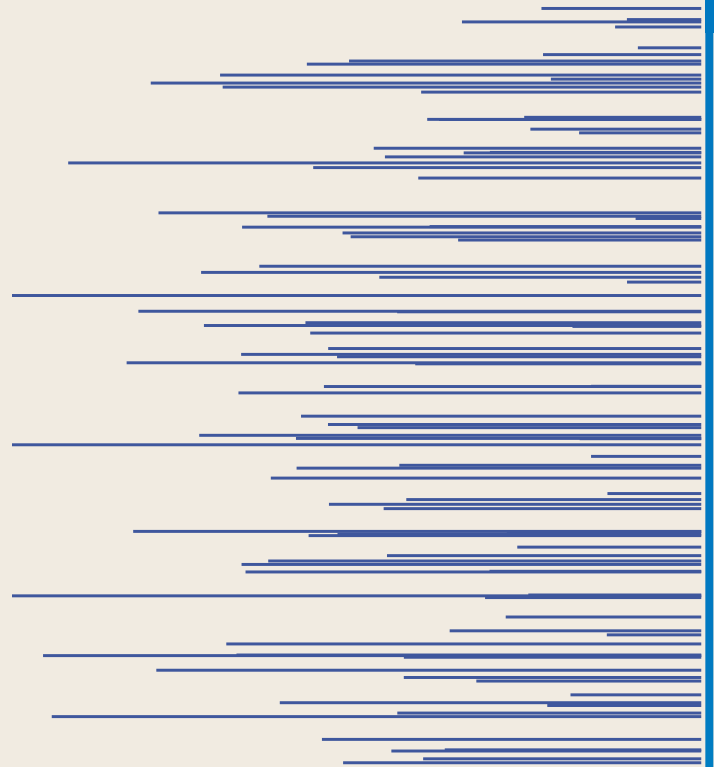
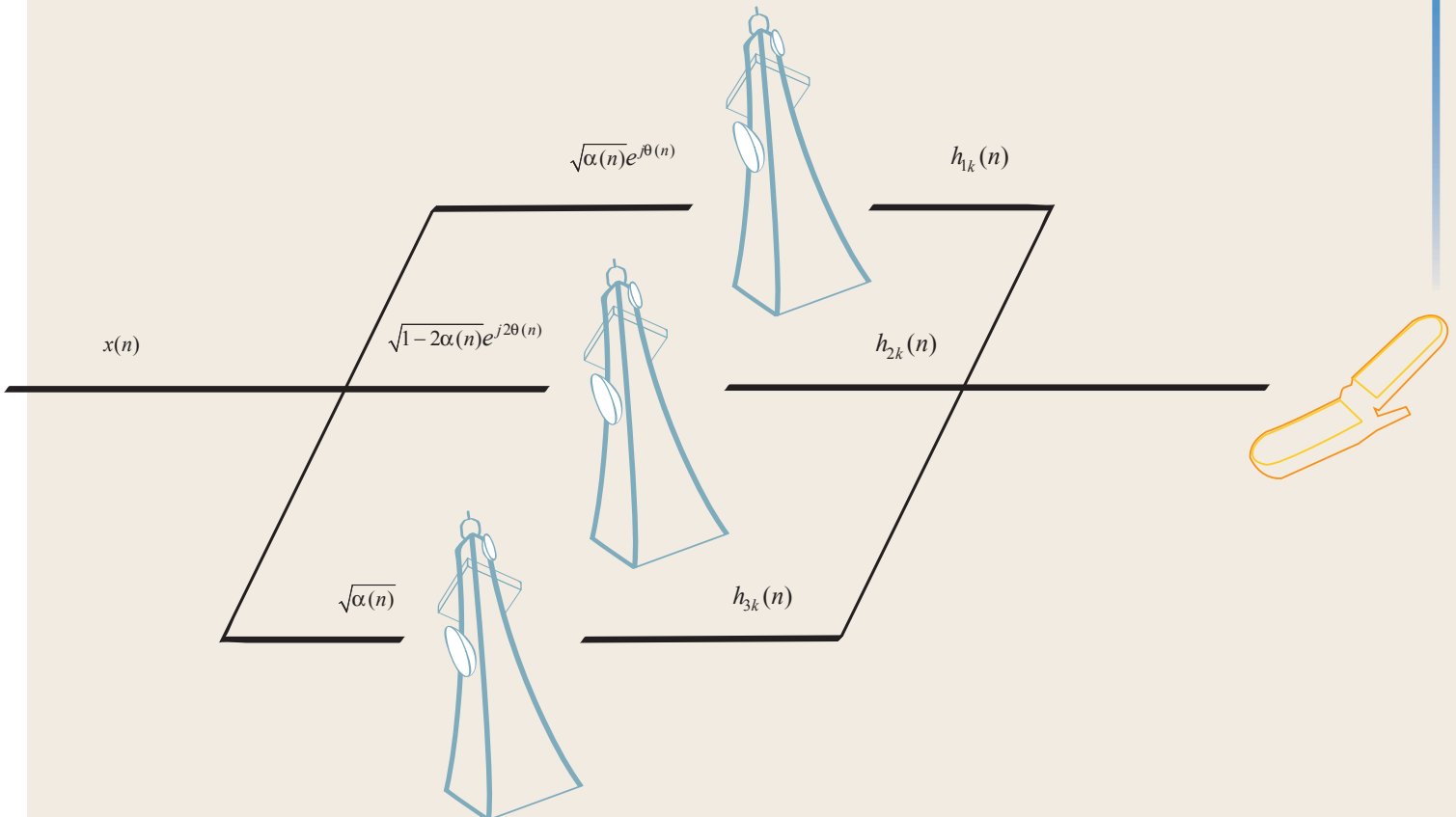


FIGURE 2. Throughput vs. Users

The same signal $x(n)$ is transmitted from three antennas with different phases $\theta(n)$ and powers $\alpha(n)$ to the user



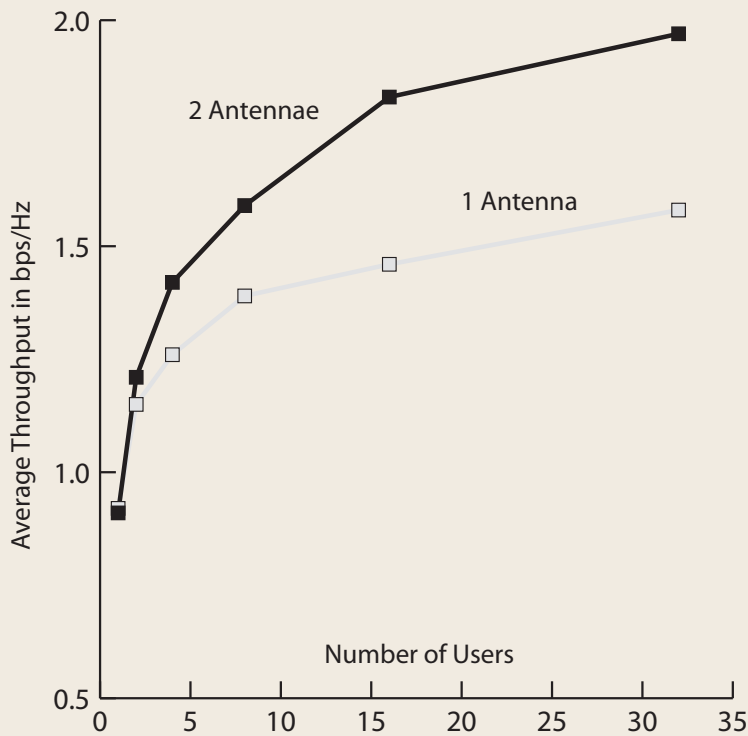


FIGURE 3. Total Throughput as a function of number of users. By looking at the two graphs, one would notice that using two antennas, the channel is fluctuated and the Multiuser Diversity gain (Average Throughput) is increased [2].

among all the present active users on the system. The average throughput is updated frequently. The scheduling algorithm always picks the user with the highest requested data rate. Thus, each user gets the transmitted signals only when its channel quality is high and the algorithm is perfectly fair over long term.

Always picking the user with the best requested data rate might sound unfair. In contrast, in the proposed algorithm, users compete not directly based on requested data rate, but after their requested data rate is normalized according to their own average throughput. For instance, User p has average throughput of 2 bits per second per Hertz (bps/Hz) and requests the data rate of 1 bps/Hz at time slot n. On the other hand, User q has the average throughput of 6 bps/Hz and requests the data rate of 2 bps/Hz at time slot n. Even though User q requested the highest data rate, the scheduler schedules transmission to User p, since by EQ. 1,

$$(EQ 2) \quad (\text{user } p) \frac{1}{2} > \frac{2}{6} (\text{user } q)$$

In other words, the scheduler schedules transmission to the user when its channel quality is high relative to its own average throughput.

The Multi-user Diversity is limited in environments with little or no scarcity. In such environments, a natural question comes to mind: Why not induce fluctuations to harness the benefits of Multi-user Diversity? Therefore, we use multiple transmitting antennas at the base-station to induce channel fluctuation; see Figure 2. Suppose we have N transmitting antennas at the base-station. Let y_k be the channel gain from antenna l to the user k at time n. At the same time n, $x(n)$ is transmitted from all the antennas except it is multiplied by $\sqrt{\alpha_l(n)}e^{j\theta_l(n)}$ at antenna l. The received signal at user k is

(EQ 3)

$$y_k(n) = \left(\sum_{l=1}^N \sqrt{\alpha_l(n)} e^{j\theta_l(n)} h_{lk}(n) \right) x(n) + z(n)$$

where $z(n)$ is the natural atmospheric noise. This denotes the power allocated to antenna l and the phase shift applied at each antenna to the transmitting signal. By varying from 0 to 1, it is possible to induce fluctuations in the channel even if there is no fluctuation in the overall channel. Each signal path from each antenna to the user, interfere with other different signal paths by a different antennas to the same user, thus, the interference induces channel fluctuation.

There is no need to measure the individual channel fluctuation from each antenna to the user k. In fact, user k is aware of the existence of multiple antennas. We only need a single signal pilot at the receiver to measure the overall channel quality as opposed to measuring each antenna gain.

We would like the channel fluctuation to be as fast as possible; however, there are practical limitations that must be taken into account. The fluctuation should be slow enough so that the system can reliably measure the overall channel quality, the channel as seen by the users does not change abruptly and a stable tracking loop is formed.

system analysis

It is important to discuss the number of users over the network. As can be seen in Figure 1, the more people using the system, the higher the average throughput. The more users on the wireless network, the higher the likelihood of finding a user with a high channel quality. Using By looking at Figure 3, we notice that more antennas lead to higher signal fluctuation, which in turn, leads to a larger signal strength gain. Thus, we would like to have as many antennas as possible at the base-station.

Note that to exploit Opportunistic Beamforming, the phase and power of each antenna must vary over time. To make this variation possible, each antenna needs to

the concept of Opportunistic Beamforming, we also discussed inducing artificial fading. In environments with no fading, we use multiple transmitting antennas at the base-station to induce fading in the channel due to constructive and destructive interferences of independent paths. By looking at Figure 3, we notice that more antennas lead to higher signal fluctuation, which in turn, leads to a larger signal strength gain. Thus, we would like to have as many antennas as possible at the base-station.

Note that to exploit Opportunistic Beamforming, the phase and power of each antenna must vary over time. To make this variation possible, each antenna needs to be equipped with an extra radio-frequency (RF) card and its own power amplifier. An important constraint on this variation is that it should be slow enough so that it can be recorded accurately and fed back to the base station.

The area covered by each base-station (incoming calls reach the base-station within this area), is called the cell; see Figure 4. In traditional wireless systems, each cell is zoned into smaller sub-cells to better allow the transmission of the signals from an antenna to individual users and to reduce the interference from other users in different cells. In the Opportunistic Beamforming scheme, the transmitting antennas at the base-station not only increase the channel fluctuation within the cell but also increase the amount of channel fluctuation in the adjacent cells. Hence, Opportunistic Beamforming has the dual benefits of increasing the Multi-user Diversity gain in a cell and in the adjacent cells.

Overall, Multi-user Diversity and Opportunistic Beamforming are proven to be very effective techniques for boosting the average performance for today's wireless networks.

conclusion

Traditionally, the major design technique in wireless systems revolved around making individual point-to-point connections between the base-station and the user. In such systems, channel fading was a source of uncertainty and needed to be minimized. In recent implementations, designers have shifted from the individual links between the users and the base-stations to a system with multiple users sharing the same resources using the technique of Multi-user Diversity. In such systems, fading causes channel fluctuations and the scheduler schedules transmissions to the user with the best channel quality.

Multi-user Diversity provides a very significant boost in the performance in wireless systems. The only major requirement is the tight feedback of channel quality (magnitude and phase) from the users to the base-station. In environments where there is little/no fading, we use multiple transmitting antennas at the base-station. We conclude that using the Opportunistic Beamforming tech-

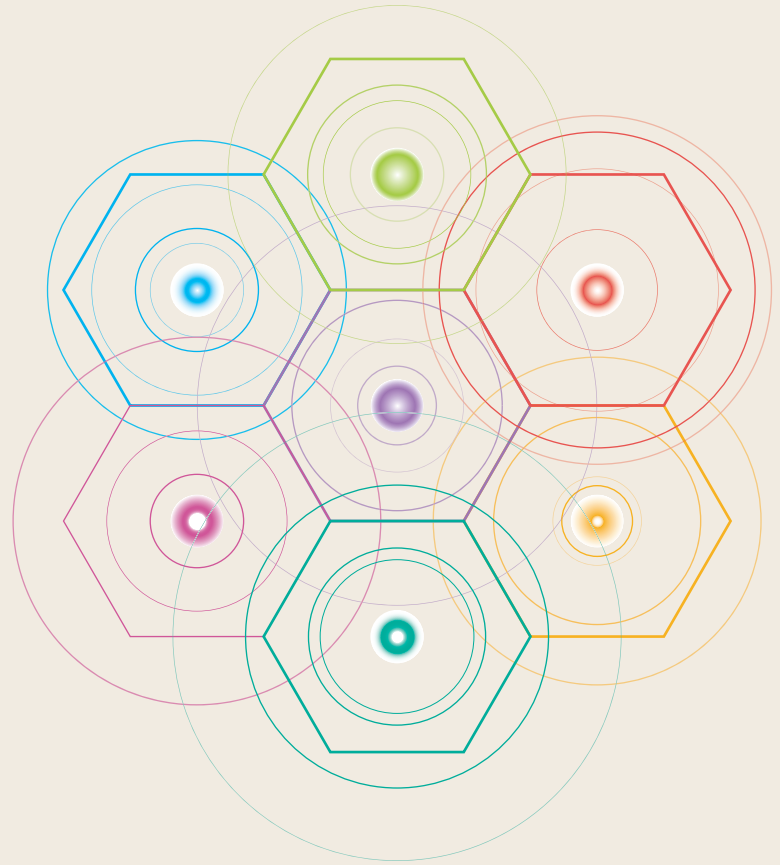


FIGURE 4. An overly simplified wireless cells, where each cell is hexagonal with a base-station at the center.

nique, there is no more need for expensive towers. Antennas could be placed at low altitude, where there is more channel fluctuation.

references

1. P. Viswanath, D. Tse, R. Laroia, "Opportunistic Beamforming Using Dumb Antennas," IEEE Transactions on Information Theory, VOL. 48. No. 6, JUNE 2002
2. D. Tse, P. Viswanath, Fundamentals of Wireless Communication, in preparation.