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A REVIEW OF DIVERSITY TECHNIQUES FOR WIRELESS COMMUNIATION SYSTEMS

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ABSTRACT

Wireless communication technology is now popular worldwide and has made mobile communication very attractive and in high demand. For higher data rates to meet the ever increasing demands in mobile communications, multiple-input multiple-output (MIMO) technology has been standardized as the 4G communication systems. MIMO, a wireless communication system which utilises multiple antennas at both sides of the transmission link, has received high attention in the last few decades due to its ability to achieve high data rate transmission. Several papers have presented different techniques in the implementation of MIMO wireless systems which include diversity methods. Physical diversity is one of these methods that is well known and can be used to combat multipath fading, a common problem in wireless communications. This paper summarizes physical diversity as well as virtual diversity techniques. The paper shows that unlike the former, virtual diversity methods such as co-operative diversity and multiuser diversity are techniques that are implementable at the network or link layer of a wireless communication system.

Keywords: MIMO,Diversity,wireless communication,STBC.

INTRODUCTION

A state-of the-art concept in mobile communications in recent times is the multiple-input multiple-output (MIMO) wireless communication system.The use of multiple antenna at either ends of the link enables the system to have increased spectral efficiency without increased bandwidth or transmitted power.

The main difficulty today is that users demand higher data rates for their applications whereas the usable spectrum is limited (both technically and by regulations). This is due to the increase in the popularity of mobile applications as for example cell phones or wireless internet access. Wireless systems do not provide the option of just adding an additional wire as in wire or fiber-optics based systems. Therefore the spectral efficiency needs to be increased in order to enable not only a higher throughput but also ensure signal reliability.

That is the problem MIMO is out to solve. Instead of just transmitting one single signal over the ‘air’ from the transmitter to the receiver (as common with most systems today), several independent signals are sent over the common channel ‘air’ by using multiple antennas for transmitting and receiving.

In most applications, every signal sent from a transmitting antenna reaches the receiving antenna over multiple paths. This phenomenom is called *multipath propagation* (Figure 1). It is produced by eloctromagnetic waves that are reflected off walls and other objects. The signal at the receiver is therefore generally a superposition of direct and delayed versions of the original signal. Multipath propagation is generally considered as a nuisance because it causes signal distortion and some systems try to circumvent it by establishing a line-of-sight (LOS) connection.

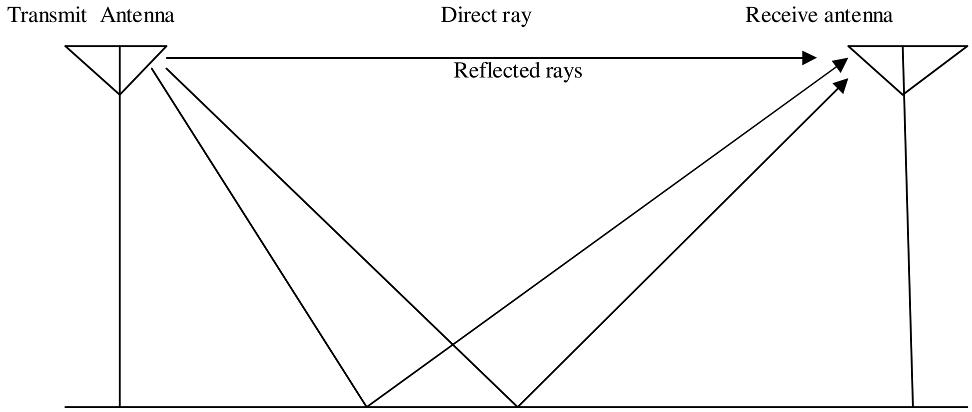

Figure 1. Multipath propagation

Instead of seeing multipath propagation as a factor that decreases the system performance, clever approaches use it as an advantage in MIMO systems. One can imagine the following setup:

a. Transmitter using antennas t_1 and t_2
b. Receiver using antennas r_1 and r_2
c. t_1 and t_2 transmitting different signals
d. Both are placed inside a building – assuming no LOS

As illustrated in Fig 2, signal sent from t_1 to r_1 follows a different path compared to the signal sent from t_2 and received at r_2. The same is true for signals from t_1 to r_2 and from t_2 to r_1. If it is assumed that the different paths are known at the receiver, clever calculations can remove the effect of the superposition and decode both streams. In that case the data rate would have been doubled without using additional spectrum. Due to the spatial distribution of the antennas, the reliability of the link is increased at the same time.

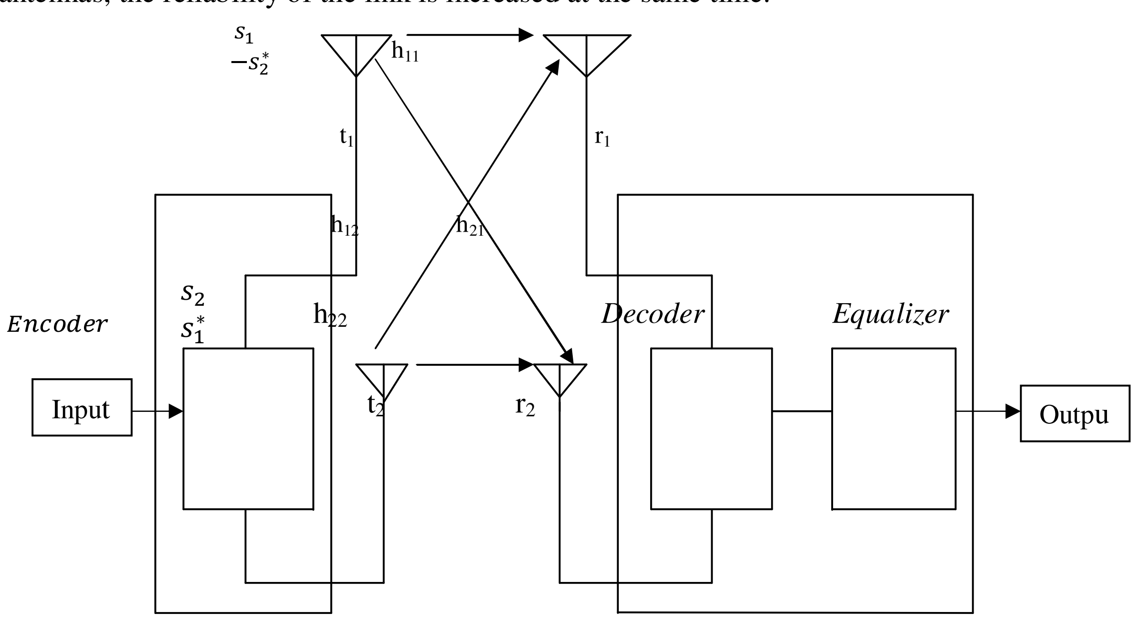

Figure 2. A simple MIMO Wireless system

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PHYSICAL DIVERSITY TECHNIQUES

In wireless commuication systems, the reliabilty of the communication operation can be increased between transmitter and receiver while maintaining a high spectral efficiency. The ultimate solution relies in the use of diversity, which can be viewed as a form of redundancy. There are many diversity techniques that can be applied to wireless communication systems. Some of them are time diversity, frequency diversity and space diversity. In time diversity the same information carrying signal is transmitted in different time slots. In frequency diversity, the information carrying signal is transmitted on different subcarriers where good gain can be achieved with greater seperation between subcarriers. In space (or spatial) diversity, the same information-bearing signal is transmitted or received via different antennas. This method can achieve maximum diversity gain by combining the signals arriving via independent (or lowly correlated) channels.

Spatial Diversity (Transmit)

The pioneering work in transmit diversity was done by Alamouti (1998), where he proposed his famous *2x1* space-time code. Alamouti scheme achieves diversity gain while requiring only a linear decoder. Unlike other codes, Alamouti's code is the simplest complex orthogonal space-time code which uses two transmit antennas and one receive antenna. Fig 3 shows how this encoding process is achieved and how the transmission matrix is obtained.

At a given time t_1, symbols S_1, S_2 are transmitted resulting to S_1 and $-S^*_2$ as shown in Fig 2. At time t_2, S_2 and S^*_1 result. Thus space-time block codes (STBC) arrange the symbols into transmission matrix block '*S*' in which the rows are the tansmit data at each antenna and the columns are the data at time slots.

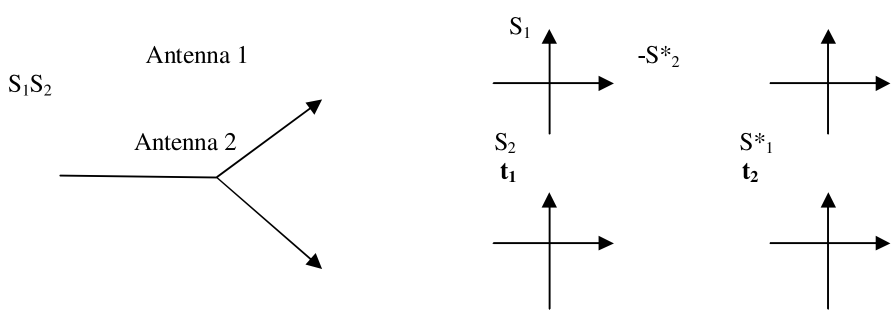

Figure 3. Alamouti STBC scheme

$$S=\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \qquad (1)$$

The basic property of this system is the maximum diversity and simple detection (Jayalakshmy et al., 2011). For this type of space-time codes, the following conditions must be applied:

i. Square transmission matrix (number of transmit antennas N_t equal to number of used time slot m)

ii. A unity code rate (number of used time slots t_m equal to number of transmitted symbols ℓ).

A complex orthogonal space-time code using 4 and 8 antennas was later proposed by Tarokh et al., (1999). Their work turned out to be the basis for a thoery of generalized complex orthogonal designs. Genaralized complex orthogonal designs are distinguished from Alamouti code by the following:

i) A non-square transmission matrix (number of used time slots ≠ number of transmit antennas).
ii) A fractional code rate (number of transmitted symbols < number of used time slots).
iii) Orthogonality of the transmission matrix is only guaranteed in the time sense.

As a consequence of these characteristics, the spectral efficiency is reduced and the number of time slots over which the channel should be constant is increased.

The transmission of a generalized complex space-time code with 3 antennas, 4 transmitted symbols and 8 used time slots is given as (Haykin et al.,2005):

$$\mathbf{G_3} = \begin{pmatrix} S_1 & S_2 & S_3 \\ -S_2 & S_1 & -S_4 \\ -S_3 & S_4 & S_1 \\ -S_4 & -S_3 & S_2 \\ S^*_1 & S^*_2 & S^*_3 \\ -S^*_2 & S^*_1 & -S^*_4 \\ -S^*_3 & S^*_4 & S^*_1 \\ -S^*_4 & -S^*_3 & S^*_2 \end{pmatrix} \qquad (2)$$

Table 1 summarizes the difference between Alamouti and the generalized complex orthogonal space-time code characterized by the transmission matrix $\mathbf{G_3}$.

Table 1. Comparison between Alamouti and Generalized complex space-time code

Space-Time Code	*Number of Transmit antenna*	*Number of Transmitted symbols ℓ*	*Number of used time slots m*	*Orthogonality of Transmit matrix*	*Rate= ℓ/m*
S	2	2	2	Spatio-temporal Sense	1
G_3	3	4	8	Only temporal Sense	½

These shown schemes can be transmitted in space-time , space-frequency or space-frequency-time domains. The coding schemes are thus known as ST, SF and STF coding respectively (Suto et al.,2004). More research was done to increase the rate of space-time codes by Su and Xi (2003).

Space Diversity (Receive)

This method at the receive side makes use of multiple antennas such that the spacings between the antennas are in such a way as to reduce mutual correlation between the antennas and as a consequence diversity gain is increased. However, in many practical wireless applications, e.g. for small-size mobile units or indoor base stations, the receiving antennas are not sufficiently widely seperated and thus the received and combined signals are correlated with each other. Received signals are combined at the receiver to achieve diversity gain. The most well known combining techniques are selection combining (SC), switching receiver(SR), equal gain combining (EGC) and maximal-ratio-combining (MRC).

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In SC, the signal at the branch with maximum signal-to-noise ratio (SNR) is selected and the other signals are rejected. A weighting vector **W**=(w_1, w_2,---w_N) is used to weight the received branch signals rejecting all other branches except that with maximum signal-to-noise ratio (SNR). In a switching receiver, the signal from only one antenna is fed to the receiver for as long as the quality of that signal remains above some prescribed threshold. If and when the signal degrades, another antenna is switched in.

Switching is the easiest and least power consuming of the antenna diversity processing techniques but periods of fading and desynchronization may occur while the quality of one antenna degrades and another antenna link is established. In EGC the weighting vector is **W**=(1,1,---$1)_M$, that is, received signals from the branches are weighted equally, then aligned before being combined coherently. MRC technique weights the received signal vector **Y**=(y_1,y_2,----y_N) according to their reliability. A more reliable signal has a high weight while a less reliable signal has a small weight. Also, the channel phase distortion is compensated. Finally, signals are alligned then combined.

It is known that, from a performance point of view , MRC is optimum and gives the best performance among other combining schemes (Lindenmeier et al.,2007). Such a system provides the greatest resistance to fading but since all the receive paths must remain energized, it also consumes the most power. Figure 4 depicts a simple block diagram of a MRC scheme.

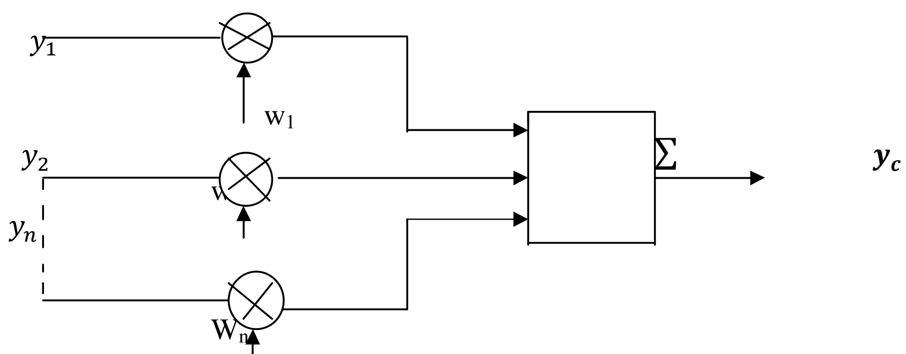

Figure 4. Simple block diagram of MRC

Here the combined signal $\boldsymbol{y_c}$ for n-branches is given as

$$y_c = \sum_{i=1}^{N} yn \qquad (3)$$

and shows the output per symbol SNR of the n_{th} diversity channel of a MRC receiver (Simon et al, 2005).

Diversity and Multiplexing Gains for MIMO

Wireless communication system performance is limited by fading. Diversity techniques such as frequency, space, time and polarization diversity have been used in wireless communication systems to combat the effect of fading and improve coverage, capacity and reliability.

For a MIMO system with M transmit and N receive antennas, define $K = min(M, N)$. At large Signal-to-Noise ratio, $S/N \rightarrow \infty$, the optimum multiplexing gain r and optimum diversity gain d are given as, (Zheng, 2003)

$$R \sim r \log(\text{SNR}) \qquad r = 0, 1, \ldots.K \qquad (4)$$

$$P_e \sim (SNR)^{-d} \qquad (5)$$

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

$r \to K$ multiplexing only (6)

$d \to M.N$ diversity only (7)

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

$r = 0,1,\ldots,k$ and

$d(r) = (k-r)^2 + (k-r)|M - N|$ (8)

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.

The various diversity schemes presented in Figure 5 are 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 in MIMO systems as well as other forms of MIMO configurations like single-input multiple-output (SIMO) and multiple-input single-output (MISO) systems.

The diversity and multiplexing gains offered by MIMO in Equations 4-8 are valid for Raleigh 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 the gain might therefore be less than predicted.

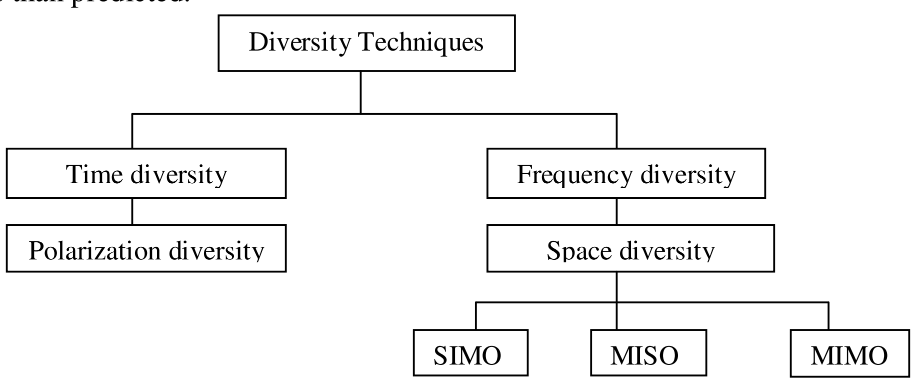

Figure 5. Diversity techniques for wireless communications

VIRTUAL DIVERSITY TECHNIQUES

Co-operative Diversity

In *co-operative diversity*, several nodes each with one antenna, form a kind of coalition to co-operatively act as a large transmit or receive array. When terminals co-operate as a transmit array,they first exchange messages and then co-operatively transmit those messages as a multi-antenna broadcast transmitter; similarly for receive co-operation. The channel therefore shares characteristics with the MIMO channel, such as diversity.

In a co-operative diversity network, users co-operate 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 system. It relies on data transmission by several

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nodes. Each node acts as a virtual antenna and co-operatively transmits data to a particular destination. Hence it is one form of Virtual diversity technique.

Co-operative diversity systems are presented in Hwang et al., (2008), Barua et al., (2008), Xu et al., (2009), Gokturk et al., (2008), Mahinthan et al., (2009) and Le et al.,(2008).The first three papers deal with co-operative diversity and another virtual diversity technique known as *Opportunistic relaying*. In Hwang et al., (2008), opportunistic relaying with co-operative 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 probabilty (SEP) of co-operative diversity with opportunistic amplify-and-foward (AF) relaying is presented in Barua et al., (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 co-operative communication systems with opportunistic decode-and-forward for relaying and selection combining (SC) receivers at the destination is analyzed in Xu et al.,(2009), and axact closed-form expression for the outage of the system over dissimilar Nakagami fading channels are presented.

A cross layer random access scheme that enables co-operative transmissions in the context of ALOHA system is presented in Gokturk et al., (2008). The aim is to demonstrate that co-operative transmissions emulates multi-antenna systems and can improve the quality of signal reception. Mahinthan et al., (2009) proposed a co-operative diversity system employing truncated stop-and-wait automatic repeat request (ARQ) for error control. The co-operative-ARQ scheme employs selection relaying and all the transmission channels are assumed to exhibit Nakagami-*m* fading.

Cross-layer optimization frameworks for multi-hop wireless networks using co-operative diversity are presented in Le et al., (2008). The numerical results show significant improvement in terms of power consumption and source rates due to cooperative diversity.

Co-operative Communication as Virtual MIMO

In co-operative communication, a mobile can act as both a user and relay. As consequence, mobile sends to the base station its own data bits and some of other mobiles (sometimes called partner) information bits. Figure 6 shows a co-operative cellular system where for simplicity three co-operative users and one base station are considered (Nostratinia et al.,2004). As depicted in the Figure, user 1 co-operates with users 2 and 3 to send its own information. As a result, the overall co-operative system can be seen as virtual-MIMO (V-MIMO) and in the figure below it is 3xN_{BS} MIMO system (for uplink) where N_{BS} is the base station's number of receive antennas. Users 2 and 3 can simply amplify and forward user 1 received information or detect and forward. Another method of co-operation is the coded co-operation where different coded portions are sent via different fading channels (Hunter et al.,2006).

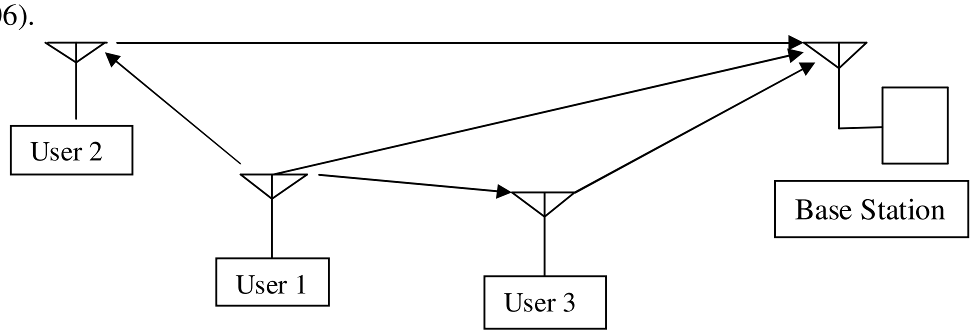

Figure 6. Co-operative communication as virtual MIMO

Multiuser Diversity

Multiuser diversity (MUD) is based on assigning channels to users with better channel quality to maximize the system throughput. Papers by Song et al., (2009), So et al., (2008), Yang et al., (2008) and Wang et al., (2008) deal with MUD performance. In Song et al., (2009), an opportunistic feedback protocol is proposed for multiuser diversity systems with propotional fair scheduling and maximum-throughput scheduling. An analytical model is also provided for evaluating the proposed feedback protocol.

In So et al., (2008), a time-slotted MIMO point-to-multipoint network is considered.The transmitter decides which receivers to serve in each slot to maximize the minumum normalized average data rate realised 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 Wang et al., (2008). Capacity-fairness trade-off can be achieved by grouping users and using a two-step selection process. In Wang et al., (2008), a game theoretic approach is used to show that the network can enforce fairness among different users by employing a pricing policy that favours equal access probabilities.

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: Song et al.,(2009), Zeng et al., (2008), Zeng et al., (2009),Ozdemir et al., (2008), Ding et al., (2008), Chen et al.,(2009) and Jing et al., (2009).

A random-access-based feedback protocol with a reservation based (RB) channel is proposed in Song et al, (2009), for multiuser diversity in a wireless time-division-duplex (TDD) 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. Spartial diversity property of multi-hop wireless networks is explored in Zeng et al., (2008). Here, the impacts of multiple rates, interference, candidate selection and prioritization on the maximum end-to-end throughput or capacity 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 et al, (2009). It is shown that rich 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 multi-user diversity.

Opportunistism requires a large number of users in the same system in order to reach the performance of the true beamforming that uses perfect channel state information (CSI). The benefit of having spatial CSI at an opportunistic transmitter is investigated in Ozdemir et al., (2008). It is shown that opportunistism can be beneficially used to increase the average throughput of the system. Performance gain achieved by co-operative diversity comes at the price of the extra bandwidth.

Several opportunistic relaying strategies are developed to fully utilize the different types of channel information which increases the spectral efficiency of co-operative diversity, especially at slow signal-to-noise ratio, Ding et al., (2008). Causes of channel diversity in wireless communications at different layers of multi-hop wireless networks are presented in Chen et al., (2009). In this paper link layer diversity challenges and possible diversity schemes at the network are considered.

Relay selection schemes, with more than one co-operative relay is discussed in Jing et al., (2009). It is shown that they out-perform single relay selection methods. In addition for large

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networks, these multiple relay selection schemes require the same amount of feedback bits from the receiver as single relay selection schemes.

Multi-User diversity (MUD), Co-operative diversity (CD) and Opportunistic Relaying (OR) are different techniques of Virtual Diversity as represented in Fig.6. These techniques provide similar diversity and multiplexing gain advantages to those offered by MIMO systems, without its limitations.

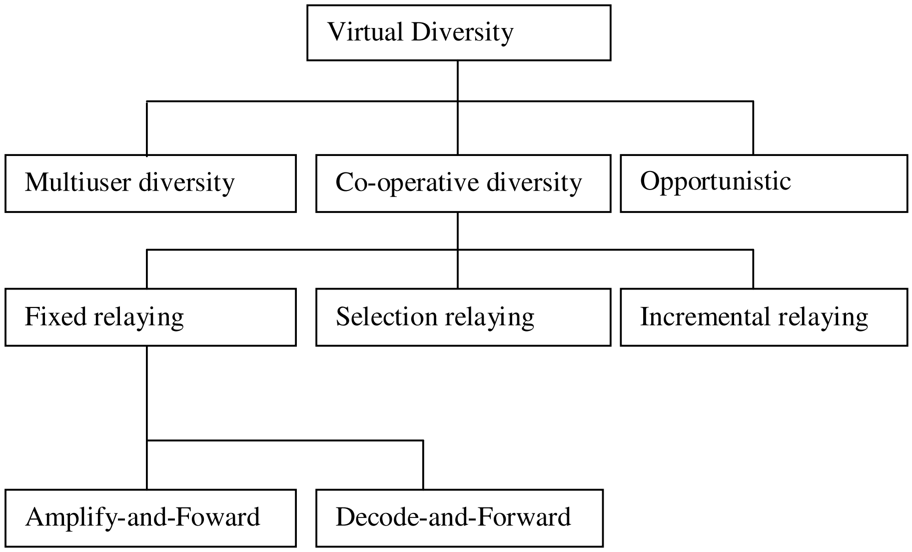

Figure 7. Virtual Diversity Techniques

CONCLUSION

In this paper we reviewed and presented in a simple manner two types of diversity techniques used in wireless communications. These techniques are used in wireless communications to combat the effects of multipath fading and other forms of interference and thus enhance system performance. Physical diversity techniques such as time, space, frequency and polarization have been very much in use in the implementation of MIMO wireless communication systems. Different forms of virtual diversity such as multiuser, co-operative and opportunistic relaying have been presented showing how different users can act in a co-operative manner by amplifying and fowarding information received from one another.

It should be noted that the review showed physical diversity as implementable at the physical layer only while virtual diversity is for the network layer.

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