Virtual Lab Experiments for Wireless Communications

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1 Virtual Lab Name and Discipline

Name of Lab: Virtual Lab in Wireless Communications
Discipline: Electronics and Communication Engineering
Target group: UG, MS, and PhD students

2 Relevant AICTE Course

Mobile communications and networks is a core ECE course in the AICTE model curriculum ECEL09, page 392.

3 List of Experiments

The experiments being proposed are listed below:

No.	Name of Experiment
1.	Pathloss and Shadowing
2.	Outage probability and cell coverage
3.	Two ray model based wireless channels
4.	Wireless Fading Channel: Clarke's Model
5.	Spatial diversity (SIMO, MISO)
6.	Spatial multiplexing (MIMO)
7.	Multiplexing vs. Diversity
8.	Receiver architecture: ZF and MMSE
9.	Orthogonal frequency division multiplexing

4 Related Virtual Labs available on the Web

To the best of the author's knowledge, there is no virtual lab available on the link-level experiments of wireless communication systems. However, there is a virtual lab titled "Fading Channels and Mobile Communications" that is currently available on `http://vlabs.iitkgp.ernet.in/fcmc/#`. It is to be noted that this lab deals with experiments on various operational aspects of cellular networks. Nonetheless, the proposed list of experiments has no overlap with this virtual lab.

5 Pedagogical Value of Experiments

The Virtual Labs for Wireless Communications complement the theory (textbook) approach and the simulations to understanding the concepts. The focus of these experiments is to build a collection of small simulations in which the student may either (a) watch the execution of a concept (b) drive the experiment by using controls (buttons) to achieve the result of simulating a given concept. In the next few subsections, we sketch the need and structure of the experiments we wish to build. More details of the structure of the experiments will become apparent once their development commences.

5.1 Pathloss and Shadowing

5.1.1 Topic Description

Link budget is an important aspect of wireless communication system design. The link budget basically depends on various design parameters (like operational frequency, transmission power, and antenna gain) and wireless propagation environment impact in terms of path-loss and shadowing. Path loss is caused by isotropic dissipation of the power radiated by the transmitter while the path-loss exponent is a type of propagation environment including urban, suburban, and rural, etc. However, shadowing is the phenomenon of additional path-loss caused by obstacles between the transmitter and receiver that attenuate signal power through absorption, reflection, scattering, and diffraction. For example, the receiver located in the basement of a building may experience a huge path loss as compared to when it is situated at the top of the building. These variations in path-loss are described by the shadowing.

5.1.2 Need for experiment

An accurate characterization of the path-loss and shadowing are crucial for planning the link budget for the wireless systems for a given propagation environment and communication rage requirement. The path-loss variance (at a given distance between transmitter and receiver), spatial decorrelation distance and path-loss exponent are the major components of the path-loss and shadowing models which mainly depend on the propagation environment. This experiment will help the students in understanding the path-loss and shadowing in detail and their impact on the link budget.

5.1.3 Experiment description

- **Aim** : The objective of this experiment is to comprehend how
  - the path-loss is dependent on the distance between transmitter and receiver d, the carrier frequency of transmitted signal f_c, the antenna gain G, and path-loss exponent α etc.
  - the impact of shadowing depends on the mobile user's position with respective to its surrounding environment.
- **Visualization**: A user interface will be developed to allow the student to vary the design parameters and receiver position to observe how path-loss and shadowing impact the received signal power.

- **Controls**: The system parameters that can be controlled are 1) transmission power, 2) carrier frequency, 3) density of building, 4) position of the mobile user, 5) antenna gain, and 6) path-loss exponent.

A schematic of the experiment's visual interface is shown in Figure 1.

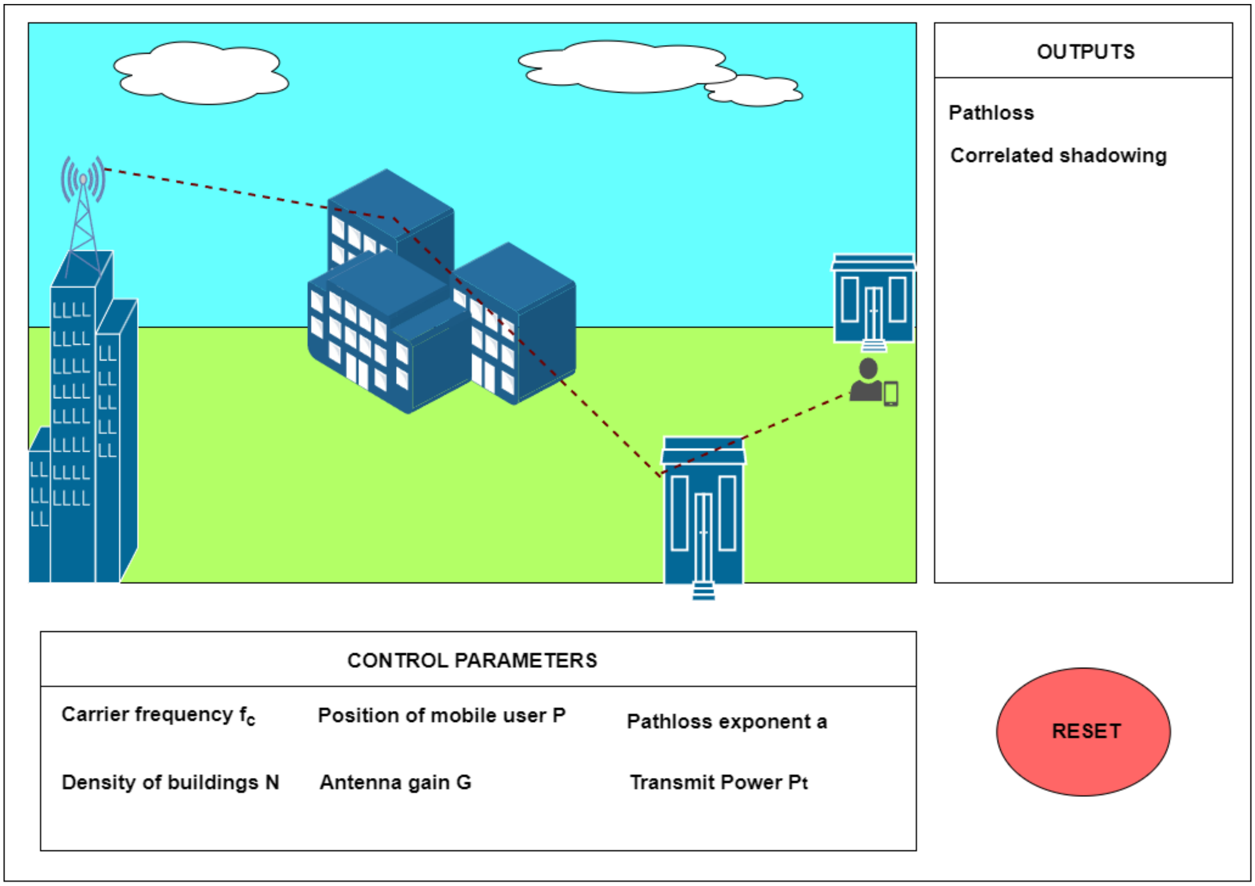

Figure 1: Pathloss and Shadowing

5.2 Outage probability and cell coverage

5.2.1 Topic description

In wireless systems, there is typically a target minimum received power level P_{min} (or, equivalently minimum required signal-to-noise ratio) below which the bit error rate (BER) performance of the decoder/receiver becomes unacceptable. As described in Experiment 1, the path loss experienced at a given distance is random because of the shadowing which in turn makes the received power random for a given distance between the transmitter and receiver. This is characterized by outage probability $P_{out}(d)$ defined as the probability that the received power at a given distance d is below a predefined threshold.

The cell coverage area of a cellular base station (BS) is defined as the percentage of area within a cell that has received power above the target P_{min}.

5.2.2 Need for virtual experiment

Outage probability is a critical parameter in the design of wireless systems because it helps determine the required transmission power, transmission capacity, and other key system parameters to achieve a desired level of reliability in wireless communications. Analysis of outage probability can help determine the cell coverage area, equivalent to the average number of mobile users in the cell that experience the received SNR above a certain threshold. Therefore, cell coverage is an important parameter to ensure the desired level of quality of service (QoS) in the cellular networks.

5.2.3 Experiment Description

- **Aim**: The objective is to understand the concept of the outage probability and the cell coverage area and how they get affected by the configuration of system parameters.
- **Visualization**: A user interface will be developed to provide a good visualization to the students explaining the concepts of the outage probability and cell coverage area.
- **Controls**: System parameters that can be controlled are 1) cell radius, 2) transmission power, 3) Shadowing variance 4) distance b/w the BS and mobile user and 5) path-loss exponent.

A schematic of the experiment's visual interface is shown in Figure 2.

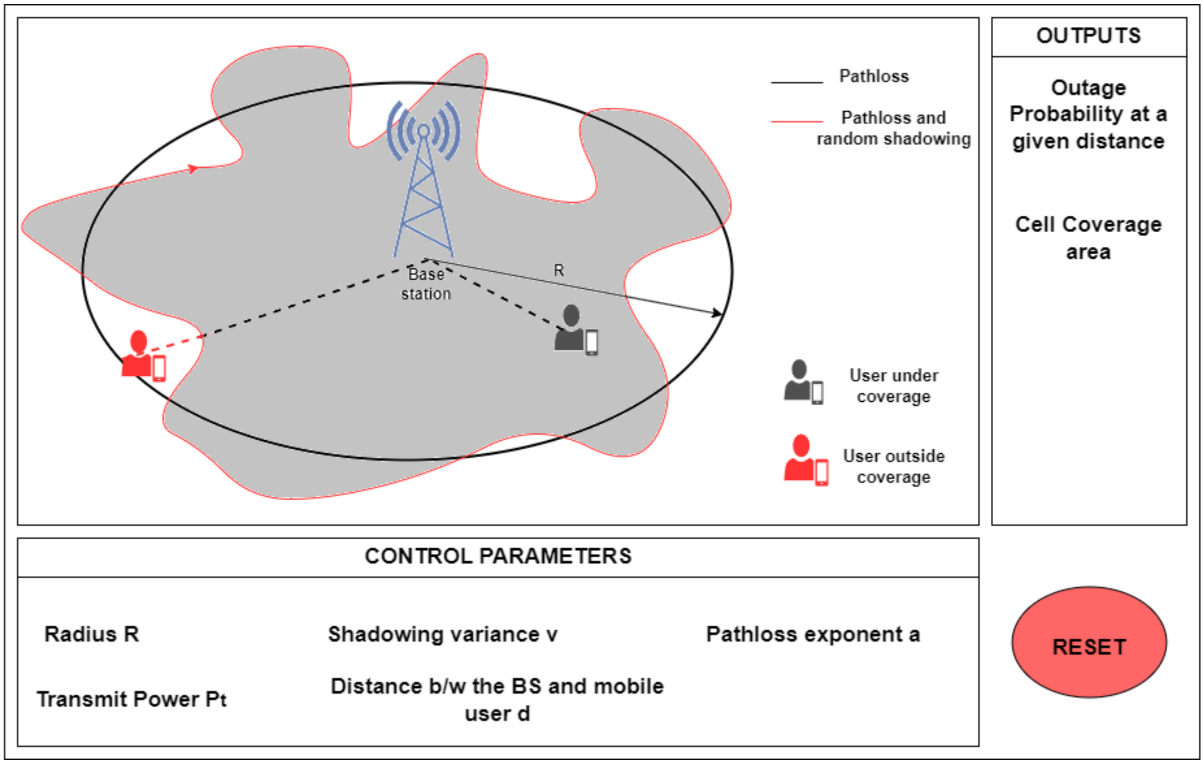

Figure 2: Contour of coverage area

5.3 Two ray model based wireless channels

5.3.1 Topic description

Experiments 1 and 2 deal with the path-loss and cell area, both of which are results of the large-scale fading of wireless propagation. The transmitted signal reaches the receiver through multiple paths (because of signal gets reflected from multiple obstacles present in the propagation environment). These multi-path signals get added at the receiver in a constructive or destructive manner which in turn results in the multi-path fading of the wireless channel. Furthermore, because of mobility, the mobile user undergoes the pattern of constructive or destructive superposition of the multi-path component, which makes the wireless channel as time-varying system. The multi-path fading effect of the wireless channels is characterized by 1) coherence time, 2) Doppler spread, 3) delay spread and 4) coherence bandwidth.

5.3.2 Need for virtual experiment

The multi-path component in the received signal is generally a result of a large number of paths. Thus, applying the law of large numbers, it is possible to statically characterize the behavior of the wireless channel multi-path fading. However, it limits the understanding of how multi-path fading affects the coherence time and coherence bandwidth of the channel. Therefore, to give a useful insight into how the parameters associated with wireless channel behaves, this experiment describes simple cases of two-ray-based wireless channels including 1) free space with a fixed receiver, 2) free space with a moving receiver, 3) reflected wall with a fixed receiver, and 4) reflected wall with the moving receiver. Case 1 mainly deals with the electromagnetic wave (EM) received in the free space. Case 2 deals with the Doppler shift (resulting due to mobility) and coherence time. Case 3 deals with the deal spread and coherence bandwidth. Finally, Case 4 provides a fading effect with all the above cases combined.

5.3.3 Experiment Description

- **Aim** : The objective is to understand the Coherence time, Coherence Bandwidth, Doppler spread and Delay spread using the the following simple cases of two-ray-based wireless channel

    1. Free space with fixed receive antenna
    2. Free space with moving receive antenna
    3. Reflecting wall with fixed receive antenna
    4. Reflecting wall with moving receive antenna

- **Visualization** : A user interface will be provided that will prompt the user to select a particular case and configure the system and allow to observe the behaviour of wireless channel parameters associated with that particular case.

- **Controls** : The system parameters that can be controlled are 1) Carrier frequency, 2) Velocity of the mobile user, 3) Distance between the Tx and Rx, and 4) Distance between the Tx and reflecting wall.

A schematic of the experiment's visual interface is shown in Figure 3.

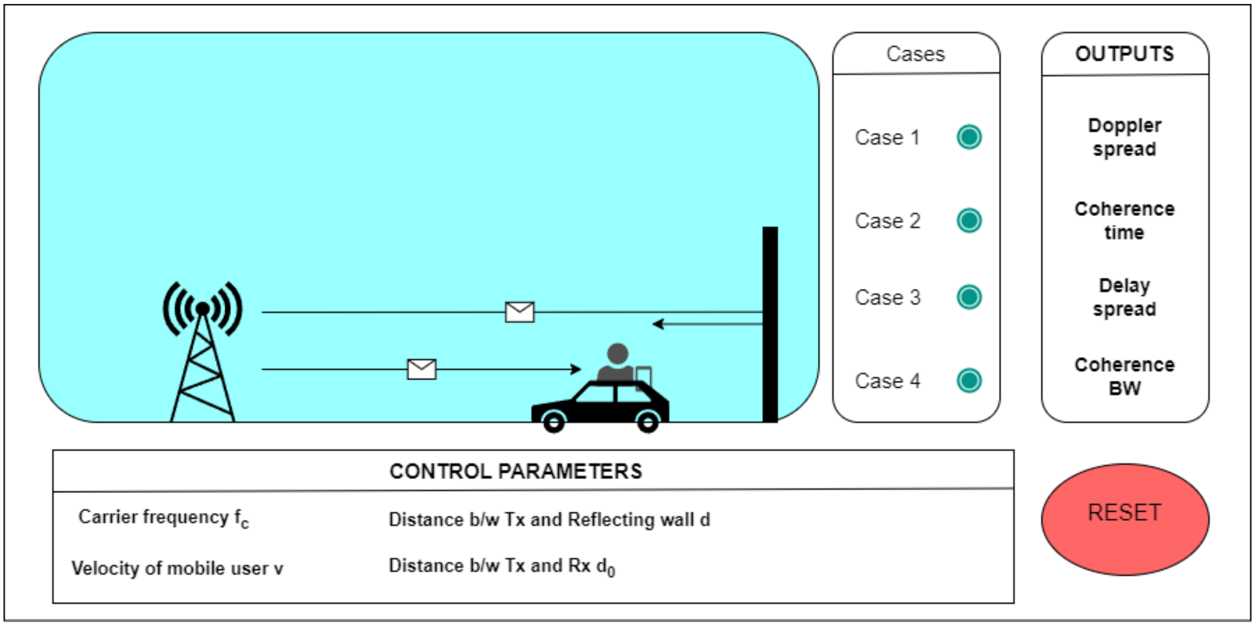

Figure 3: Illustration of Case 4 (Combination of Cases 1,2, and 3)

5.4 Wireless Fading Channel: Clarke's Model

5.4.1 Topic Description

As highlighted in Experiment 3, the multi-path fading coefficient of the wireless channel is a random process that exhibits the temporal correlation depending on the velocity of the mobile user or the observed Doppler shift. Furthermore, at a given time, the multi-path fading coefficient can be modeled as the complex Gaussian using the argument of the Central Limit Theorem for the super-positioning of a large number of multi-path components received from isotropically distributed obstacles in the absence of the direct line of sight components. This model is referred to as the Rayleigh fading model. However, in order to generate the multi-path fading random process observed by the mobile user, it becomes imperative to generate correlated complex Gaussian random samples. Such multi-path fading can be implemented using Clarke's model.

5.4.2 Need for experiment

The wireless channel model is time-varying and its rate of variation increases with the increase of mobile user velocity (i.e., a faster-moving mobile user observes rapidly changing multi-path fading coefficient). Besides, interestingly, the multi-path fading exhibits a stationary behavior over a small time scale. In other words, the multi-path fading can be treated as a random process with a high correlation over a small time interval. This implies that the wireless channel can be treated as the LTI system over a small time interval whose impulse response changes after every coherence interval period. Therefore, to understand how mobility affects the coherence time of the wireless channel, it is important to implement the correlated multi-path fading.

5.4.3 Experiment description

- **Aim**: Implementation of the multi-path fading process observed by a mobile user using Clarke's model.
- **Visualization**: A user interface will be developed to show the behaviors of the multi-path fading process observed by the mobile user. Here, students will be able to control the moving speed to observe changes in the wireless channel variations. As the statistical behavior metrics, we will also provide the visuals of auto-correlation (time domain characterization) and Doppler spread (frequency domain characterization) of the fading process observed by the mobile user.
- **Controls**: The control parameters are 1) velocity of mobile user, 2) number of multi-paths, 3) drop in the percentage of coherence time, and 4) carrier frequency.

A schematic of the experiment's visual interface is shown in Figure 4.

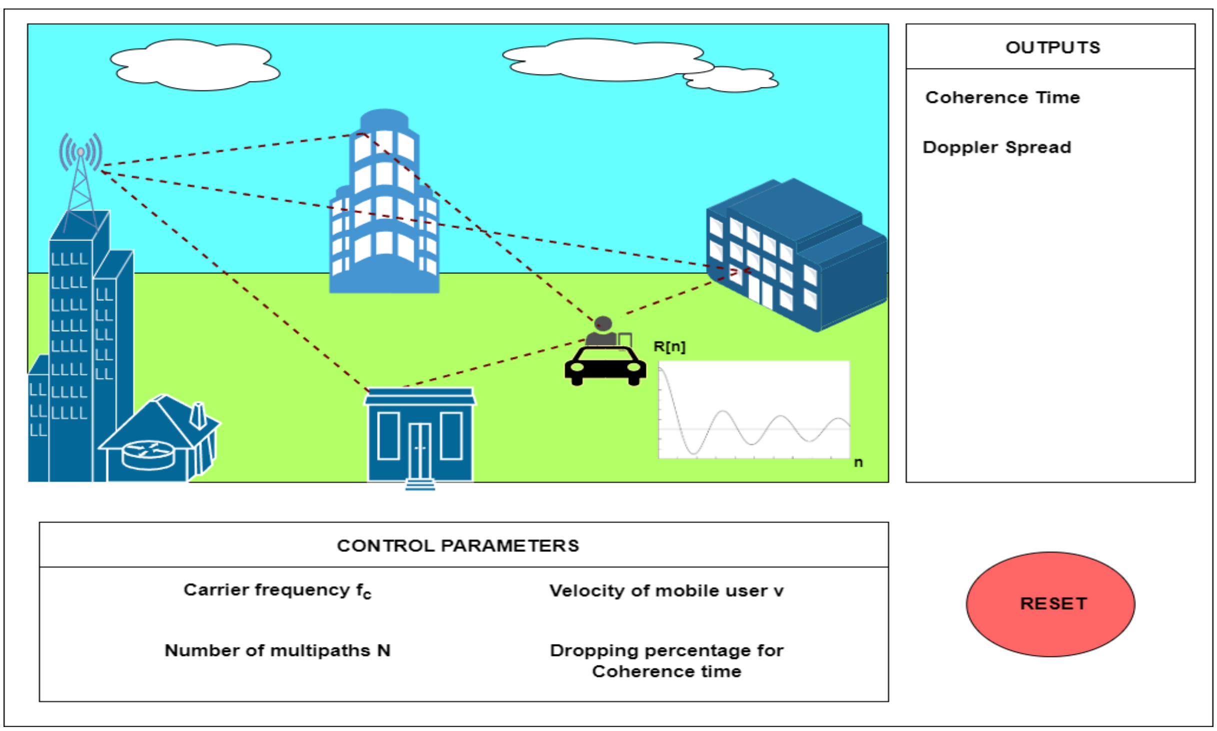

Figure 4: Temporally correlated multipath fading

5.5 Spatial diversity (SIMO and MISO)

5.5.1 Topic Description

As discussed above, wireless fading is a random process where the strength of the received signal varies with time. This implies that there is a probability that the received SNR goes below a predefined threshold for which the communication becomes unreliable. This probability is called a probability of deep fade.

The wireless channel fading varies over time, space and frequency. This experiment is focused on utilizing the spatial diversity of wireless channels. The wireless channel fading appears to be independent when observed from different antennas separated by a distance larger than $\lambda/4$. Utilizing this fact, the receiver can employ multiple antennas to increase diversity in the signals (received along multiple antennas) so that they can be combined/used to push overall received SNR above the threshold and thereby decrease the deep fade probability. This system is called a single-input-multiple-output (SIMO) communication system. Similarly, the transmitter can employ multiple antennas to get the diversity gain. This system is called a multiple-input-single-output (MISO) communication system.

5.5.2 Need for experiment

The deep fade probability is a crucial aspect that limits the capacity of the wireless channel. Basically, the deep fade probability increases with the increase of transmission rate as the required minimum SNR threshold increases for reliable communication at higher transmission rates. Therefore, the transmission rate becomes restricted from the perspective of reliable communication because of the deep fades. Through this experiment, the student can learn how spatial diversity can be exploited by employing multiple antennas at the transmitter or receiver to increase the received SNR. This will help to reduce the deep fade probability which in turn allows reliable communication at a higher rate.

5.5.3 Experiment Description:

- **Aim**: The objective is to study the diversity of SIMO and MISO systems for the following combining techniques
  1. Selection combining
  2. Equal gain combining
  3. Maximum ratio combining
- **Visualization**: A user interface will be developed to highlight the diversity in the received signal along the different antennas. Further, we will also provide the appropriate visuals for each combining technique and its resulting mean SNR, SNR distribution and improvement in the deep fade probability.

- **Controls** : The control parameters are 1) number of antennas, 2) noise power, and 3) spacing between the antennas.

A schematic of the experiment's visual interface is shown in Figure 5.

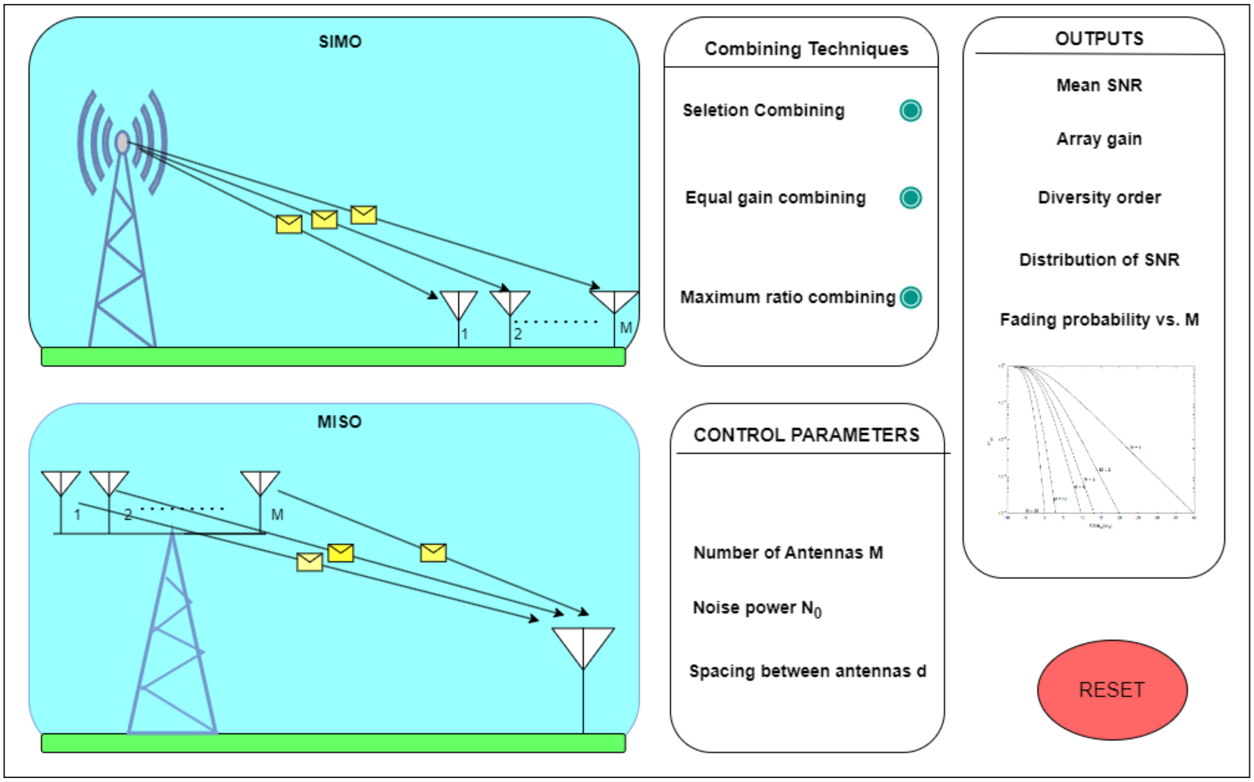

Figure 5: Spatial diversity: SIMO and MISO systems

5.6 Spatial multiplexing (MIMO)

5.6.1 Topic Description

In the previous experiment, we learned about how the spatial diversity via multiple antennas can be used to enhance the received SNR and thereby ensure reliable communication. In this experiment, the objective is to maximize the transmission capacity by making use of spatial diversity through the multiple antennas at the transmitter and the receiver, i.e. multiple-input and multiple-output (MIMO) system. Assuming the knowledge of the channel state information (CSI) at the transmitter, we can convert the MIMO channel into multiple non-interfering parallel SISO channels via singular value decomposition (SVD) based preprocessing and postprocessing at the transmitter and receiver, respectively. Then multiple independent streams of data can be multiplexed along these parallel SISO channels which in turn gives an increased transmission rate. This scheme is called spatial multiplexing. The maximum number of parallel channels, also called multiplexing order, is equal to the minimum of the number of antennas at the transmitter and receiver. Therefore, the overall transmission capacity that can be achieved by spatial multiplexing is equal to the multiplexing order times the transmission capacity of the SISO channel. The achievable transmission capacity for each data stream is equal to that of the SISO channel. Therefore, to further maximize the overall transmission capacity, the optimal power allocation to parallel channels can be done using a Waterfilling algorithm.

5.6.2 Need for experiment

As highlighted above, the transmission rate can be maximized via the spatial multiplexing. However, the concepts of parallel channel decomposition and optimal power allocation to improve the transmission capacity are crucial for understanding the fundamentals of MIMO systems. Through this experiment, we intend to provide visual insights into the working principle of spatial multiplexing. In particular, we focus on describing how the MIMO system can improve the channel capacity as compared to the SISO system and how it is related to the dimensions of transmit and receive signals, and the transmission power available at the transmitter.

5.6.3 Experiment Description

- **Aim**: To study the working principle of spatial multiplexing scheme for MIMO systems.
- **Visualization**: A user interference will be developed to highlight the various operational features of parallel SISO channels that can be established via spatial multiplexing and also show their capacity performance.
- **Controls**: The control parameters are 1) number of transmit antennas M_T, 2) number of receive antennas M_R, and 3) total transmission power P.

A schematic of the experiment's visual interface is shown in Figure 6.

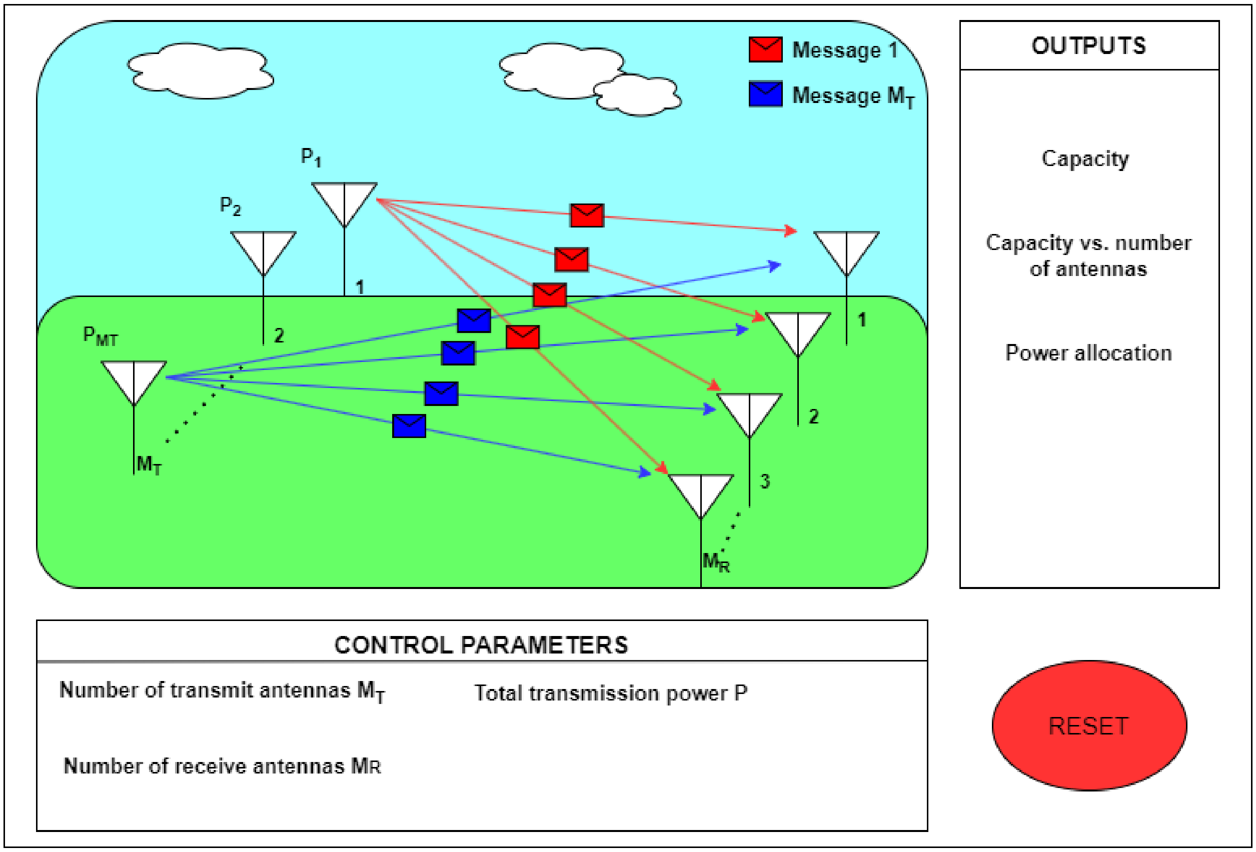

Figure 6: Spatial multiplexing in MIMO system

5.7 Multiplexing vs. Diversity

5.7.1 Topic Description

In the previous two experiments, we learned about two key techniques, named spatial multiplexing and diversity, for MIMO wireless systems. The spatial multiplexing decomposes the MIMO wireless channels into parallel SISO channels in order to facilitate the simultaneous transmissions of the data streams and thus provide higher transmission capacity. On the other hand, the diversity technique is aimed at improving the received SNR to ensure reliable communication. However, it is possible to get the benefits of both these techniques combined by appropriately configuring the transmit and receive antennas for interference cancellation (via SVD-based approach) and signal combining (via maximum ratio combining).

5.7.2 Need for experiment

It is not necessary to use the antennas purely for multiplexing or diversity. Some of the space-time dimensions can be used for diversity gain, and the remaining dimensions used for multiplexing gain. This gives rise to a fundamental design question in MIMO systems: should the antennas be used for diversity gain, multiplexing gain, or both? For $M_T \times M_R$ MIMO system, the maximum diversity order is equal to $M_T M_R$ and the maximum multiplexing gain is equal to $\min(M_T, M_R)$. However, there is a trade-off between diversity and multiplexing when both schemes are used together. The diversity order reduces to $(M_T - r)(M_R - r)$ when the multiplexing gain is r. This experiment helps understand the interplay between diversity and multiplexing gains, or more generally the trade-off between data rate and probability of error.

5.7.3 Experiment Description

- **Aim**: The objective is to study the diversity-multiplexing trade-off for a MIMO system.
- **Visualization**: A user interface will be developed to show how the optimally configured transmit and receive antennas provide multiplexing and diversity gains. To facilitate better learning, the MIMO (antenna-to-antenna) links will be highlighted appropriately to show the parallel streams (giving multiplexing gain) and combining links (giving diversity gain).
- **Controls** : The control parameters are 1) number of transmit antennas M_T, 2) number of receive antennas M_R, 3) desired multiplexing order $r < \min(M_T, M_R)$, and 4) total transmission power P.

A schematic of the experiment's visual interface is shown in Figure 7.

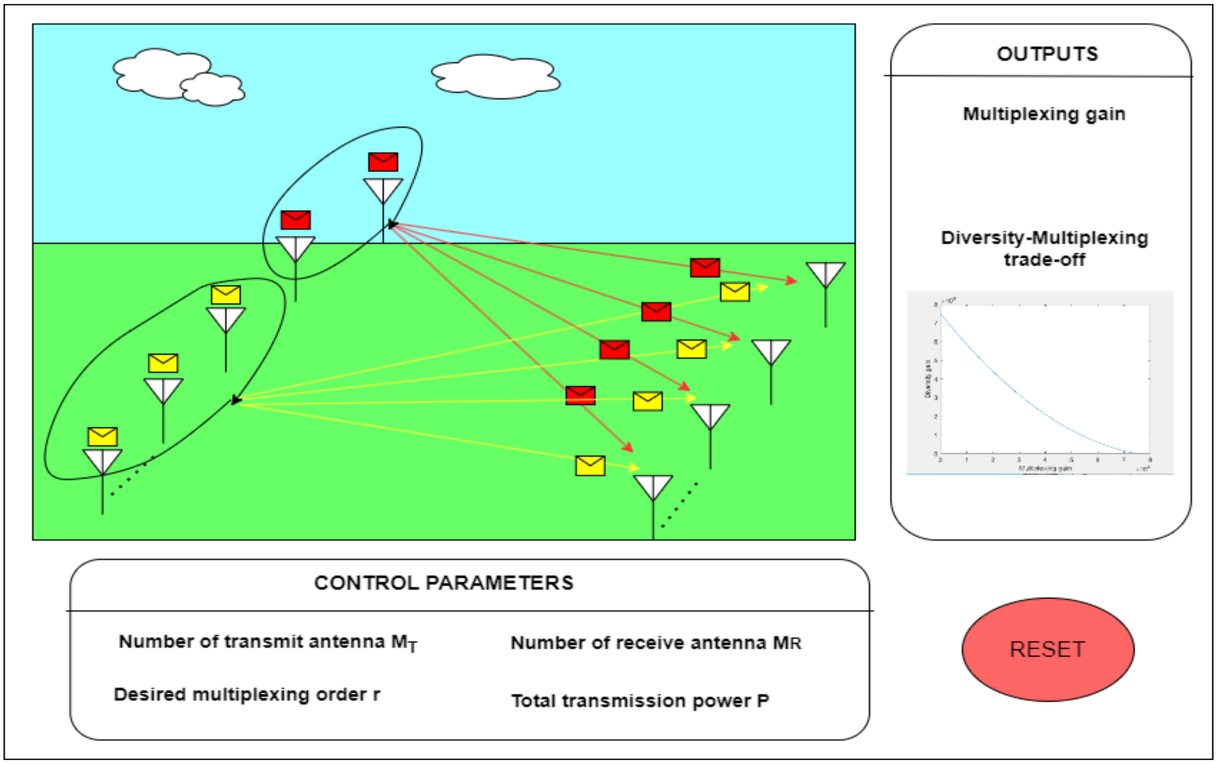

Figure 7: Illustration of diversity-multiplexing tradeoff

5.8 Receiver architecture: ZF and MMSE

5.8.1 Topic Description

An important aspect of wireless channels is frequency selective fading, which is inevitable when the transmission symbol duration is small (or equivalently the transmission bandwidth is large). The frequency selective fading will lead to the inter-symbol-interference (ISI). There are three main techniques that can negate the ISI in the wideband channel including 1) channel equalization, 2) multi-carrier modulation and 3) spread spectrum. These three techniques will be covered in the next three experiments.

This experiment is designed to visually explain the working principle of most fundamental channel equalization methods, namely 1) zero-forcing (ZF) and 2) minimum mean square error (MMSE). The objective of the ZF is to negate the impact of the wireless channel, whereas the MMSE minimizes the mean square error in estimating the transmitted symbol.

5.8.2 Need for experiment

ZF equalization method suffers from poor BER performance in the low regime of SNR. This is typically because of the ZF method may cause in amplifying the noise component in the process of reversing the channel impact when the channel gain is small. On the other hand, the MMSE equalization aims to maximize the output SNR and provide better BER performance for a wide range of SNR as compared to ZF. This experiment will be designed to offer visual learning of the comparative performance analysis of ZF and MMSE equalization methods for wideband wireless channels. Besides, this experiment will also present the implementation of ZF and MMSE equalizers using a N-tap transversal filter.

5.8.3 Experiment Description

- **Aim**: The objective is to demonstrate the working operation and analyze the performance of
    1. Zero forcing equalizer
    2. minimum mean square error (MMSE) equalizer
- **Visualization**: A user interference will be provided to show the complete chain of a single process from the transmitter input to the receiver output, particularly highlighting the operation of channel impact and equalizer operation. In addition, we will also provide visual insights in a comparative performance analysis of the ZF and MMSE equalizer.
- **Controls**: The students will be able to control 1) transmission power P, 2) channel bandwidth W, and 3) the number of taps N.

A schematic of the experiment's visual interface is shown in Figure 8.

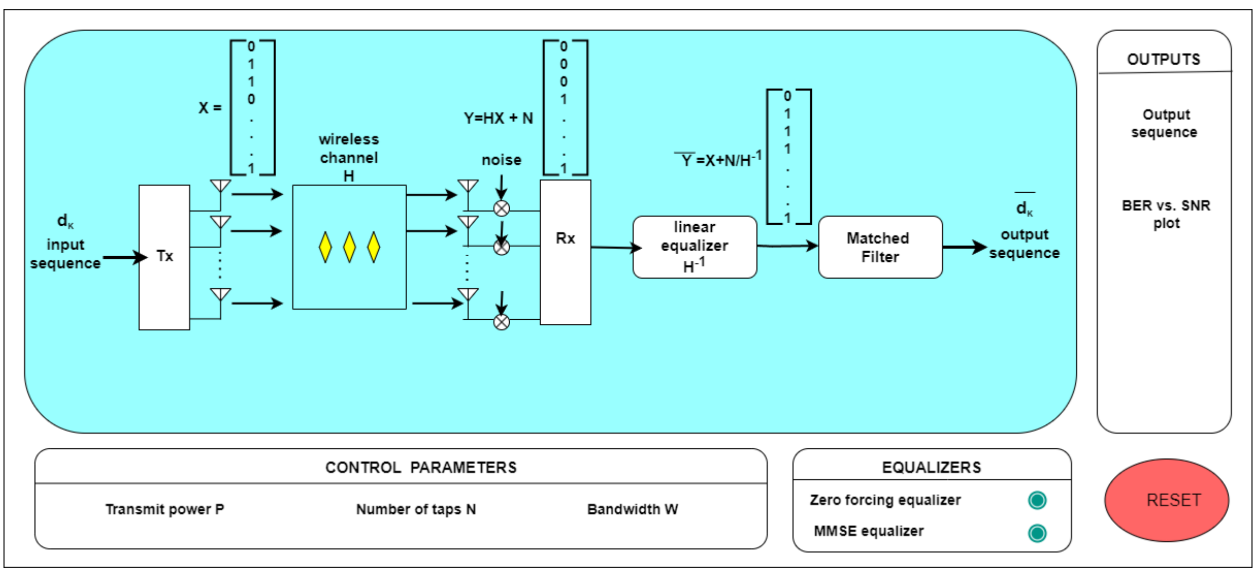

Figure 8: Single carrier communication with channel equalization

5.9 Orthogonal frequency division multiplexing

5.9.1 Topic Description

Orthogonal frequency division multiplexing (OFDM) is one of the most popular multi-carrier modulation schemes for overcoming ISI in wideband channels. Basically, OFDM divides system bandwidth into multiple sub-carriers such that each sub-carrier can be modulated using an independent stream of data symbols. This way the wideband channel is converted into multiple narrow band channels. In OFDM, the subcarrier frequencies are chosen so that the subcarriers are orthogonal to each other which eliminates the inter-sub-carrier interference. This greatly simplifies the design of both the transmitter and the receiver. The transmitter performs the IFFT operation to transform the modulated sub-carriers in a time domain signal and then transmits it. The receiver employs FFT operation on the received signal to transform it to acquire modulated sub-carriers in the frequency domain and then decode each subcarrier independently.

5.9.2 Need for experiment

OFDM is the most widely utilized modulation scheme in wireless communication standards including 4G, 5G, WiFi, etc. However, its design architecture heavily relies on the fundamental concepts from signal processing for converting the wideband channel into N parallel non-interfering narrowband channels. These concepts sometimes can be difficult for students to understand. Therefore, to facilitate better learning, this experiment is designed to provide step-by-step operational details of the OFDM system.

5.9.3 Experiment Description

- **Aim**: Implementation of the OFDM system.
- **Visualization**: A user interface will be provided to explain the step-by-step operations of various blocks involved in the OFDM system.
- **Controls**: The control parameters are 1) number of sub-carriers N, and 2) signal bandwidth W.

A schematic of the experiment's visual interface is shown in Figure 9.

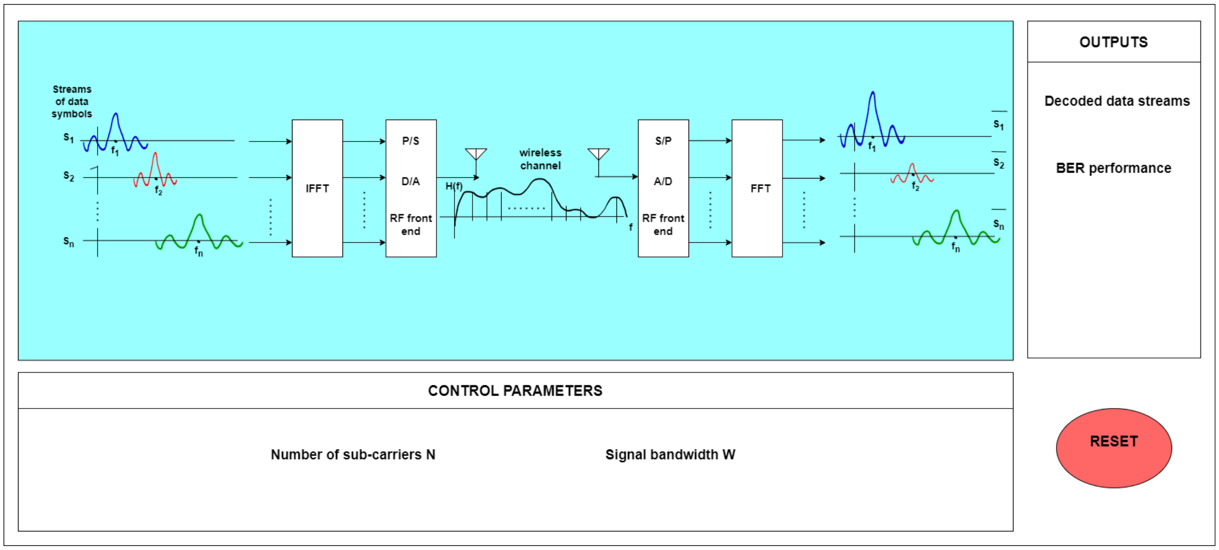

Figure 9: OFDM communication system

6 Familiarity and experience with the subject matter

The author's primary focus in teaching and research is wireless communication, and the proposed list of experiments is well-aligned with his expertise. The author has been teaching the listed topics as a part of wireless communications theory course at IIIT for the past two years and plans to continue doing so for several more years. Additionally, the author has published several research articles closely related to some of the listed experiments.

7 Technology

All the experiments will be developed as static web applications using Javascript (or Elm, which compiles to Javascript), HTML5 and CSS.