Wi-Fi sensing Human Detection with Kolmogorov-Wiener Filter and Gated Recurrent Neural Networks

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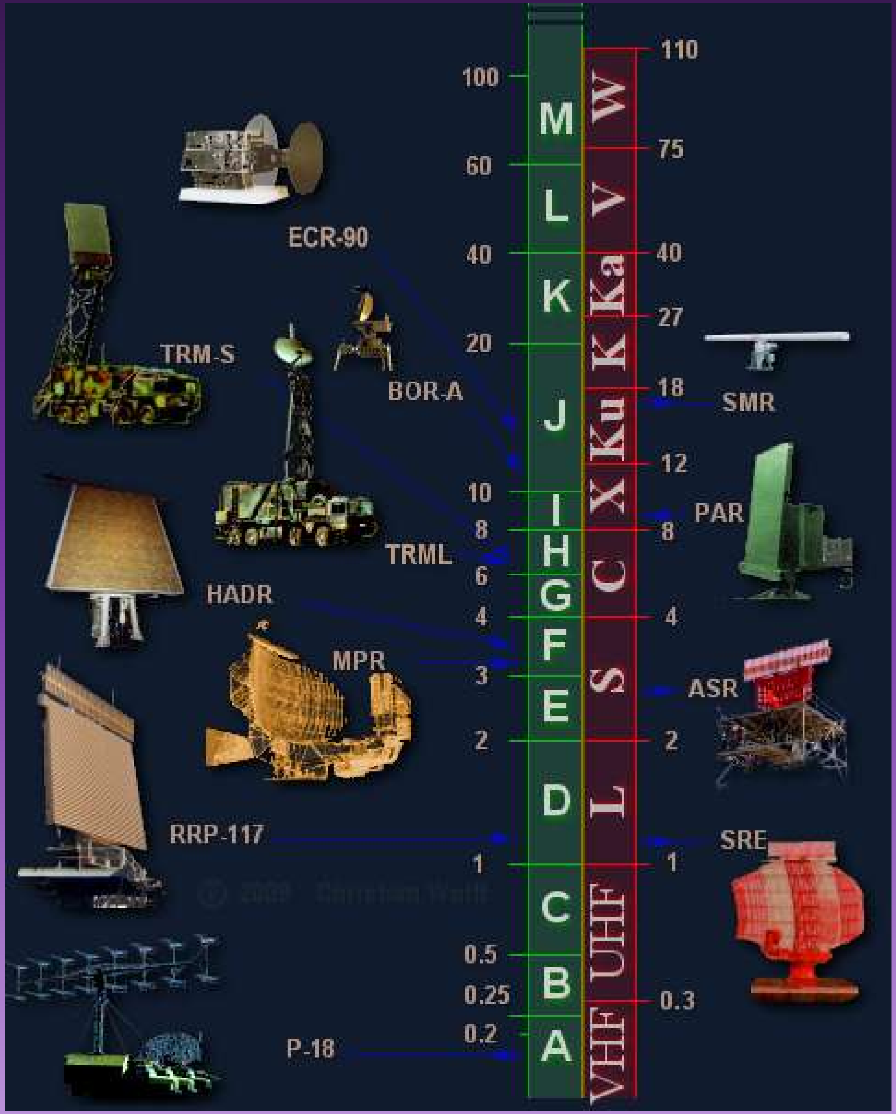
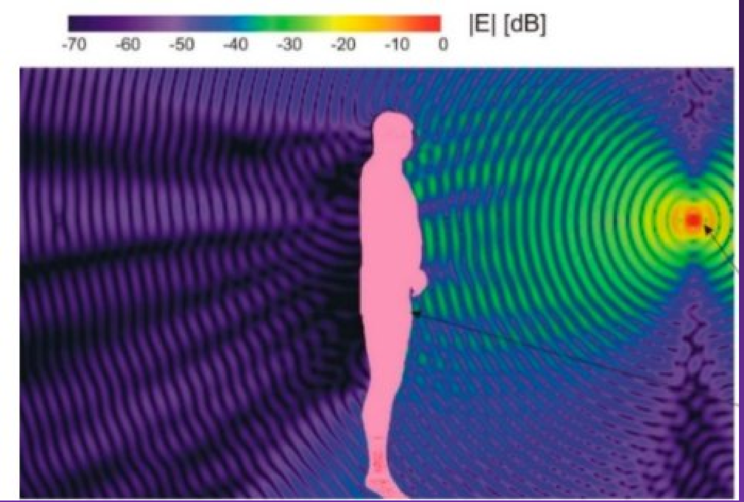
Wi-Fi Sensing – Physics



Local radar
Distance:
8-20 meters

Frequency bands:
390-1550 MHz
5200-6000 MHz
modernarmy.ru

Wi-Fi
2412-2472 MHz
5160-5825 MHz



XFDTD Sim

Human body has unique RSSI adsorption characteristics. – ______. Range – <u>from 9 to 30 dB</u> (human body consists 68% of H_2O)

RF Absorption Rates by Common Materials

Material	Absorption Rate
Plasterboard/drywall	3–5 dB
Glass wall and metal frame	6 dB
Metal door	6–10 dB
Window	3 dB
Concrete wall	6–15 dB

Certified Wireless Network Adm. Study Guide

RSSI
(Received Signal Strength Information/Indicator)

It is measured in dBm and characterizes the total power of the signal received by the receiver. RSSI is influenced by many factors.

$$P_d = P_0 - 10 \cdot n \cdot \lg\left(\frac{d}{d_0}\right),$$

d – distance from transmitter to receiver, m

d_0 – distance to control point (here we measure P_0), m

P_0 – “control” RSSI value on the distance d_0, dBm

n – absorption rate

P_d – calculated RSSI value, dBm

Problem Statement

Input:

$r_t[n] = [r_1, r_2, r_3, \ldots, r_n]$(1)

RSSI values

$y_t[n] = [y_1, y_2, \ldots, y_n]$ (2)

labels (1 – human is present,
0 – human is absent)

Find:

Algorithm $A(r)$ maximizing accuracy_score to determine human presence based on the unlabeled RSSI data r.

- Statistical approach: clean the noise, determine outliers
- ML approach: preprocess time series, tune the model, train it on the labeled data (supervised learning)

Approach analysis

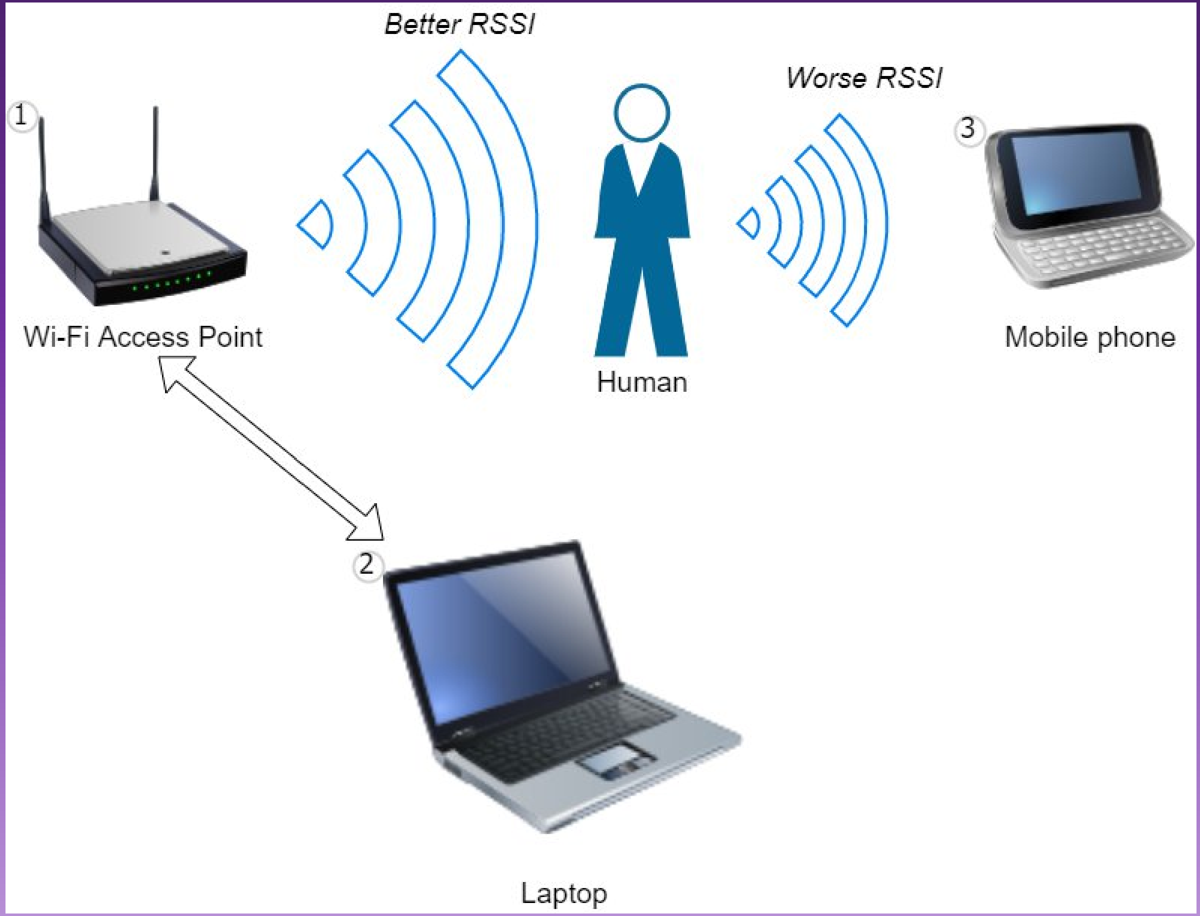
Publication	Algorithm class	Denoising	Accuracy	Hardware	Venue
Zhang et al. [1], 2020	Kalman Filter + threshold variance estimation	Kalman filter	95%	3 WSN-node	3 m x 3 m
Yuan et al. [2], 2013	Sophisticated k-means	Part of k-means	94%	TelosB	18 m x 18 m
Xu et. al. [3], 2013	Markov random fields	Part of MRF*	86%	Chipcon CC1100	Office, 150 m^2
G. Troester et al. [4], 2014	Combination of means, variance и max-min with threshold	-	>= 90% (different conditions)	Nexus One smartphone	University halls
Hiroshi Saito et al [5], 2021	Weighted moving averages with thresholds	EWMA + MA*	100% (special ZigBee hardware)	Zigbee	Lab

Noise smoothing with a filter is a good solution. However, there are no publications where the Wiener-Kolmogorov filter / GRU neural networks are used to solve the RSSI–based problem (GRU might be a “fast” alternative to the popular LSTMs)

*MRF – Markov Random Fields, MA – moving average, EWMA – exponential weighted moving average

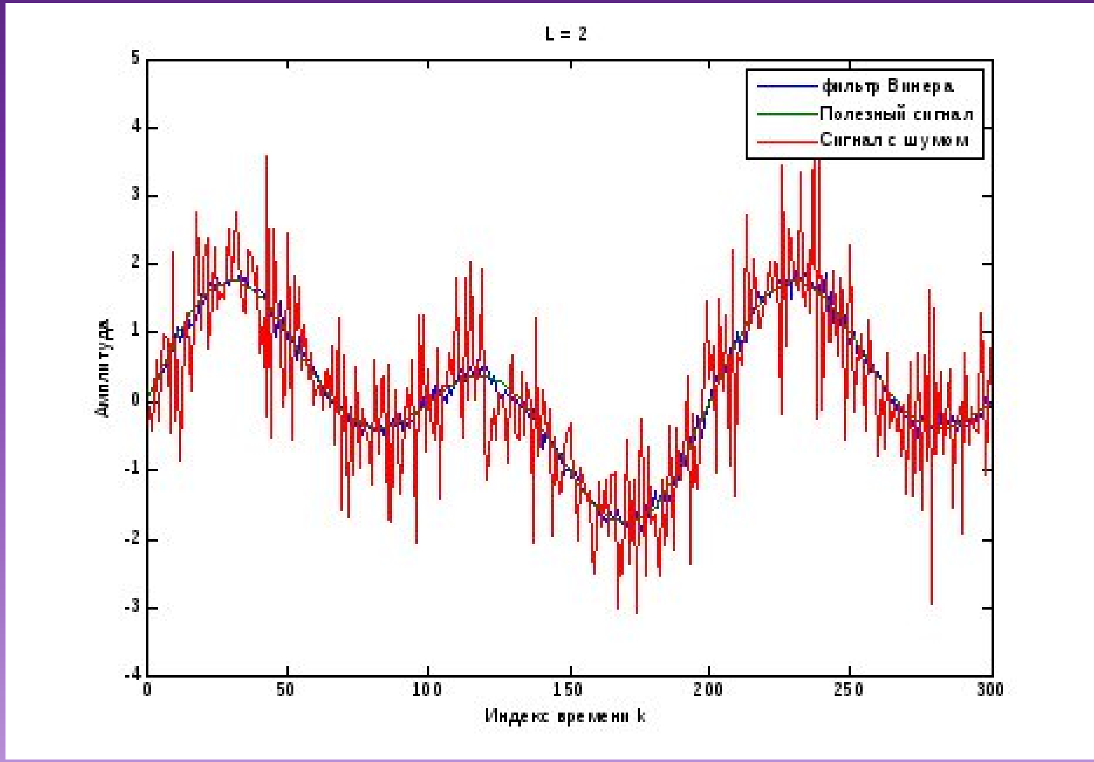
Chosen approach

Experimental stand design



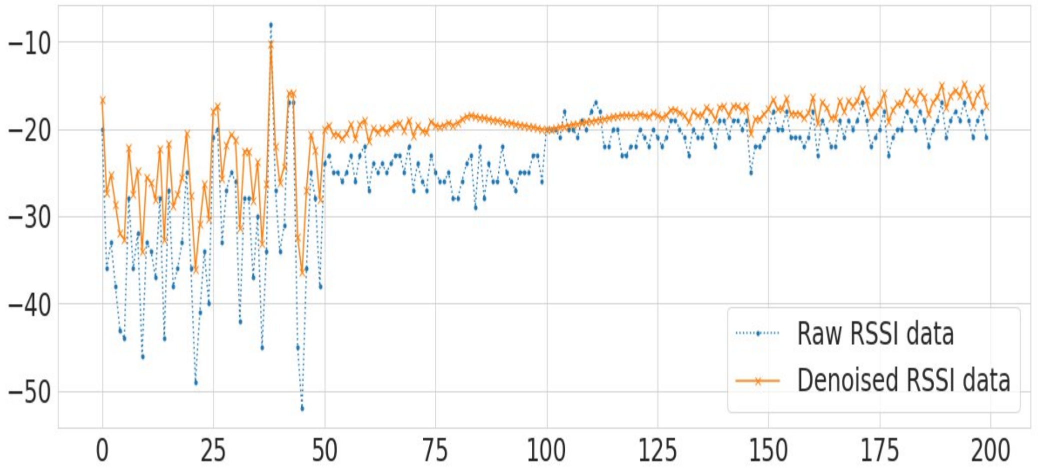
Data processing

- Smoothen with Kolmogorov-Wiener filter + detect outliers with Hampel method

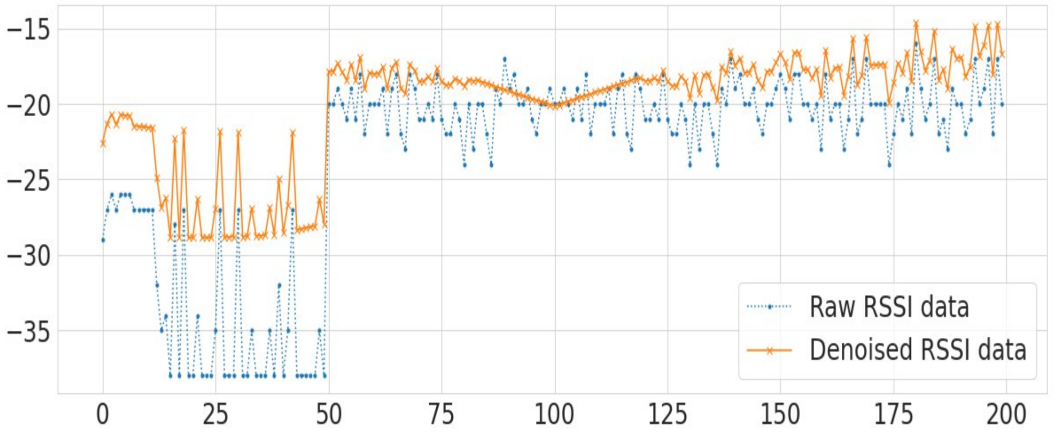


Discrete Kolmogorov-Wiener

The measured discrete signal is fed to the filter input: $r_t[n]$. There is also an unknown useful signal. $s[n]$. Signal $r_t[n]$ is fed Kolmogorov-Wiener filter to obtain output signal $x[n] = \sum_{i=0}^{N} a_i r_t[n-i]$, where N is a number of measurements in the past (often called the order of the filter), $\{a_i\}$ are filter coefficients. Coefficients are obtained with least squares method: $e[n] = x[n] - s[n]$, $a_i = \arg\min E[e^2[n]]$



RSSI in the Living Room



RSSI in the Office Room

PREPROCESSING

To apply machine learning algorithms, RSSI data is preprocessed $r_t = [r_1, \ldots, r_n]$. Window size w is chosen and matrix $M = [\,[r_1, \ldots r_w]\,,\ [r_2, \ldots, r_{w+1}]\,, \ldots, [r_{n-w}, \ldots r_n]]$ is generated. Matrix is split into two parts: M_{train} (71,5% of data) и M_{test} (28.5% of data).

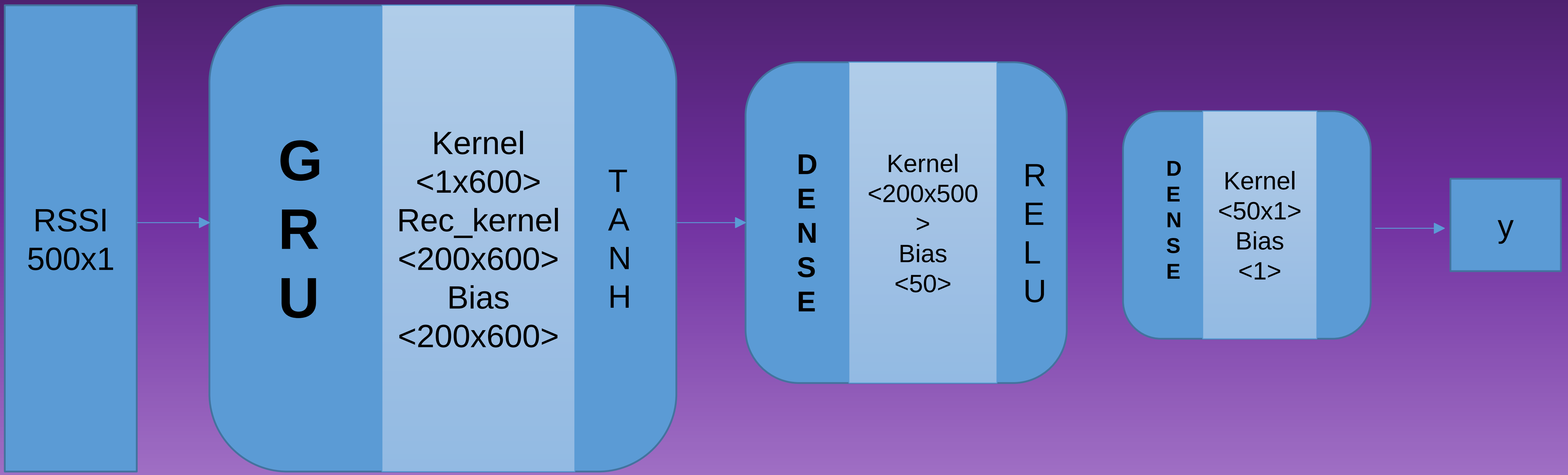
ALGORITHMS BASED ON TREES

AdaBoost (Adaptive Boosting), Gradient Boosting, Random Forest are considered. All these algorithms are based on a combination of decision trees.

LOGISTIC REGRESSION

It is based on the maximum likelihood method and gradient descent. The output values are in [0, 1], rounding to the nearest integer occurs.

GRU Neural Network



Model Comparison
living room

Model	Accuracy_score	TPR	TNR
Kolmogorov-Wiener filter	0.90	1.00	0.83
RandomForest	**0.99**	**0.99**	**0.99**
AdaBoost	0.98	0.98	0.99
Gradient Boosting	0.99	0.99	0.99
GRU network	0.98	0.97	0.99
Logistic Regression	0.98	0.97	0.99

Model Comparison
office room

Model	Accuracy_score	TPR	TNR
Kolmogorov-Wiener filter	0.94	1.00	0.90
RandomForest	0.98	0.98	0.99
AdaBoost	0.97	0.95	0.99
Gradient Boosting	0.99	0.98	0.99
GRU-network	0.98	0.97	0.99
Logistic Regression	0.98	0.97	0.99

Model Comparison
living room → office room

Model	Accuracy_score	TPR	TNR
Kolmogorov-Wiener filter	0.75	0.97	0.46
RandomForest	0.985	0.99	0.97
AdaBoost	0.98	0.99	0.96
Gradient Boosting	0.985	0.99	0.96
GRU-network	0.86	0.83	0.95
Logistic Regression	0.98	0.98	0.97

Model Comparison
office room → living room

Model	Accuracy_score	TPR	TNR
Kolmogorov-Wiener filter	0.72	0.94	0.44
RandomForest	0.76	0.99	0.63
AdaBoost	0.76	0.94	0.73
Gradient Boosting	0.88	0.82	0.96
GRU-network	0.85	0.81	0.96
Logistic Regression	0.78	0.93	0.76

Findings from Experiments

- The Kolmogorov-Wiener filter needs special tuning for the noise of a particular room
- Machine learning algorithms are more precise
- Machine learning algorithms are more "portable"
- GRU NN current design is not sufficient to beat Logistic regression and tree-based methods in the majority of cases

Further Work

- Use GRUs for CSI predictions based on CSI data
- Collect a publicly available dataset with RSSI and CSI values to compare Wi-Fi sensing algorithms
- Use CSI and RSSI data simultaneously
- Explore techniques for sensing with multiple APs

Thank you for Attention!

- Github
- Me on telegram: @golanger