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Diversity Techniques in Wireless Communication Systems: A Review

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Abstract:

Fading can be considered as the major impairment of wireless communication channels. To overcome this problem, diversity techniques have been proposed. Diversity is a powerful communication technique that can be applied in time, frequency, and spatial domains in order to enhance communication system performance. The doctrine of diversity is based on the idea of deploying multiple antennas to transmit/receive multiple copies from the desired signals over independent paths to avoid simultaneous fading. In this paper a review of diversity techniques is done. An overview of differently proposed diversity techniques is made to highlight the problem statement in each of it and how the solutions are suggested and applied to conclude the best proposed ones to mitigate the problem of fading in wireless communication channels. The use of multiple antennas at both ends of the system and the principles of MIMO systems is also discussed in this article. Finally, the application of MIMO systems into 5G communication systems is reviewed.

Keywords: *Fading, Diversity techniques, MIMO systems, Diversity combining methods, and 5G.*

Introduction

Path loss, thermal noise (modeled as Additive White Gaussian Noise), shadowing, and fading are the major parameters that the wireless communication channels suffer from it (Foschini, & Gans, 1998). Fading problem can be considered as the most significant impairment of wireless communication channels. Time-varying multipath fading is the basic phenomenon that leads to the difficulty of having a credible wireless transmission (Alamouti, 1998). Due to scattering by different objects in the wireless environment between transmitter and receiver, multiple signal copies follow multiple propagation paths and face different delays, phase shifts, distortions, and attenuation. At the receiver side, constructive and destructive interference can occur. When the interference is destructive, the signal power notably decreases. This phenomenon is called fading which strictly cause degradation in the performance of the system (Mitić, et al., 2014).

Fading channels are mainly characterized by several parameters such as: Delay Spread (Td), Coherence Bandwidth (Wc), Doppler Spread (Ds), and Coherence Time (Tc) (Popa, Draghiciu, & Reiz, 2008). Based on these parameters and the desired signal characteristics, fading channels can be classified into: Flat Fading Channels, Frequency-selective Fading channel, Fast Fading Channel, and Slow Fading Channel (Haykin, & Moher, 2005; Bertoni, 2000; Hottinen, Tirkkonen, & Wichman, 2003; Paulraj, Nabar, & Gore, 2003).

Figure 1. Shows the classification of fading channels based on signal characteristics and channel parameters.

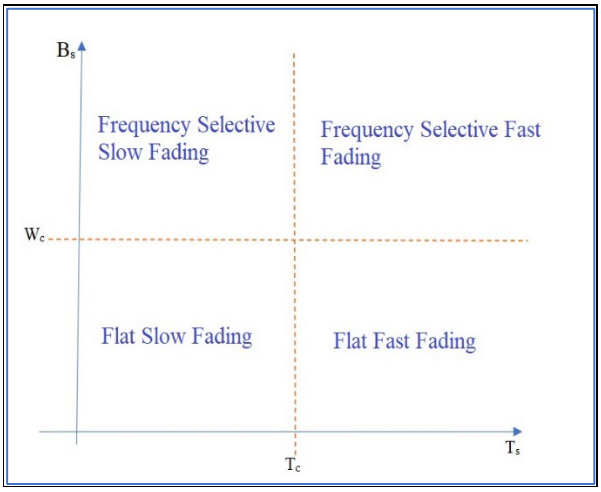

Figure 1. Fading Types Based on Signal Characteristics and Channel Parameters

To overcome this problem, different techniques have been proposed. Some of the proposed techniques were inefficient solutions such as adding a fading margin at the transmitter and some others were considered as the basis for diversity concept such as increasing the number of inputs in the receiver side to manipulate the uncorrelated signals (Mahender, Kumar, & Ramesh, 2019).

The diversity techniques were time and frequency diversity. Diversity improvement can satisfy through time interleaving and error correction coding. But in the case of slowly varying channels, time interleaving leads to large delays. To manipulate the multipath fading impairment in scattering environments, antenna diversity is a practical, effective, and a widely applied technique (Foschini, & Gans, 1998). The traditional scheme of diversity is to use multiple antennas at the receiver and perform combining methods such as selection and switching in order to improve the quality of the received signal. Cost, size, and the power of receiver site units are the most significant drawbacks of using the receive diversity scheme. The use of multiple antennas and radio frequency (RF) chains or selection/switching circuits makes the units at the receiver site larger and more expensive.

Conventional single-antenna transmission techniques aiming at an optimal wireless system performance operate in the time domain and/or in the frequency domain. However, due to the ever-growing demands of wireless services, the concern is now more about evolving the antenna part of the radio system. In fact, when utilizing multiple antennas, the previously unused spatial domain can be exploited. The great potential for the use of multiple antennas on both sides of wireless communication systems became evident only during the past decades. In particular, at the end of the 1990s, it was found that multi-antenna technology provides a new way to achieve higher bit rates and smaller error rates (Mietzner, et al., 2009).

Next section of this paper discusses the doctrine of diversity and the different diversity techniques. Section III is covering MIMO systems. And a comparative overview of MIMO deployment for 5G smartphones is performed in section IV. Section V concludes the study.

Diversity Techniques

Diversity is a powerful communication technique that avails from the random nature of radio propagation to find independent paths for signal communication. Diversity is used to send several copies from the same signal to the receiver in order of enhancing the radio channel performance. The idea behind sending multiple copies from the desired signal through different channels instead of one channel is to avoid the possibility of that all the copies may undergo deep fades simultaneously. Diversity can be classified into many major kinds which are commonly used in wireless communication Systems (Hourani, 2005).

Frequency Diversity

In frequency diversity, the information signal is modulated through several different carriers. To ensure that each copy of the signal undergo independent fading, the separation between one carrier and another should be at least the coherence bandwidth (Wc). At the receiver side, different diversity combining methods can be used to receive the independently faded signal copies. Frequency diversity is mainly used to struggle frequency selective fading. This type of diversity is shown in Figure 2.

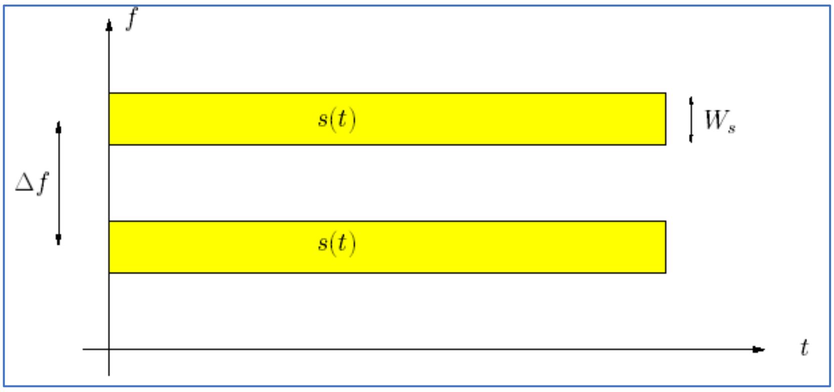

Figure 2. Frequency Diversity
Source: Hourani, 2005

Time Diversity

In time diversity, many copies of each symbol from the desired signal are transmitted at many different periods of time. To ensure that each copy of the symbol undergo independent fading, the interval between one symbol and another should be at least the coherence time (Tc). Time diversity is mostly used to warfare fast fading (time selective fading). This type of diversity is shown in Figure 3.

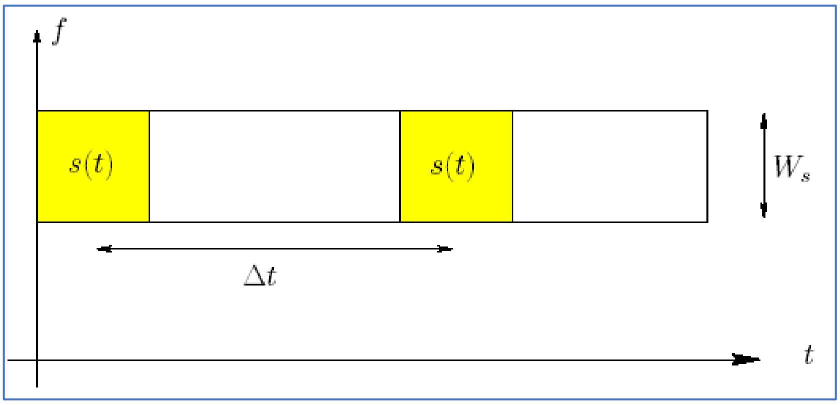

Figure 3. Time Diversity
Source: Hourani, 2005

Space Diversity

Space diversity is the more powerful and simplest form of diversity. It is achieved by using multiple antennas at the base station or at the mobile station or at both ends. When multiple antennas are used to receive multiple copies from the desired signal, they should be physically separated. To ensure that each received copy of the transmitted signal undergo independent fading, the space between one antenna and another should be far enough (ideally separated by one half or more wavelengths). This technique differs from both frequency diversity and time diversity techniques in that no additional work is needed at the receiver side. One of the major limits of space diversity technique is the physical constraints that may face its application. Space diversity is commonly used to fight both frequency selective fading and time selective fading (fast fading) (Weik, 2000). This type of diversity is shown in Figure 4.

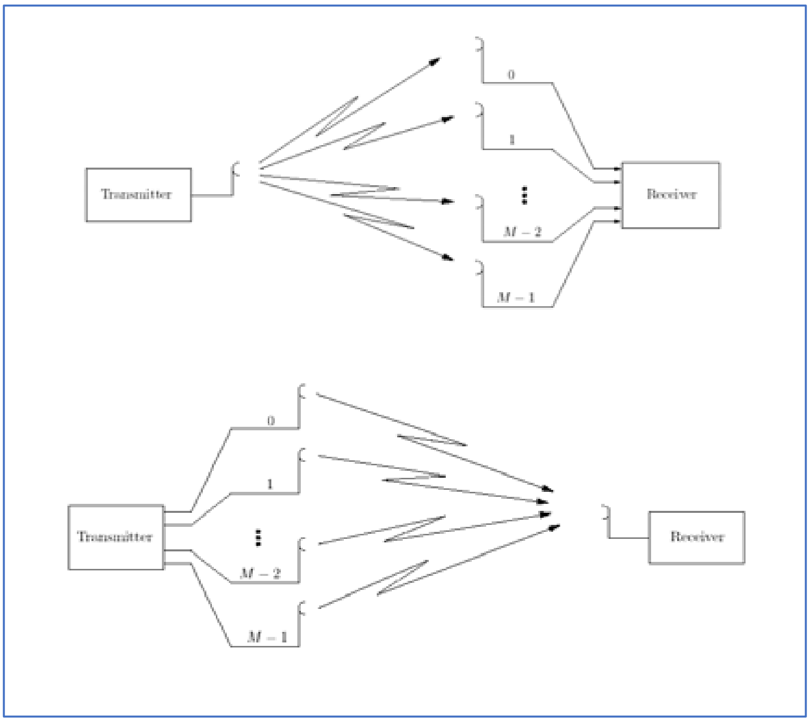

Figure 4. Space Diversity
Source: Hourani, 2005

Not only at the receiver side, multiple antennas can be also deployed at the transmitter side to propagate multiple copies of the desired signal. If multiple antennas are deployed at both sides of the communication systems then the field is referred to as a multiple-antenna system, often known as Multiple-input Multiple-output (MIMO) system. It has a significant role in the performance promotion of wireless communication systems and of course it has some limitations too (Bliss, Chan, & Chang, 2004). Multiple-input Multiple-output (MIMO) system is explained with more details in the next section.

Multiple-Input Multiple-Output (MIMO) Systems

Typically, in any communication system to obtain a certain quality of Service (QoS), a high bit rate and a good error performance are very essential. The uncooperative characteristics of wireless channels caused by fading problem and multipath propagation make it very challenging to achieve both of these goals simultaneously. Traditionally, when a single-antenna is employed in transmission techniques to achieve an optimal performance for the wireless system, the operation was in the frequency domain and/or time domain. But now and with the increased demand of wireless services, multiple-antennas are employed. With the utilization of multiple-antennas, the previously unfamiliar spatial domain is now exploited (Paulraj, et al., 2004). By 1990s, the novel techniques to fulfill higher bit rates, smaller error rates, and also to reduce co-channel interference were multiple-antenna techniques (Mietzner et al., 2009). They were shown as a key technology for modern wireless communications. The advantages of multiple antennas for wireless communication systems are shown in Figure 5.

The benefits of multiple antennas technique for wireless communication systems are explained with more details in the following subsections:

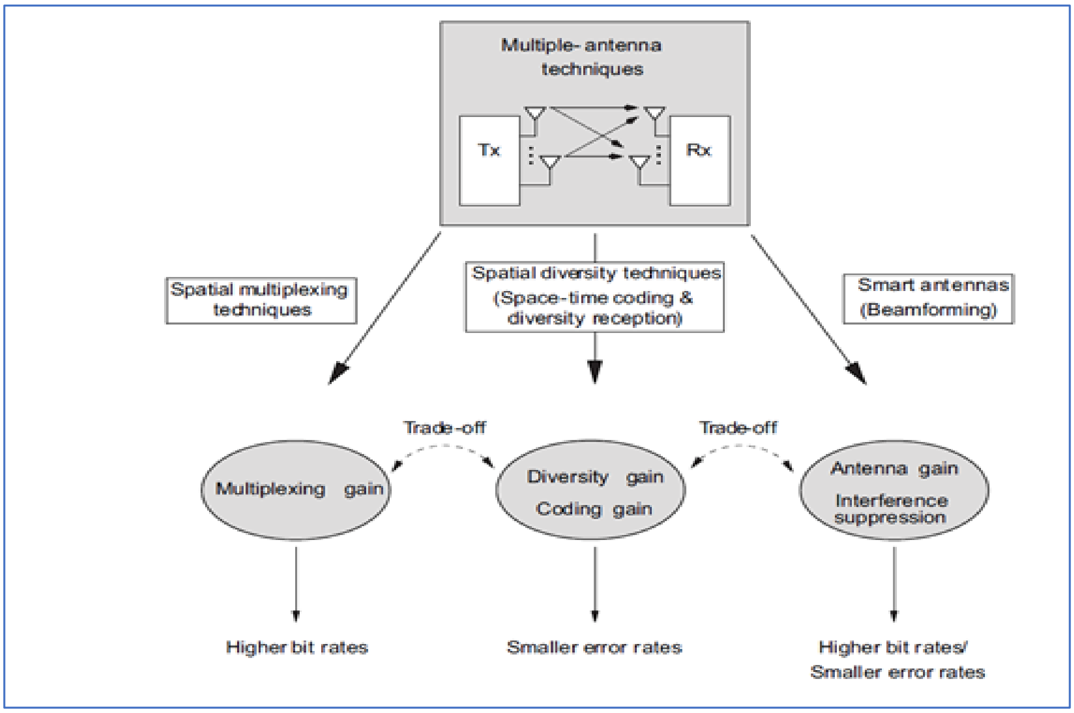

Figure 5. Benefits of Multiple Antenna Techniques for Wireless Communication
Source: Mietzner et al., 2009.

Spatial Multiplexing

Simultaneously, space-time coding and the principles of spatial multiplexing were draw up in the 1990s (Raleigh, & Cioffi, 1998). The doctrine of spatial multiplexing is based on the transmit of different layers (symbols) from each antenna and have the receiver differentiate these symbols based on the fact that, due to spatial selectivity, the spatial signature of each transmit antenna is different from the others at the receiver.

If we assumed that M antennas are used at the transmitter side, then the overall bit rate in comparison with the traditional single-antenna systems is thus increased by a factor of M without the need for an extra bandwidth or extra transmission power.

Bell-Labs Layered Space-Time Architecture (BLAST) is one of the well-known and popular spatial multiplexing schemes (Foschini, 1996). In spatial multiplexing, the achieved gain in terms of bit rate is referred to as a multiplexing gain.

Spatial Diversity

Channel coding is commonly used for the purpose of achieving a specific error rate of a system. Similarly, multiple antennas can also be used to improve the error performance. The latter is obtained by transmitting/receiving redundant signals to act for the same information sequence. Information sequence is spread out over multiple transmit antennas through space-time coding technique which is a two-dimensional coding technique. At the end side, diversity reception technique can be used to improve the error performance further more multiple receive antennas can also be used (Kwon, Im, Lim, 2009). Spatial diversity accommodates the redundancy in spatial domain not in time domain as in conventional channel coding technique. Performing the redundancy in spatial domain means achieving coding and diversity gains without any degrading the effective bit rate compared with traditional transmissions via single-antenna. This is the advantage of spatial diversity over conventional channel coding. Alamouti's transmit diversity scheme (Alamouti, 1998) and space-time trellis codes (Tarokh, Seshadri, & Calderbank, 1998) are famous spatial diversity techniques for multiple transmit antenna systems.

Smart Antennas

Previously, diversity combining methods were used at the receiver side which called receive diversity. The idea of receive diversity (or diversity mainly) is to combine several copies of the transmitted signal, which undergo independent fading, to increase the overall received power. Different types of diversity call for different combining methods such as Selection Combining (SC), Maximal Ratio Combining (MRC), and Equal gain combining (EGC). In SC the strongest signal branch is selected, in MRC method, the diversity branches are weighted for maximum SNR, and in EGC each branch signal is rotated first by an exponential rate, and all branch signals are then added. Among different combining techniques, MRC has the best performance and the highest complexity, while SC has the lowest performance and the least complexity. Figure 6 shows the models of both selection combining and maximal ratio combining methods.

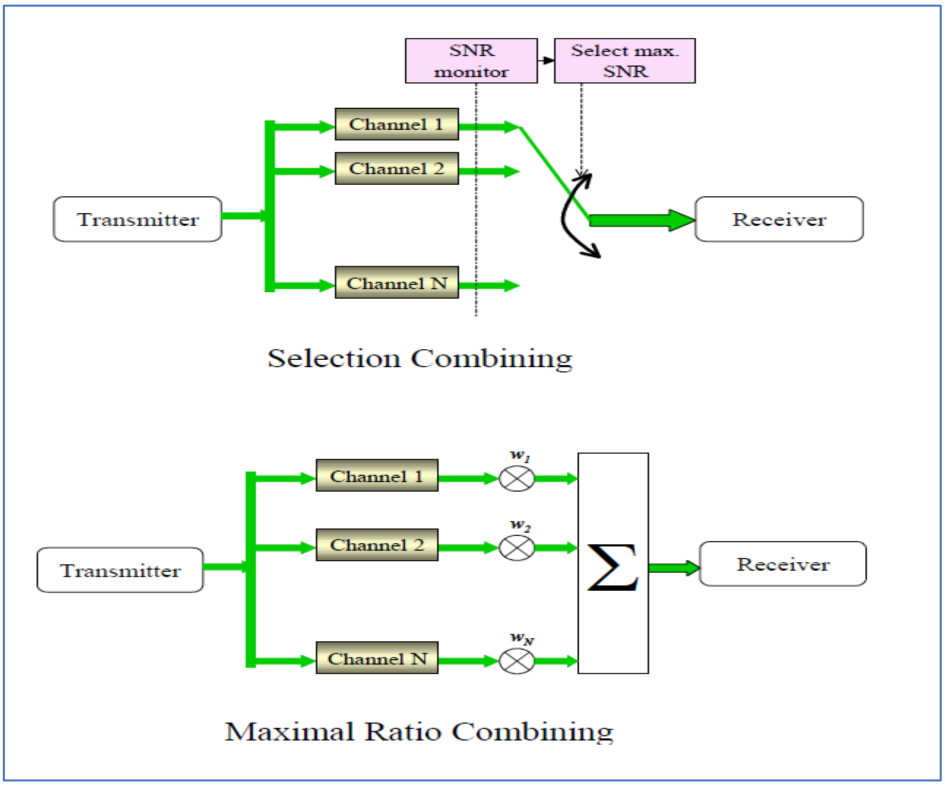

Figure 6. SC and MRC Diversity Combining Methods
Source: Hourani, 2005

Not only the data rates can be increased and error rates can be improved by deploying multiple antennas, but also the SNR at the receiver site can be improved and the co-channel interference in a multi-user scenario can be suppressed by using it. Both goals can be accomplished by means of smart antennas and the use of beam-forming techniques (Chang, & Hu, 2012).

Beamforming perform the functionality of linear filtering in spatial domain (Hegde, Cheng, & Pesavento, 2017). If we assumed that there is an array of N antenna elements, which receives a signal from a certain direction. Then, the influencing radio frequency (RF) signal because of the geometry of the antenna array will arrives at each individual antenna elements at different time instants, as a result a phase shifts occur between the multiple received signals. But, if received complex baseband signal is considered to be a narrowband signal, the possibility of change is very low or it may not change during these small-time differences.

Another method may also be applicable if the direction of the influencing signal is known. In this method, the phase differences of the Radio Frequency (RF) signals can be compensated by means of phase shifters or delay elements, prior to the combination of the received signals. The outcome of this is that the overall antenna pattern of the phased array will show a maximum in the direction of the influencing signal. The principle of this method is known as the conventional beamforming (Godara, 1997). In the case of manipulating only the phases of the received signals, then the shape of the pattern of the overall antenna remains as its, and just an angular shift result. Conventional beamforming can be interpreted as an alternative to the mechanical rotation of the antenna array (mechanical beam steering).

On the other hand, if the amplitudes of the received signals are also manipulated prior to the combining step, then there is a possibility to modify also the shape of the overall antenna pattern. In detail, if there is an antenna array with N antenna elements which provides (N−1) degrees of freedom, i.e., altogether (N−1) angles can be specified for which the overall antenna pattern is supposed to display either a maximum or a minimum. If the prementioned scenario assumption of having the complex baseband signal with narrowband is not met, the baseband signal can change during time intervals which are equal to the relative delays between the received RF signals. Thus, the individual antenna elements will observe different versions of the complex baseband signal. For such cases, broadband beamforming techniques are needed that combine narrowband beamforming (i.e., spatial filtering) with time-domain filtering, e.g., in the form of a two-dimensional linear finite impulse response (FIR) filter (Godara, 1997).

Notably, the different benefits provided by multiple antenna techniques are not coming without cost. the multiple parallel transmitter and receiver chains which are needed, lead to an increased hardware cost. Also, deploying multiple antennas might need increased power consumptions. Moreover, implementing near-perfect multiple antenna techniques in real time can actually be challenging. however, experimental trials have demonstrated that noticeable performance improvements over single antenna systems can be achieved in practice, even if low-cost hardware components are used (Kaiser, et al., 2006).

MIMO FOR 5G Smartphones

Actually, after all the advances in the field of antenna array communications, the strong push promised by MIMO is finally bringing multi-antenna devices to the market. doubtlessly, MIMO is an integral feature of emerging wireless systems such as Long-Term Evolution (Sesia, & Toufik, 2009), Ultra Mobile Broadband, and IEEE 802.16 WiMAX (Andrews, Ghosh, & Muhamed, 2007) and very soon in 5G too. Therefore; in this section a comparison among multiple very hot researches of high quality about the deployment of MIMO system in 5G networks is performed. The aim is to analysis the different approaches proposed by the researchers for the purpose of deploying and developing Multiple-Input Multiple-Output antennas for 5G smartphones.

In Sun, et al. (2020) a wideband dual-antenna pair of orthogonal mode with a shared radiator for 5G multiple input multiple output (MIMO) smartphones are presented. Their design shows that using one pair from this proposed antenna can present a 3.3-5.0 GHz impedance bandwidth which is a wide impedance bandwidth and an isolation of more than 21.0 dB across the entire band without any need for additional decoupling structures. They added, if four pairs of this dual-antenna design are arranged at the four side edges of the smartphone, then the fulfilled 8x8 Multiple Input Multiple Output system can offer now a better isolation of more than 12.0 dB and an envelope correlation coefficient of lower than

0.11 between all ports. They also measured the average efficiencies of their design and the measurements showed 74.7% and 57.8% for the two antenna elements of the proposed dual pair design. In Sharawi, Ikram, & Shamim, (2017) the proposed design is an integrated design with a MIMO antenna for the applications of both 4G and 5G systems. Regardless of 4G sub-part details, they have integrated in their design an array of connected antennas which is based on a two element (MIMO) antenna system for a potential 5G band. Their integrated antenna system covers a (16.50-17.80 GHz) band for 5G. At 17 GHz, an 8 dBi gain is measured for the 5G MIMO antenna systems. Although their design seems to be simple, planar, and tight in structure to be suitable for wireless mobile devices and terminals, but it seems that the authors focused more on achieving the integration between 4G and 5G rather than designing a promising MIMO system for 5G smartphones. That is clear when the researchers added that their design is the first from this type that combine between fourth and fifth generations using such methodology. They didn't insist too much on their design for 5G applications. A highly isolated 8-antenna MIMO array operating in the band in between (3.4-3.6 GHz) for future smartphones is proposed in Li, et al. (2019). According to the authors of (Li, et al., 2019), their design can provide a balanced slot mode and a required polarization diversity can also be satisfied. Where the latter can mitigate the coupling between antenna elements further more. Their results show an impedance matching of return loss > 10 dB, high isolation >17.5 dB, high total efficiency >62%, and low envelope correlation coefficient (ECC, <0.05) across the desired operation bandwidth.

The article in Sun et al. (2020) proposed a self-decoupled pair MIMO antenna with a shared radiator for 5G smartphones. They have tried in their design to avoid the need for any extra decoupling structures, the two ports of their design were naturally isolated across a wide bandwidth. The proposed design of (Sun et al., 2020) shows a (11.5) dB better isolation across a 5G band of (3.3-4.2 GHz). They also tested an antenna array system (8 × 8 MIMO) constituted by four pairs from the proposed design. They simulated, fabricated, and measured the array to validate the concept of their study. Their results show a total efficiency of (63.1-85.1%) at (3.3-4.2 GHz). They supported their design scheme by characteristics such as self-decoupling, shared radiator, simple structure, and advantages of wide bandwidth and high efficiency.

An 8-element MIMO antenna array formed by combining 4 sets of dual-antenna pairs operating in the 5G new radio band (3.3-4.2 GHz) and 5 GHz band (4.8-5GHz) in mobile handsets is presented in Cui, et al. (2019). According to the authors, their results show a good reflection coefficients and acceptable isolations for the unit structure and decoupling structures, the antenna efficiencies achieved was better than 53% across the LB (3.3–4.2 GHz) and HB (4.8–5 GHz).

Conclusions

This study provides a general overview on the major impairment of wireless communication channels and the main mitigation strategy. This paper concludes that diversity technique is a powerful tool to mitigate the fading problem especially the space diversity technique. Space diversity is the most important diversity type because it's considered as the base for the promotion of MIMO systems. MIMO systems are very important and essential technology in modern communication systems. But there was a concern that the multiple parallel transmitter and receiver chains may lead to an increased hardware cost. Also, deploying multiple antennas might need increased power consumptions. Moreover, there was a doubt from the possibility of implementing multiple antenna techniques in real time. however, the provided review in the last section of this paper about its recent applications and proposed models for 5G smartphones showed that MIMO systems can be implemented and the concerns can be addressed. Based on the results presented by last section researches, MIMO systems are a good option for smartphones in 5G communication systems and the practical implementations of proposed designs showed desired results in terms of efficiency, bandwidth, isolation, decoupling, and diversity. It can be concluded that the implementation of multiple antenna techniques in real time is possible at a relatively low power consumption level and a relatively low cost if the power and cost of the smartphone is taken as a reference.

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