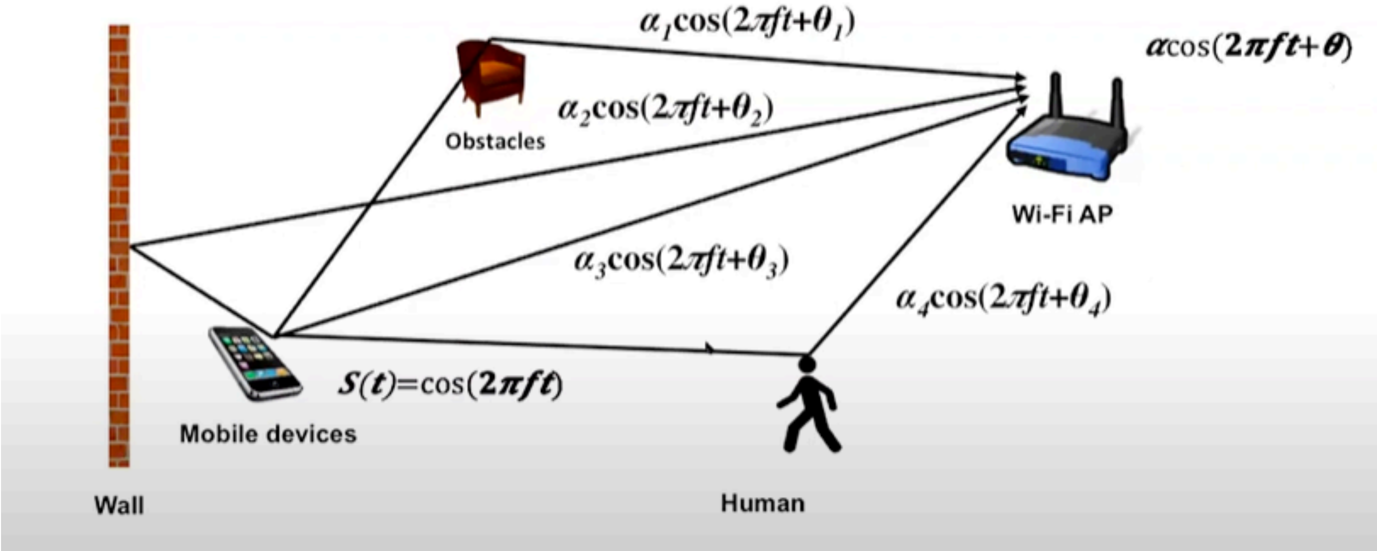
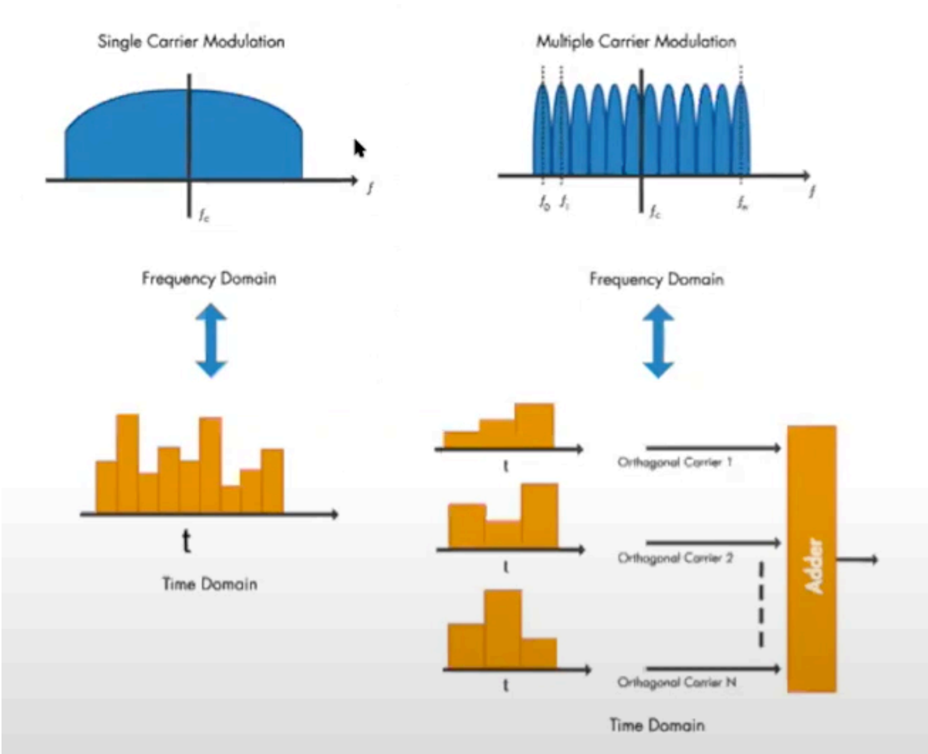
Wifi Sensing

1 Basic Knowledge of WiFi Sensing



WiFi signals carries information about the obstacles in the propagation environment because of the multipath reflections. As the above picture shows, when the mobile devices send $\mathbf{s}(t)$ to the WiFi AP, the WiFi signals (electromagnetic waves) will be reflected by the surroundings, thus results in the multi-path effect.



The above picture shows the multiple carrier modulation in the newest WiFi standards. Recent WiFi standards (11n/ac/ax) require Channel State Information (CSI). Commodity WiFi chipsets are now capable of extracting CSI. The CSI let us know the detail of how different frequency components be affected by the envionment. The wider the wifi bandwidth is, the more amount of CSI information generated by it will be.

Lets consider a very simple example. Suppose that you have a transmitter and a receiver which have 3 antennas separately. Every antenna of the transmitter will send packets to all of the antennas of the receiver. So, in this way, we can have a $\mathbf{3} \times \mathbf{3}$ matrix to present the fading channel of each group of packets.

To be more general, in a MIMO communication system, the most commonly used model is the linear.

$$\mathbf{y} = \mathbf{Hx}+\mathbf{n}$$

$\mathbf{y}$ is the received signal vector, $\mathbf{H}$ is the channel state matrix, generally CSI matrix, $\mathbf{n}$ is noise.

2 Time Reversal Focusing Effect

2.1 Time Reversal System

The signal is transmitted by the source node and transmitted through the complex space environment. The signal is sampled and recorded by the surrounding closed time reversal cavity (TRC) surface and stored, and then sent back to the space after the time reversal reverse order operation. The final signal is reconstructed at the source node.

Suppose the transmitter and receiver of the system is A and B seperately, according to **Channel Reciprocity Theorem**, the impulse response received by B is $h_{AB}(t)$. On the contrary, if the transmitter is B, and the impulse response received by A is $h_{BA}(t)$. The channel reciprocity theorem can be presented as:

$$h_{AB}(t) = h_{BA}(t)$$

2.2 Multipath Effect

The multipath effect is formed due to the existence of multiple transmission paths between the transmitter and the receiver. The actual propagation environment may be more complicated, and each reflecting surface is not an ideal mirror surface. Even within a stretched pulse, it is composed of many micropaths, so it appears as a stretched pulse.

At the same time, the signals of multiple paths are superimposed at the receiving end. Because these signals have a phase difference, when the signals arriving from different paths are in the same phase or the phase difference is an acute angle, the amplitude increases; otherwise, the amplitude decreases.

The channel impulse response can be written as:

$$h(t) = \sum_{l=1}^{l} \alpha_l \delta(t - \tau_l)$$

where α_l and τ_l represent the amplitude and delay of the multipath seperately.

The signal received by the receiver is:

$$y(t) = x(t) * h(t) = x(t) * \sum_{l=1}^{l} \alpha_l \delta(t - \tau_l)$$

where $x(t)$ is transmitted signal. The received signal is processed to get $y(-t) = x(-t) * h(-t)$, and then the processed signal is transmitted again. At this time, the signal received at the source node is the required signal:

$$y_{TR}(t) = y(-t) * h(t) = x(-t) * h(t) * h(-t) = x(-t) * h_{eq}(t)$$

where $h_{eq}(t)$ is known as Equivalent Channel Impulse Response in time reversal wireless communications.

$$\begin{aligned} h_{eq}(t) &= (\sum_{l=1}^{L} \alpha_l \delta(-t - \tau_l)) * (\sum_{k=1}^{L} \alpha_k \delta(t - \tau_k)) \\ &= \sum_{l=1}^{L} \alpha_l^2 \delta(-t - \tau_l) * \delta(t - \tau_l) + \sum_{l=1}^{L} \sum_{k=1,k\neq l}^{L} \alpha_l \alpha_k \delta(-t - \tau_l) * \delta(t - \tau_k) \end{aligned}$$

The first part of the above equation is:

$$R(t) = \sum_{l=1}^{L} \alpha_l^2 \delta(t)$$

which is the autocorrelation function of L propagation multipaths. Obviously, $R(t)$ is a maximum amplitude value at the center instant and is very similar to the unit impulse function.

The second term is the cross-correlation function of different propagation paths, and its sub-dimension is obtained by the superposition and cancellation of incoherent signals, so the summation is much smaller than the autocorrelation function, mainly distributed in the focus peak of the autocorrelation function $R(t)$ sides.

2.3 Time Reversal

The spatial focusing characteristics of time reversal have adaptive characteristics, which can realize spatial multiplexing. When using time reversal technology, at point C, which is a certain distance from point A of the source node, the channel impulse response between point B of the receiver is denoted as $h_{BC}(t)$. Therefore, the expression for the received signal at the non-source node C is:

$$R_C(t) = x(-t) * h_{AB}(-t) * h_{BC}(t)$$

However, the latter two are non-autocorrelated, and the signals will be coherently canceled. The obtained $R_C(t)$ and $x(t)$ are two completely different signals. It can be seen that the restoration of $x(t)$ only occurs at the original launch point A.

The peak power of the signal received at source node A is:

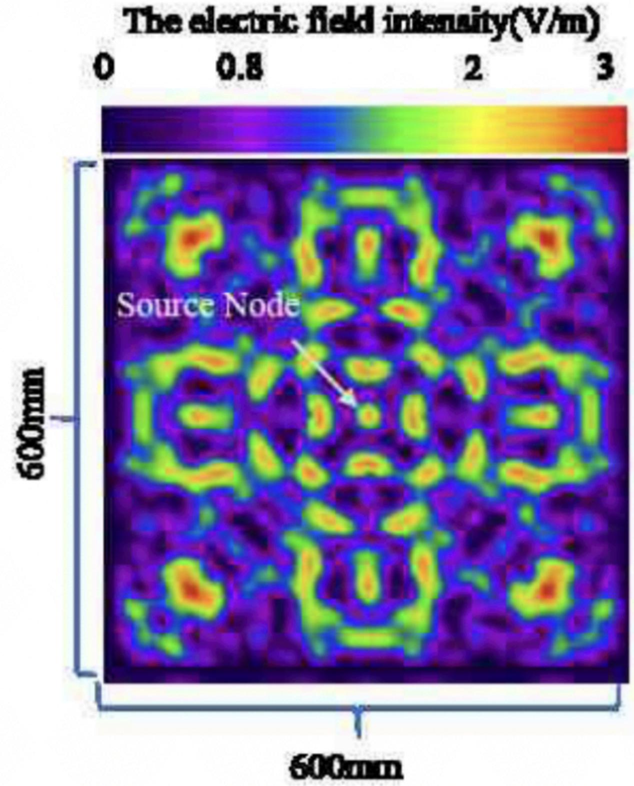
$$P_1 = [max(R_A(t))]^2$$

The peak power of the signal received at the non-source node C is:

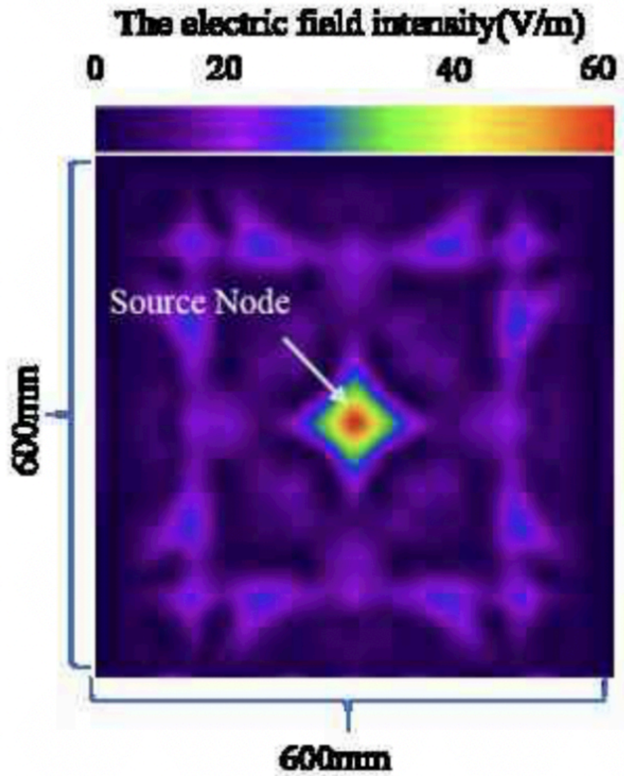
$$P_2 = [max(R_C(t))]^2$$

The ratio of the peak power of the signal received by the source node to the non-source node is defined as:

$$\mu = P_1/P_2$$



Not processed by time reversal



Processes by time reversal

3 Time-reversal Resonating Strength

Time reversal is a physical phenomenon that the energy of the transmitted signal will be focused in both space and time domains when combined with tis time-reversed and conjugated counterpart.

To put it in the context of the WiFi channel, the received CSI, when combined with its time-reversed and conjugated counterpart, will add coherently at the intended location but incoherently at any unintended location, creating a spatial focusing effect as has been analyzed. This explains, fundamentally, why multipath profiles using CSI can underpin high-resolution location distinction. Therefore, we introduce TRRS, a metric that quantifies the time-reversal focusing effect, as the similarity measure for CSI as follows.

The TRRS between two Channel Impulse Response (CIRs) $\mathbf{h}_1$ and $\mathbf{h}_2$ is defined as:

$$\kappa(\mathbf{h}_1, \mathbf{h}_2) = \frac{\left(\max_i |(\mathbf{h}_1 * \mathbf{g}_2)[i]|\right)^2}{\langle \mathbf{h}_1, \mathbf{h}_1 \rangle \langle \mathbf{g}_2, \mathbf{g}_2 \rangle}$$

Where $*$ denotes the linear convolution, $\langle \mathbf{x}, \mathbf{y} \rangle$ is the inner product between vector $\mathbf{x}$ and $\mathbf{y}$, and $\mathbf{g}_2$ is the time-reversed and conjugated version of $\mathbf{h}_2$, i.e. $\mathbf{g}_2[k] = \mathbf{h}_2^*[T-1-k], k = 0, 1, \ldots, T-1$.

In practice, the frequency domain Channel Frequency Response (CFR) is more often used. Equivalently, the TRRS can be expressed for two CFRs H_1 and H_2 As:

$$\kappa(H_1, H_2) = \frac{|H_1^* H_2|^2}{\langle H_1, H_1 \rangle \langle H_2, H_2 \rangle}$$

Obviously, $\kappa(H_1, H_2) \in [0, 1]$, and $\kappa(H_1, H_2) = 1$ if and only if $H_1 = cH_2$ where $c \neq 0$ is any complex scaling factor.