Quality of Transmission Estimation for Multi-User Free Space Optical Communication Using Supervised Machine Learning

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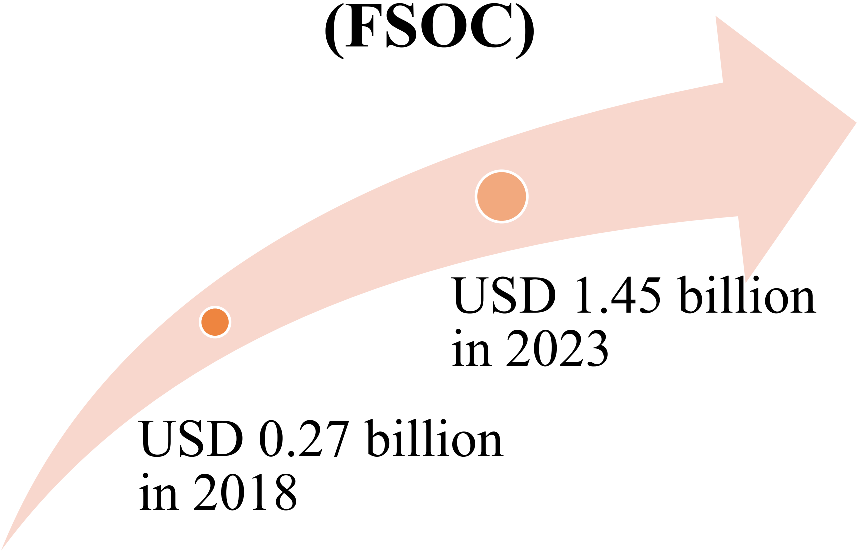
INTRODUCTION

FREE SPACE OPTICAL COMMUNICATION (FSOC)

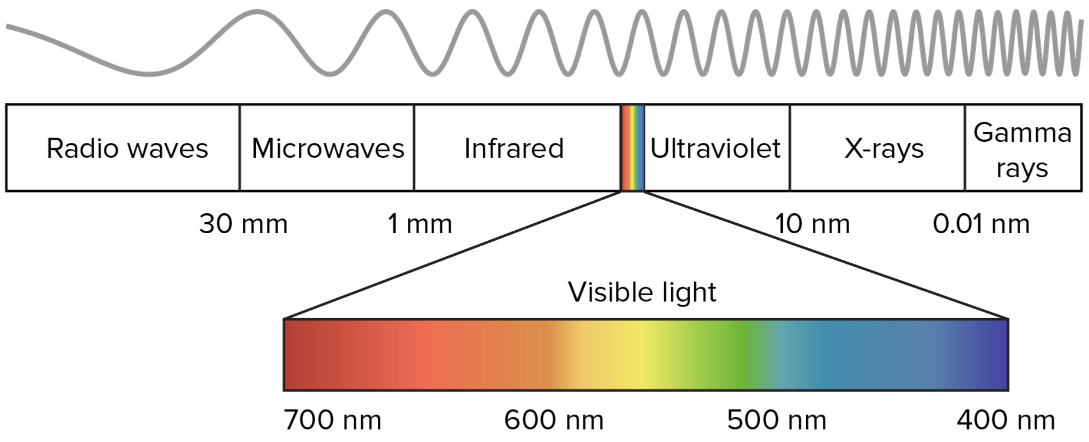


INTRODUCTION

NASA with the Lunar Laser Communications Demonstration (LLCD), during the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission, developed and tested optical communication technology.

Project Loon addresses internet connectivity scarcity with a network of high-altitude balloons traveling the stratosphere. FSOC has been adopted for inter-balloon crosslinks.

FSOC: **infrared** portion of the optical spectrum (from 300 GHz to 430 THz)



✓ HIGH-BANDWIDTH and DATA-RATE

$$BW \approx 1\% f_c$$

$$BW_{RF}|_{f_c=2.4\,GHz,\ \lambda_c=12\,cm} \approx 10^7\ Hz$$

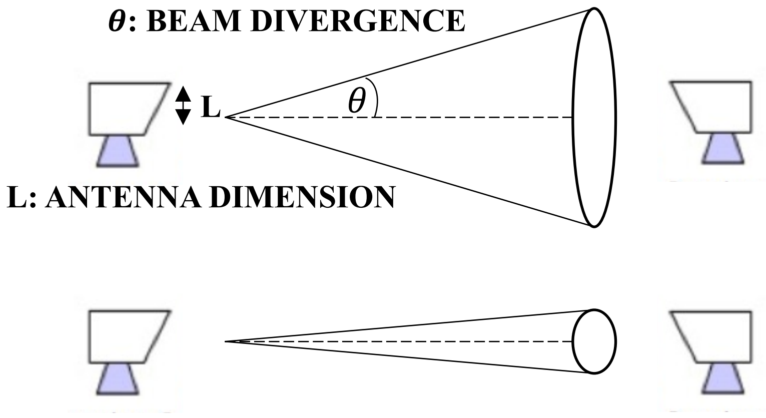
$$BW_{FSO}|_{f_c=193.4\,THz,\ \lambda_c=1550\,nm} \approx 10^{12}\ Hz$$

$$\boldsymbol{BW_{FSO} \approx 10^5\ BW_{RF}}$$

✓ LESS POWER and MASS REQUIRMENT

$$\theta \approx \frac{\lambda}{L} \rightarrow \begin{cases} \lambda_{FSO} < \lambda_{RF} \\ L_{FSO} = L_{RF} \end{cases} \rightarrow \theta_{FSO} < \theta_{RF} \rightarrow I_{FSO} > I_{RF}$$

ANTENNA GAIN $\rightarrow$ $$G \approx \frac{\lambda^2}{L^2} \rightarrow \begin{cases} \lambda_{FSO} < \lambda_{RF} \\ G_{FSO} = G_{RF} \end{cases} \rightarrow L_{FSO} < L_{RF}$$



INTRODUCTION

- ✓ **HIGH DIRECTIVITY**

ANTENNA DIRECTIVITY ➡ $D \approx G \approx \theta^2$ ➡ $D_{FSO} > D_{RF}$

- ✓ **HIGH SECURITY**
- ✓ **ROBUST TO ELECTROMAGNETIC INTERFERENCE**
- ✓ **UNLICENSED SPECTRUM**
- ✓ **EASY, LESS EXPENSIVE and QUICK DEPLOYMENT**
- ✓ **LIGHTWEIGHT and COMPACT**

MOTIVATION

- ✓ **FSOC** is a **point-to-point** technology (*Line of Sight* (LoS)) requiring strict pointing, acquisition and tracking (PAT) systems, which require bulky mechanical gimbals for maintaining link availability and omni-directional coverage.

- ✓ PAT systems are known to violate mobile communication network size, weight and power (**SWaP**) requirements.

- ✓ To further advance optical wireless networking capabilities without affecting SWaP specifications, **omni-directional** and **multi-user communication** should be provided.

- ✓ Multi-user FSOC will fulfil the **increase bandwidth, high-capacity** and **-density demands** ***of future communication networks*** and will represent a leap from the current single user limitation.

↓

Research group at *Oklahoma University* has been working on designing, developing and testing an ***omni-directional***, ***multi-user*** and ***intelligent*** FSOC system.

RELATED WORK

Machine learning (ML) has proven to be a promising methodology for introducing **intelligence** into the network and enabling systems to sense the environment and independently perform cognitive tasks.

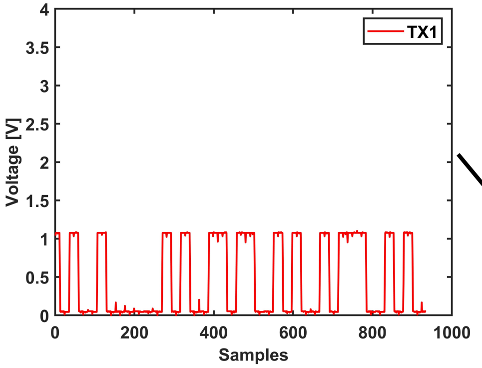
MACHINE LEARNING IN OPTICS:

- **Optical Performance Monitoring (OPM):** BER, Optical Signal-to-Noise Ratio (OSNR), Chromatic Dispersion (CD), etc.,
- **Modulation Format Recognition (MFR):** estimating the modulation format at the receiver side.
- **Quality of Transmission (QoT):** OSNR, BER, Q-factor, etc. to check if a required QoT would be guaranteed.

PROBLEM STATEMENT

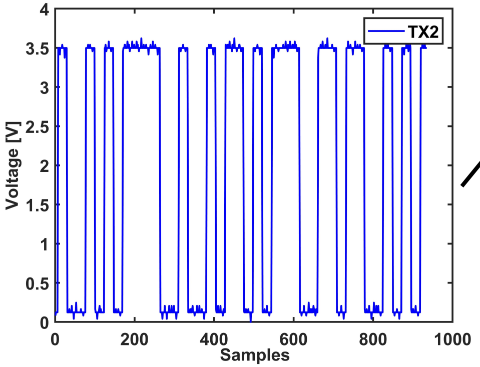
PROBLEM: Can we estimate signals quality before signal detection to decide if decoding signals?

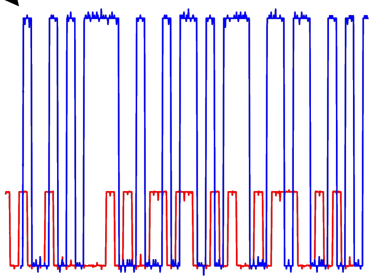
USER 1

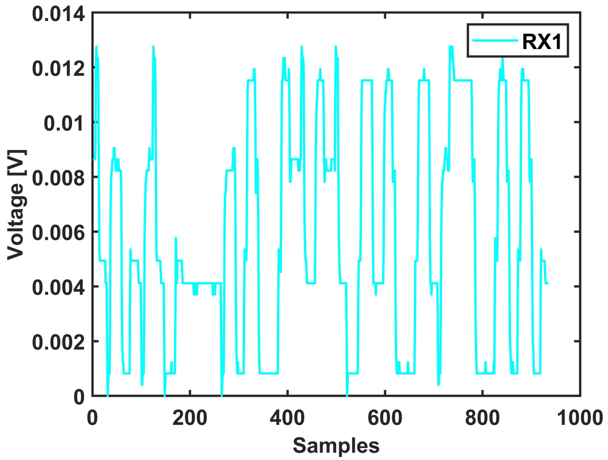


ASSUMPTION: users share time, bandwidth, and space resources

USER 2





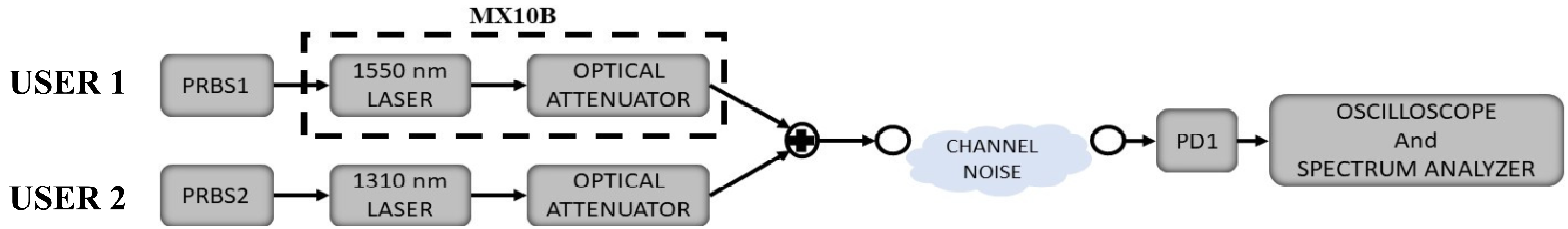


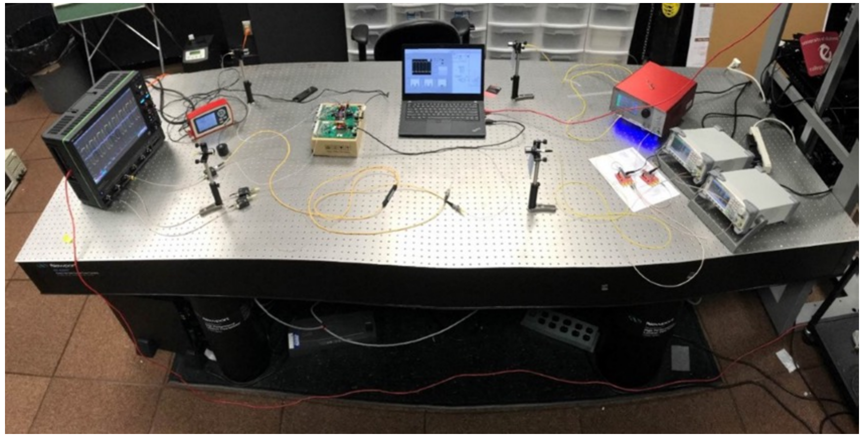
CAN WE ESTIMATE PHY PARAMETERS PRIOR TO SIGNAL SEPARATION:

- **SNR USER 1?**
- **SNR USER 2?**

SOLUTION: Developing a ML model to jointly estimate signals' SNR prior to signal separation.

EXPERIMENTAL SETUP





METHODOLOGY:

1. *Sample* background channel noise power in the lab setup.
2. *Vary* transmission power using an optical attenuator.
3. *Measure* received power per user transmission.
4. *Calculate* SNR per user by SNR[dB]=RX[dBm]-N[dBm].
5. *Collect* and *process* power measurements for SNR calculations when user1 and user2 are transmitting and received simultaneously.

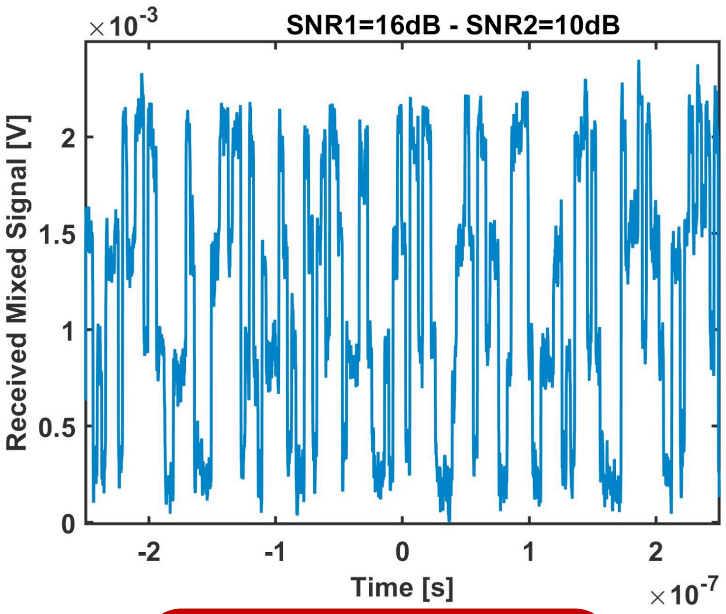
SNR1=[10:2:26]dB

SNR2=[10:2:20]dB

→ 25,967 DATA OBJECTS

METHODOLOGY

Received mixed signal with two transmitting users with SNR1=16 dB for user1 and SNR2 =10 dB for user2



For each of the 54 SNR1/SNR2 combinations, between 450 and 500 acquisitions of the time-series received mixed signal were collected resulting dataset consisted of 25967 instances.

FEATURE SELECTION → ML CLASSIFICATION MODEL → 54 CLASSES SNR1-SNR2 COMBINATIONS "1610"

1. Empirical histogram of received mixed signal amplitude
2. Local maxima (i.e., peaks) of the empirical histogram of received signal amplitude

- Decision tree (DT) [e.g., 100 number of splits]
- K-nearest neighbor (K-NN) [k=10]
- Random forest (RF) [30 learners, 53 number of split]
- Naïve bayes (NB) [gaussian kernel]
- Support vector machine (SVM) [quadratic kernel]
- ANN [one hidden layer with 50 neurons]

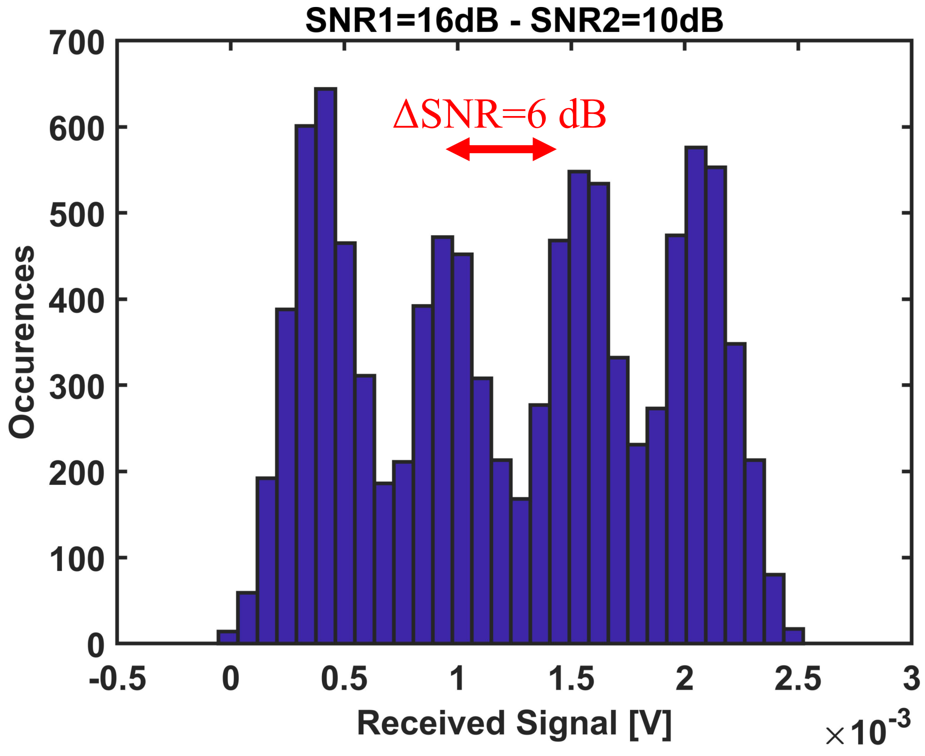
For each class, ~500 acquisitions were collected resulting in a dataset of 25967 instances. Output of the classifiers is the SNR1-SNR2 combination (i.e., 1610 indicates SNR1=16 dB and SNR2=10 dB).

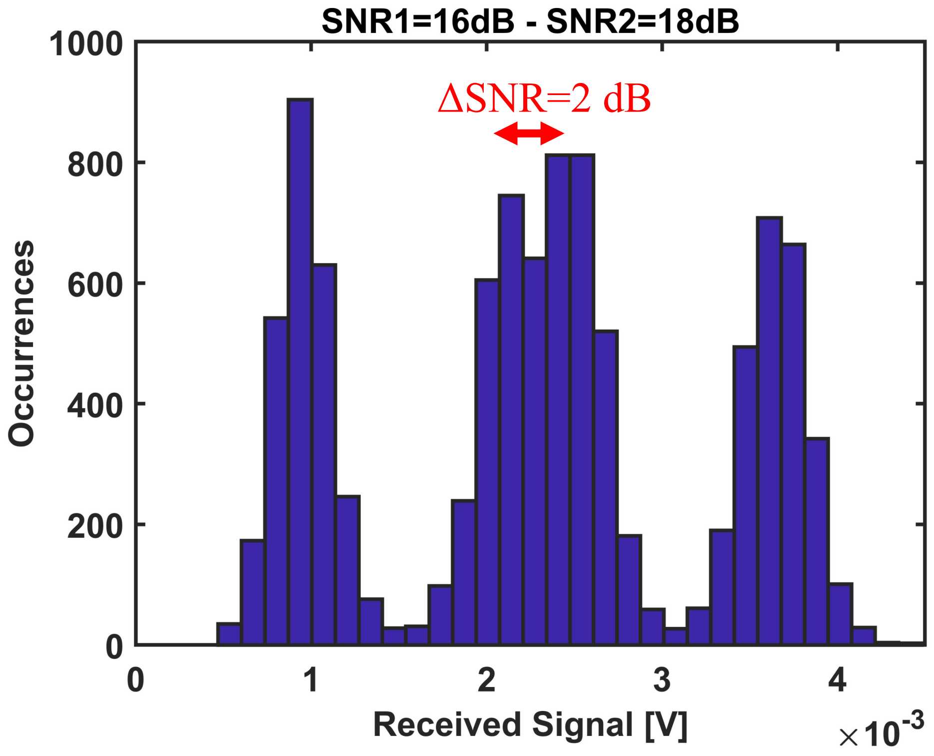
METHODOLOGY

FEATURES SELECTION
for input to ML algorithms

1st METHOD:

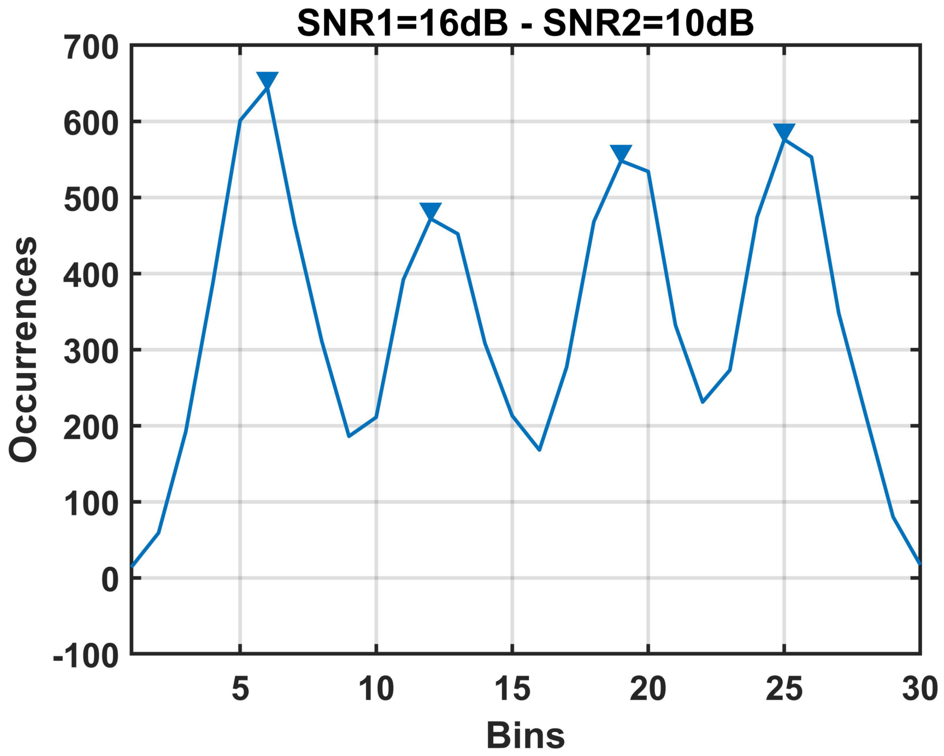
Histogram of received mixed signals
[30 features (bins)]

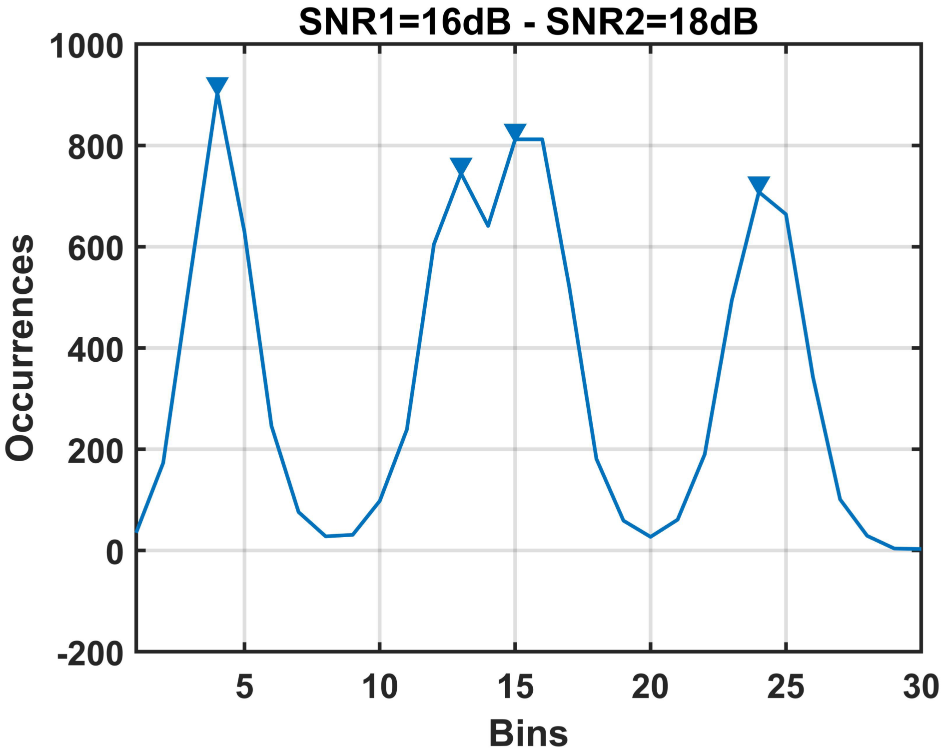




FEATURES SELECTION
for input to ML algorithms

2nd METHOD:
local maxima of histogram
[4 features]





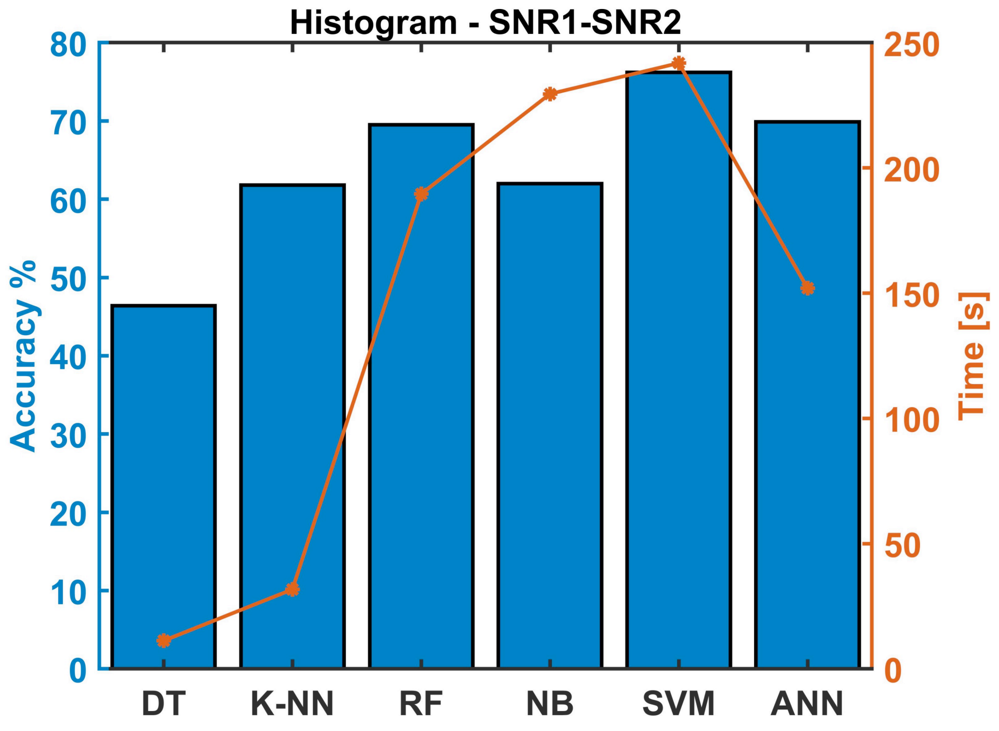
RESULTS

Joint estimation
SNR1-SNR2

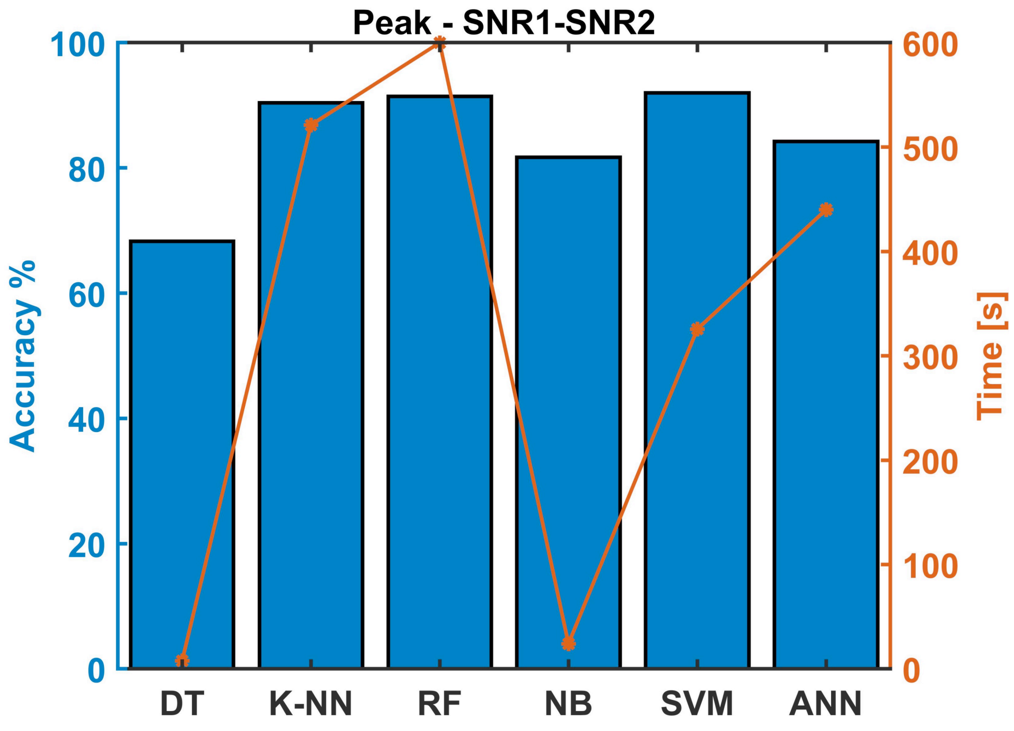
Accuracy < 80%

Accuracy > 90%

1st METHOD

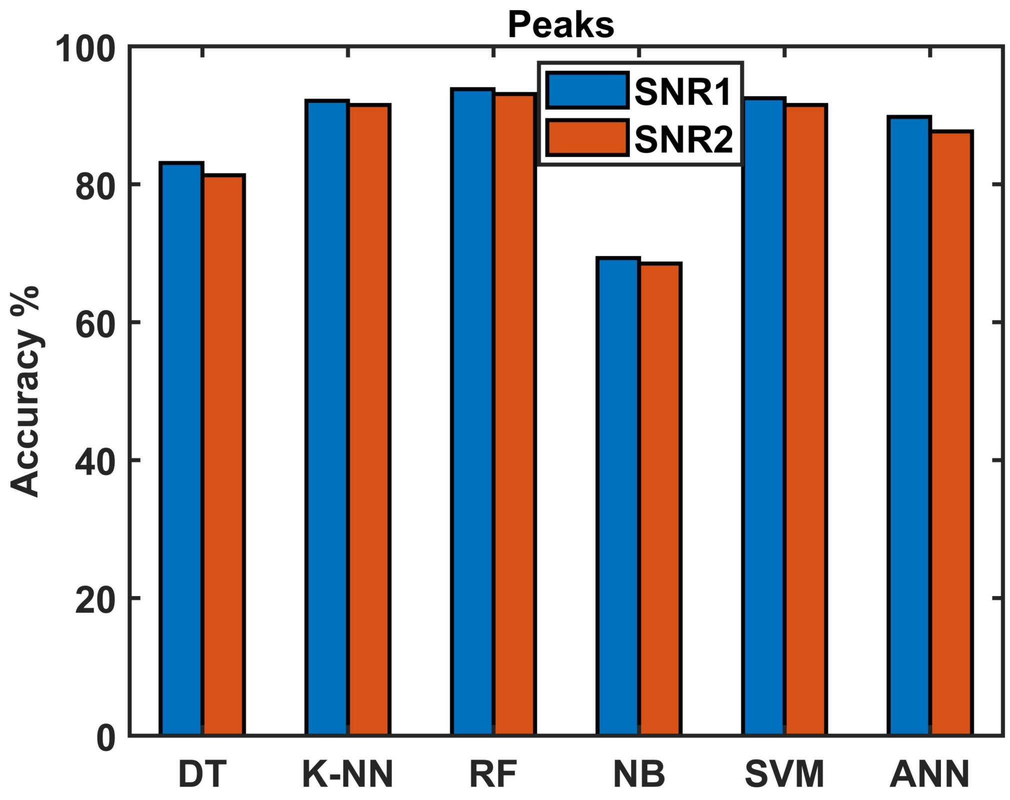


2nd METHOD



Estimation of
SNR1 and SNR2
using 2^{nd} method and same dataset of previous analysis

Does one user have more weight on the joint accuracy?

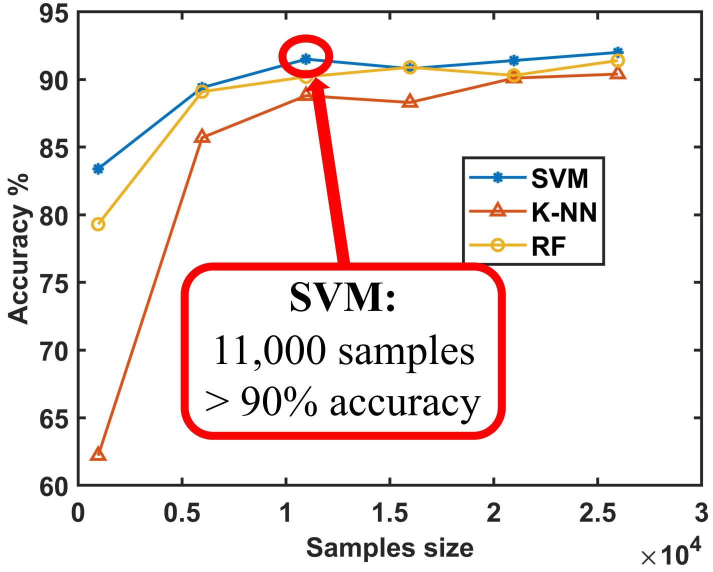


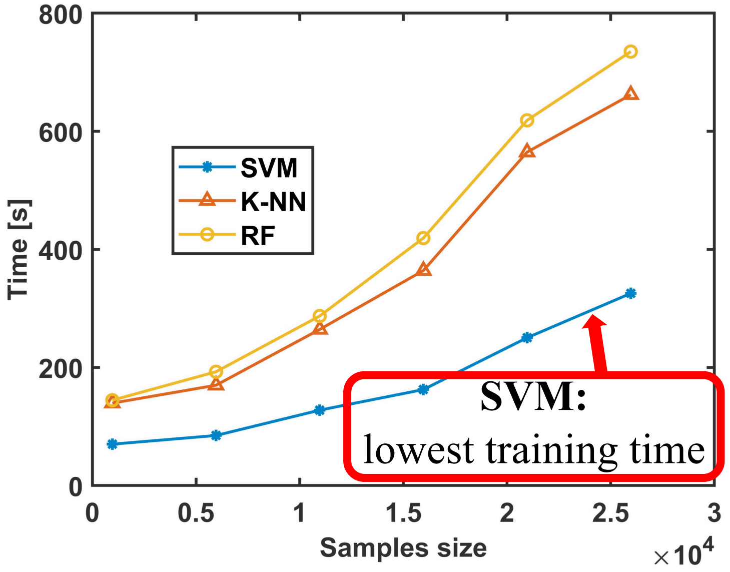
Both users have similar performance

RESULTS

1. DATA SIZE ANALYSIS

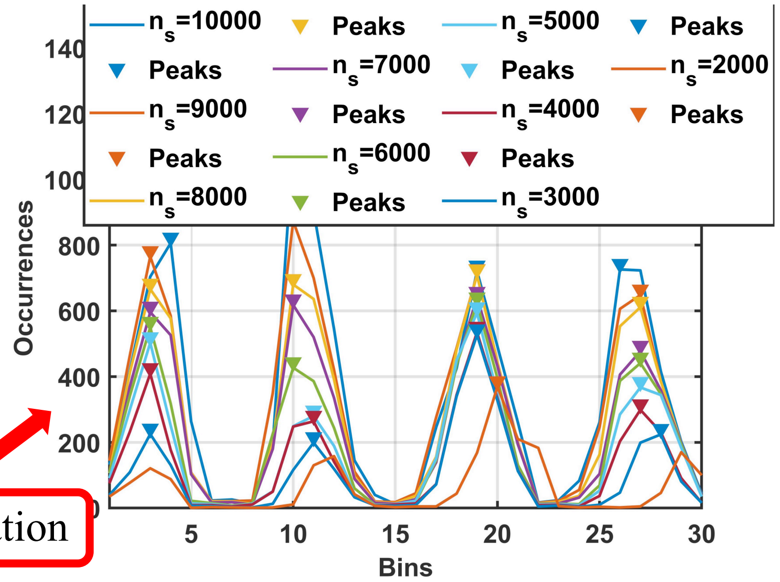
Number of data objects were reduced
[25,967 : -5,000 : 967]



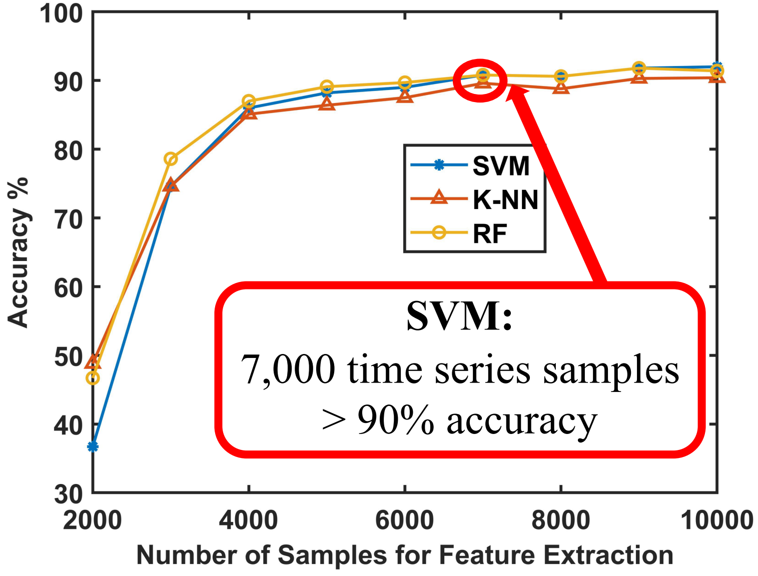


2. TIME SERIES SAMPLE ANALYSIS

Number of time series sample for features extraction were reduced
[10,000 : -1,000 : 2,000]



Varying peaks location



CONCLUSION and FUTURE WORK

- This paper proposes the use of supervised ML for QoT estimation for a multi-user FSOC link when users share time, bandwidth, and space resources.
- Two approaches for training the model were tested:
  - I. histogram of the received mixed signal amplitude
  - II. local maxima locations of the histogram were used
- SVM achieved the highest accuracy (92%) with the second methodology for feature selection.
- Effect of varying number of instances for training the classifier and number of samples for feature extraction of the time series-received signal were experimentally tested.
- Future work will study other communication/performance parameters that could be estimated to facilitate and automate multi-user FSOC and to perform performance evaluation prior to signal demodulation.

Thank you for your attention!