Physical Diversity and Virtual Diversity for Wireless Communication Networks-A Review

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Abstract. To meet the persistent increase in demand for higher data rate in wireless and mobile communication, adaptive modulation and coding (AMC) together with multiple input multiple output (MIMO) technologies have been standardized for beyond 3G, WiMAX, and other wireless networking technologies. Both AMC and MIMO are implemented at the physical layer, with increased complexity and size. Recently, several enabling technologies which can be implemented at link or network layers have been introduced. Such techniques include: Multi-User Diversity (MUD), Cooperative Diversity (CD), and Opportunistic Relaying (OR). They offer diversity and/or multiplexing gains similar to MIMO, without physical layer problems. This paper presents a summary of recent literature concerned with the performance and main applications of MUD, CD and OR.

Introduction

Wireless communication systems performance is limited by fading. Diversity techniques including: frequency, space, time, and polarization diversity have been used in wireless communication systems; fixed and mobile, to combat the effect of fading and improve coverage, capacity and reliability. In the last decade, spatial diversity with multiple antennas at both ends of the link, also known as Multiple-Input Multiple-Output (MIMO), has received large interest by the wireless communication community. MIMO and Space-Time Coding (STC) offer diversity and multiplexing gains at the expense of size and complexity. These limitations have promoted the need for diversity techniques which can be implemented at link or network layers, and hence, avoids the limiting constraints of physical diversity. Several techniques have been presented including: Multi-User Diversity (MUD), Cooperative Diversity (CD), and Opportunistic Relaying (OR). Such “Virtual Diversity” techniques provide similar diversity and multiplexing gain advantages to those offered by MIMO systems, without its limitations.

The next section summarizes the main diversity and gain results for MIMO systems. The following three sections present introduction and literature review of Cooperative Diversity, Multiuser Diversity, and Opportunistic Relaying, followed by a conclusion.

Diversity and Multiplexing Gains for MIMO

For a MIMO system with M transmit and N receive antennas, define K= min (M, N). At large Signal-to-Noise ratio S/N→∞, the optimum multiplexing gain *r* and optimum diversity gain *d* are given by, Zheng (2003):

$$R \sim r \log(\text{SNR}) \qquad r = 0, 1, \ldots K \tag{1}$$

$$P_e \sim (\text{SNR})^{-d} \tag{2}$$

Where R is the transmission rate in bps/Hz, P_e is the probability of bit-error over the i.i.d. Rayleigh flat-fading channels, r and d are the multiplexing gain and diversity gain, respectively. For the limiting cases we have:

$$r \rightarrow K \qquad \text{multiplexing only} \tag{3}$$

$$d \rightarrow M.N \qquad \text{diversity only} \tag{4}$$

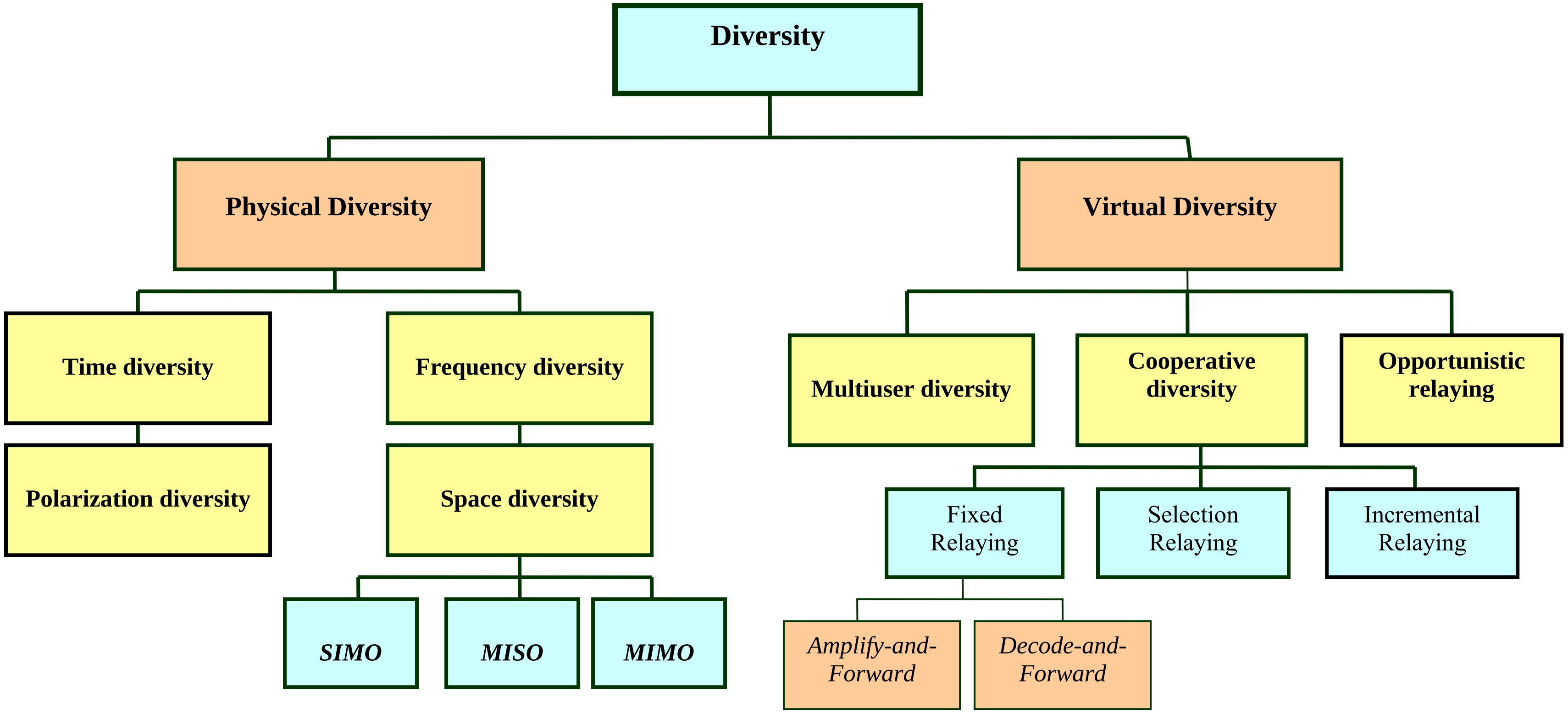

Fig. 1 Physical and Virtual Diversity for Wireless Communications

The optimal tradeoff *d(r)* is given by the piecewise linear function connecting the points (r,d), hence:

$$r = 0, 1, \ldots, K \quad \text{and} \tag{5}$$

$$d(r) = (K-r)^2 + (K-r)\,|M-N| \tag{6}$$

Fig. 1 presents physical and virtual diversity for wireless communications. The physical diversity is implemented at the physical layer and has been widely used for most of the wireless systems. Space diversity has received a remarkable interest and recently, multiple-input multiple-output (MIMO), i.e., systems that employ multiple antennas at both the transmitter and the receiver, have been shown to promise extraordinary spectral efficiencies. The capacities of these systems increase linearly with the minimum of the number of transmit and receive antennas Foschini (1998) and Telatar (1999) as shown in Eq. 1-2.

While Shannon capacity illustrates the potential of such transmission techniques, it does not give much insight into the design of practical space-time modulation schemes that fully exploit the presence of multiple antennas. The idea behind MIMO is that the signals on the transmit antennas at one end and the receive antennas at the other end are "combined" in such a way that the quality (bit-error rate) or the data rate (bits/sec) of the communication for each MIMO user will be improved. Such an advantage can be used to increase both the network's quality of service and the operator's revenues significantly, Gesbert (2003).

The diversity and multiplexing gains offered by MIMO in Eq. 1-6 are valid for Rayleigh fading channels and for uncorrelated antennas. Smaller gain values are predicted for Rician channels and/or correlated antennas. In addition, even for spaced antennas different paths might not be independent, in particular when considering shadowing and the gain might therefore be less than predicted.

Cooperative Diversity

In cooperative diversity several nodes, each with one antenna, form a kind of coalition to cooperatively act as a large transmit or receive array. When terminals cooperate as a transmit array, they first exchange messages and then cooperatively transmit those messages as a multi-antenna broadcast transmitter; similarly for receive cooperation. The channel therefore shares characteristics with the MIMO channel, such as diversity. In a cooperative diversity network, users cooperate to transmit each others' messages; to some extent nodes therefore collectively act as an antenna array and create a virtual or distributed multiple-input multiple-output (MIMO) system. Unlike MIMO systems, cooperative diversity relies on data transmission by several nodes. Each node acts as a *virtual antenna* and cooperatively transmits data to a particular destination. Since each node tends to be at different places, cooperative diversity benefits from the tendency to find multiple antennae with independent fading.

Cooperative diversity systems are presented in Hwang (2008), Barua (2008), Xu (2009), Gokturk (2008), Mahinthan (2009), and Le (2008). The first three papers deal with CD with OR. In Hwang (2008), Opportunistic relaying with cooperative diversity is introduced as a simple alternative protocol to the distributed space-time coded protocol while achieving the same diversity-multiplexing trade-off performance as a point-to-point multiple-input multiple-output scheme. Exact symbol error probability (SEP) of cooperative diversity with opportunistic amplify-and-forward (AF) relaying is presented in Barua (2008). The benefit of this opportunism to the SEP is assessed by comparing with maximal ratio combining of orthogonal multiple AF relay transmissions. The performance of cooperative communication systems with opportunistic decode-and-forward for relaying and s election combining receiver at the destination is analyzed in Xu (2009), and exact closed-form expression for the outage of the system over dissimilar Nakagami fading channels are presented.

In Gokturk (2008), a cross layer random access scheme that enables cooperative transmissions in the context of ALOHA system is presented. The aim is to demonstrate that cooperative transmissions emulates multi-antenna systems and can improve the quality of signal reception. It is shown that over a fading channel throughput can be improved by 30%, as compared to standard ALOHA protocol. A cooperative diversity (CD) system employing truncated stop-and-wait automatic repeat request (ARQ) for error control is proposed in Mahinthan (2009), The CD-ARQ scheme employs selection relaying at the partner, and all the transmission channels are assumed to exhibit Nakagami-*m* fading. Cross-layer optimization frameworks for multi-hop wireless networks using cooperative diversity are presented in Le (2008). The numerical results show significant improvement in terms of power consumption and source rates due to cooperative diversity.

Multiuser Diversity

Multiuser Diversity (MUD) is based on assigning channels to users with better channel quality to maximize the system throughput. Unlike the Round Rubin algorithm which achieves strict fairness among different users, conventional MUD can create a fairness problem. Papers by Song (2009), So (2008), Yang (2008), and Wang (2008) deal with MUD performance and the fairness problem. In Song (2009), an opportunistic feedback protocol is proposed for multiuser diversity systems with proportional fair scheduling and maximum-throughput scheduling. An analytical model is also provided for evaluating the proposed feedback protocol. In So (2008) a time-slotted MIMO point-to-multipoint network is considered. The transmitter decides which receivers to serve in each slot to maximize the minimum normalized average data rate realized by each receiver. Two forms of a hybrid multiuser scheduling scheme that provides a flexible balance/trade-off between the system achievable capacity and the fairness among users are proposed in Yang (2008), Capacity - fairness trade-off can be achieved by grouping users and then using a two-step selection process. In Wang (2008), a game theoretic approach is used to show that the network can enforce fairness among different users by employing a pricing policy that favors equal access probabilities.

The joint use of multiuser diversity and other types of diversity recently attracted much research interest: Zhou (2007), Larsson (2004), and Joung (2008). In Zhou (2007) the cross-layer interaction between these two forms of diversity in wireless networks is investigated, and explicit expressions of scheduling gain and average system capacity in various circumstances that reveal interconnections and fundamental tradeoffs among key system parameters are given. Various aspects related to the combined use of spatial diversity and multiuser diversity in a mobile network are considered in Larsson (2004). It is shown that in general, MUD benefit is not reduced by the proper use of spatial diversity. The interaction between cooperative diversity and MUD is considered in Joung (2008). An analytic expression for the average throughput of a single-cell wireless system with multiple cooperative diversity links combined with a fair-access scheduler is proposed and verified through comparisons with simulated results.

Opportunistic Relaying

Opportunistic collaborative networks have the potential of enabling new kinds of services that are capable of utilizing resources as and when they are available: So (2009), Zeng (2008), Zheng (2009), Ozdemir (2008), Ding (2008), Chen (2009), and Jing (2009).

A random-access-based feedback protocol with a reservation based (RB) channel is proposed in So (2009), for multiuser diversity in a wireless time-division-duplex system. The proposed feedback protocol achieves an almost ideal sum-rate capacity with a fixed number of feedback channels regardless of the number of users. Spatial diversity property of multi-hop wireless networks is explored in Zeng (2008). The impacts of multiple rates, interference, candidate selection and prioritization on the maximum end-to-end throughput or capacity of Opportunistic routing (OR) is investigated. Distributed opportunistic scheduling (DOS) in an ad hoc network, where many links contend for the same channel using random access, is considered in Zheng (2009). It is shown that rich PHY/MAC diversity gains can be achieved by devising channel aware scheduling in ad hoc networks. In opportunistic beam-forming artificial channel fluctuations is induced to ensure multiuser diversity.

Opportunism requires a large number of users in the system in order to reach the performance of the true beam-forming that uses perfect channel state information (CSI). The benefit of having partial CSI at an opportunistic transmitter is investigated in Ozdemir (2008). It is shown that opportunism can be beneficially used to increase the average throughput of the system. Performance gain achieved by cooperative diversity comes at the price of the extra bandwidth. Several opportunistic relaying strategies are developed to fully utilize the different types of *a priori* channel information, which increases the spectral efficiency of cooperative diversity, especially at low signal-to-noise ratio Ding (2008). Causes of channel diversity in wireless communications at different layers of multi-hop wireless networks are presented in Chen (2009) Link layer diversity challenges and possible diversity schemes at the network layer are considered.

Relay selection schemes, with more than one cooperative relay is discussed in Jing (2009). It is shown that they out perform single relay selection methods. In addition, for large networks, these multiple relay selection schemes require the same amount of feedback bits from the receiver as single relay selection schemes.

Conclusion

Diversity is a main performance enhancing technique for wireless communication. The paper presented a review of the two types of diversity used in wireless communications: physical and virtual diversity. The physical diversity is implemented at the physical layer and has been widely used for most of the wireless systems. The most prominent physical diversity; space diversity, has received a remarkable interest and recently, multiple-input multiple-output (MIMO) has been standardized for beyond 3G systems. The multiplexing gain of MIMO systems increases linearly with the minimum of the number of transmit and receive antennas and the diversity gain is proportional to their product as shown in Eq. 5-6. The diversity and multiplexing gains offered by MIMO are valid for Rayleigh fading channels and for uncorrelated antennas. Smaller gain values are predicted for Rician channels and/or correlated antennas. In addition, even for spaced antennas different paths might not be independent, in particular when considering shadowing and the gain might therefore be less than predicted.

Three "Virtual Diversity" techniques have been presented: Multi-User Diversity (MUD), Cooperative Diversity (CD), and Opportunistic Relaying (OR). Such "Virtual Diversity" techniques provide similar diversity and multiplexing gain advantages to those offered by MIMO systems, without its limitations. The common features of these virtual diversity techniques are that they are: i) implemented at link or network layers, and ii) applicable for multi-user systems. While MUD is based on optimizing resource allocation at the cost of "fairness", CD and OR are based on cooperative-relaying which can be applied in sensor networks, ah-hoc networks, and cellular communications. The paper has presented a summary of the most recent developments in these techniques.

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