An introduction to CSI from an outsider's perspective

This post gives a basic overview of this growing area of research - Using Channel State information from WiFi Routers for applications like Pose recognition, detection, localization, and other tasks in perception.

Terminology - in laymen terms

- **Channels**: In case of wireless communication, it refers to the medium surrounding Tx, Rx and in-between.
- **Channel State Information:**
  1. Refers to channel properties in wireless communication.
  2. Describes how signal propagates from Tx to Rx. ie. gives information about media b/w Tx and Rx.
- **Attenuation**: Basically refers to the gradual loss in the intensity of a wave through a medium. For example, dark glasses attenuate sunlight, lead attenuates X-rays and water and air attenuate both light and sound at variable attenuation rates.
- **Phase**: of a wave is an angle representing the number of periods spanned by that wave.

Basics of CSI

Channel state information or channel status information (CSI) is information which represents the state of a communication link from the transmit source (aka. Tx) to the receiver source (aka Rx) . CSI represents how wireless signals propagate from the transmitter to the receiver at certain carrier frequencies along multiple paths. For a WiFi system with MIMO-OFDM, CSI is a three-dimensional (3D) matrix of complex values representing the amplitude attenuation and phase shift of multi-path WiFi channels.

A time series of CSI measurements captures how wireless signals travel through surrounding objects and humans in time, frequency, and spatial domains, so it can be used for different wireless sensing applications. For example, CSI amplitude variations in the time domain have different patterns for different humans, activities, gestures, and so on, which can then be used for Preception tasks. CSI is mathematically represented as follows for each Tx-Rx pair:

$$h = |A_n| * \epsilon_n^{\phi}$$

Where A_n represents attenuation and ϕ represents phase shift for a single sub-carrier. Further, the following relation holds for CSI between all Tx and Rx pairs:

$$Y(f,t) = H(f,t) \otimes X(f,t) + N$$

which can be extended to vector or matrix values depending on the number of source and destination elements.

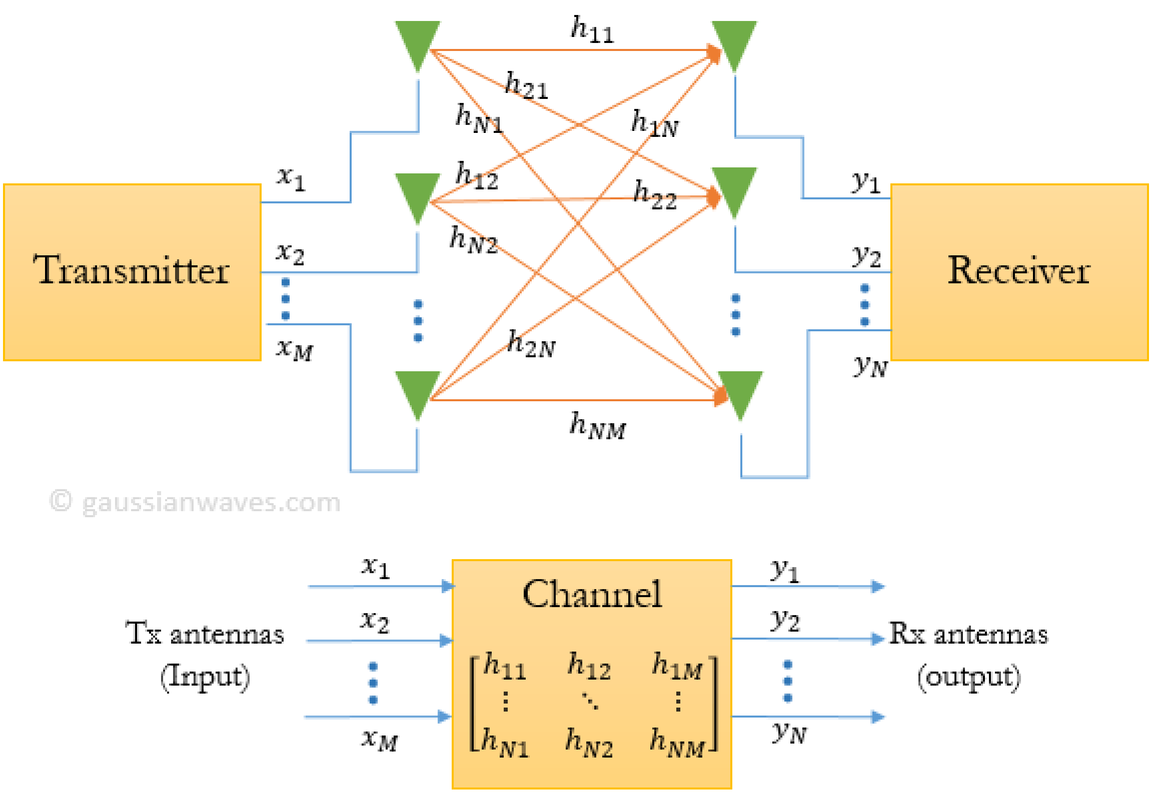
$$H(f,t) = \sum_{n}^{N} a_n(t) e^{-j2\pi f \tau_n(t)}$$

The full equation for the channel state information from baseband-to-baseband is given as follows but the explanation is avoided to maintain the simplicity of this article.

$$H_{i,j,k} = \underbrace{\left(\sum_{n}^{N} a_n e^{-j2\pi d_{i,j,n} f_k / c}\right)}_{\text{Multi-Path Channel}} \underbrace{e^{-j2\pi \tau_i f_k}}_{\substack{\text{Cyclic Shift}\\ \text{Diversity}}} \underbrace{e^{-j2\pi \rho f_k}}_{\substack{\text{Sampling}\\ \text{Time Offset}}} \underbrace{e^{-j2\pi \eta (f_k'/f_k - 1) f_k}}_{\substack{\text{Sampling}\\ \text{Frequency Offset}}} \underbrace{q_{i,j} e^{-j2\pi \zeta_{i,j}}}_{\text{Beamforming}},$$

For better interpretation in physical world please refer the following image from GaussianWaves.

Multiple Input Multiple Output (MIMO) System



MIMO from channel perspective

Types of data collection devices available

Since we can not access the CSI data directly from the devices, people came up with different tools and hacks to tap into the commercially available devices and exploit them to gather the CSI. Following is a table of all the popular tools available right now:

Table 1: Features of different CSI extraction tools, including maximum bandwidth (BW), number of spatial streams (NSS), number of receive chains (NRX), number of subcarriers (NSC), and resolution (Res.) of numbers (i = signed integer, f = signed float mantissa).

Tool	Open Source	Device	Supp. Chipset	max. BW	NSS×NRX	Supp. Std.	NSC	Res.
nexmon CSI Extractor	yes	Router, PCIE e.g. Asus RT-AC86U	BCM43{65, 66}	80 MHz	4×4	VHT/11ac	242	12 bit (f)
	yes	Smartphone, IoT e.g. Nexus 5/6P, RPi3B+/4B	BCM43{39, 58, 455}	80 MHz	1×1	VHT/11ac	242	14 bit (i) or 10 bit (f)
Linux 802.11n CSI Tool	no	PCI	IWL5300	40MHz	3x3	HT/11n	30	8 bits (i)
Atheros CSI Tool	yes	Router, PCIE	AR9580, AR9590 AR9344, QCA9558	40MHz	3x3	HT/11n	114	10 bits (i)
OpenFWWF CSI Tool	no	Router, PCI e.g. Linksys WRT54GL	BCM4318	20MHz	1x1	OFDM/11g	52	12 bits (i)

In the next blog we will go through the setup and installation process for the first tool mentioned here, ie. nexmon CSI Extractor. Other tools and details of their features can be found through following links:

- Linux 802.11n tool
- Atheros tool
- OpenFWWF tool

Areas of Application

The area of application for this unusual modality for perception tasks is huge! And can be divided broadly as follows:

1. Detection - human presence, movement; object detection
2. Recognition - activity, gesture, Id, object recognition
3. Estimation - localization and tracking for humans or objects, bio-sensing and estimation

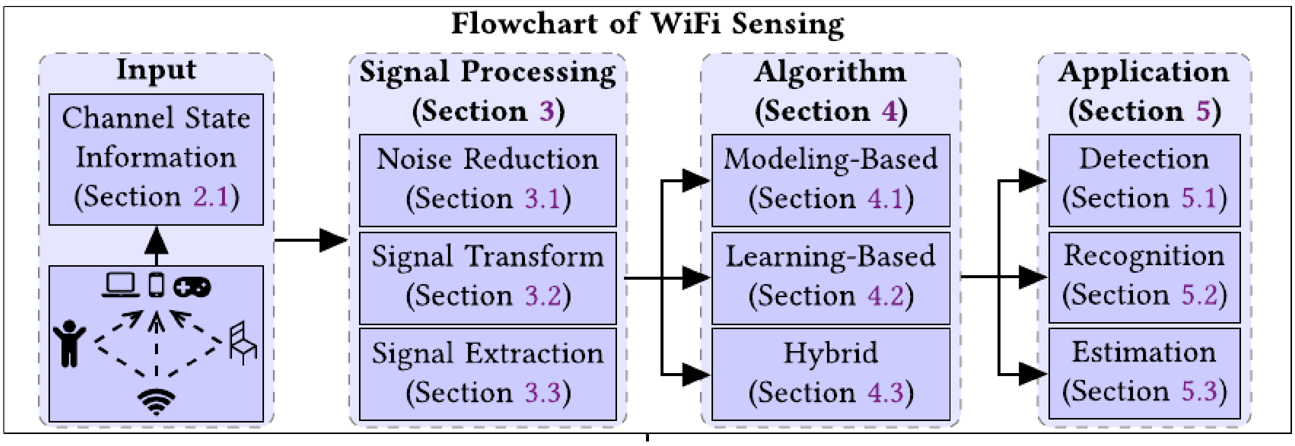
To gain a better insight I highly recommend to go through the survey paper: WiFi Sensing with Channel State Information: A Survey from where the following table is taken:

Table 6. Summary of Existing WiFi Sensing Applications

Output Type	WiFi Sensing Applications
Detection: binary classification	**Human Presence Detection** [3, 24, 67, 73, 75, 83, 112, 114, 121, 148, 149, 152]
	Human Event Detection: Fall [32, 68, 92, 135, 137], Motion [23, 27, 51, 55], Walking [126], Posture Change [57, 58], Intrusion [51, 59], Sleeping [57, 58], Keystroke [5], Driving Fatigue [16, 70], Lane Change [111], School Violence [146], Smoking [142, 143], Attack [40, 53, 54, 125], Tamper [7], Abnormal Activity [151]
	Object Detection [116]; **LoS/NLoS Detection** [113, 150]
Recognition: multi-class classification	**Activity Recognition:** Daily Activities [6, 14, 18, 20, 22, 28, 94, 98, 99, 102, 103, 107, 117], Shopping [132], Driving [16, 78], Exercising [120], Speaking [90], Acoustic Eavesdropping [108], Head & Mouth Activities [19], Walking [63]
	Gesture Recognition: Body/Head/Arm/Hand/Leg/Finger Gestures [2, 3, 33, 49, 62, 64, 72, 77, 81, 85, 88, 89, 127, 134, 140, 147], Sign Language Recognition [49, 62, 64, 81], Keystroke Recognition [4, 5, 48, 50]
	Human/User Identification [10, 11, 34, 97, 124, 133, 139]; **Human/User Authentication** [53, 54, 82, 96, 118]
	Object Recognition [111, 153, 157]; **Object Event Recognition** [66]
Estimation: quantity values of size, length, angle, distance, duration, frequency, counts, etc.	**Device-Free Human Localization/Tracking:** Position [36, 52, 69, 74, 76, 93, 109, 148], Orientation [89, 130], Motion [41, 43, 115, 130], Walking Direction [63, 115, 126, 136], Step/Gait [97, 126], Hand Drawing [84, 130, 131], Speed [137]
	Device-based Human Localization/Tracking [46, 87, 123, 131]
	Object Localization/Tracking [60, 109, 111]; **Humidity Estimation** [141]
	Breathing/Respiration Rate Estimation: Single Person [1, 58, 61, 95, 101, 138], Multiple Persons [95, 101]; **Heart Rate Estimation** [56, 80, 100]
	Human Counting: Static Humans [15, 119], Moving Humans [9, 29, 71, 91, 144], Human Queue Length [104, 105, 111]; **WiFi Imaging** [35, 42, 153, 154]

Flowchart for CSI data usage for Perception tasks (aka. WiFi Sensing)

The following figure shows how the extracted data can later be processed and used for the robot perception tasks mentioned in the previous section.



To explain how all this information relates to my project for Robot perception course, please visit my next article in which I give details of my project and current approaches, algorithms and methods used for these applications based on WiFi CSI data.

References

WiFi Sensing with Channel State Information: A Survey

Wireless communciations

Model and characterize MIMO channels