Poster ID: 23

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Poster Session at Graduate School Information Fair

Channel Prediction for Free-Space Optical (FSO)-based Vertical Networks Using Machine Learning

1. General Background

1.1. Free-space Optics (FSO)

- **FSO**: is a line-of-sight technology using infrared frequency bands for data transmission in free space.
- **Benefits**: large bandwidth, high-speed connections, high level of security, immunity to electromagnetic interference.

1.2. FSO-based Vertical Networks

- **Vertical networks**: the use of satellites, high-altitude platforms (HAP), and unmanned aerial vehicles (UAV) to provide globally high-speed connectivity.
- **Applications**: fronthaul/backhaul networks, quantum key distribution, post-disaster emergency communication, etc.

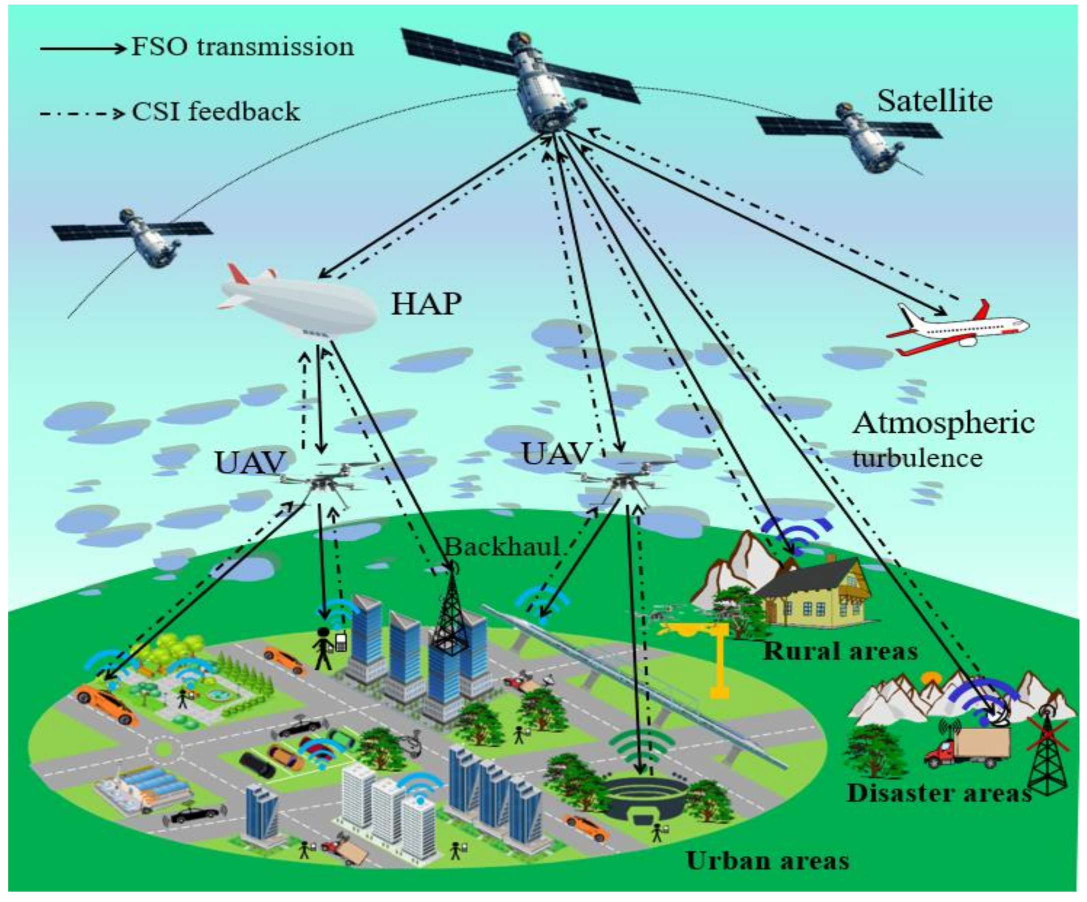

Fig. 1. FSO-based vertical networks.

1.3. Challenges

Critical Issue: FSO links are sensitive to ***atmospheric turbulence***, which causes the received power fluctuation at receivers.

➔ *Channel state information (CSI) is required at receiver side to adaptively choose proper parameters/settings for transmissions*

Challenge: The ***CSI tends to be outdated*** due to the long distance of vertical networks, which degrades the system performance.

An efficient channel prediction scheme for FSO-based vertical networks is required

2. Solutions and Motivation

2.1. Possible Solutions

Channel Prediction Schemes

Statistical-based Prediction
- Auto-Regressive (AR)
- Parametric Model (PM)

➔ *Offer a poor accuracy as the modeling is fossilized*

Machine Learning (ML)-based Prediction
- Sparse Bayesian Linear Regression
- Support Vector Machine (SVM)
- Recurrent Neural Network (RNN)
- Deep Neural Network (DNN)

➔ *Offer an excellent potential thanks to its data-driven nature*

2.2. Motivation

- ML-based channel prediction schemes have been widely applied for radio frequency (RF) systems
  ➔ *These schemes have not been studied for FSO systems, where FSO channels are entirely different from the RF ones.*
- Among ML-based prediction schemes, RNN is famous for its short-term memory capacity
  ➔ *This is especially suitable for time series prediction.*
- Echo state network (ESN), a form of RNN, can randomly construct the hidden layer and leverage a simple linear regression algorithm to train the output layer
  ➔ *ESN can effectively overcome the common drawbacks of the conventional RNNs.*

With the benefit of a simple structure yet high efficiency, the ESN is a promising candidate for turbulence channel prediction in FSO systems

3. ESN Model and Simulation Results

3.1. Turbulence Channel Data Analysis

We use the FSO channel data obtained from [1] for training and testing the model.

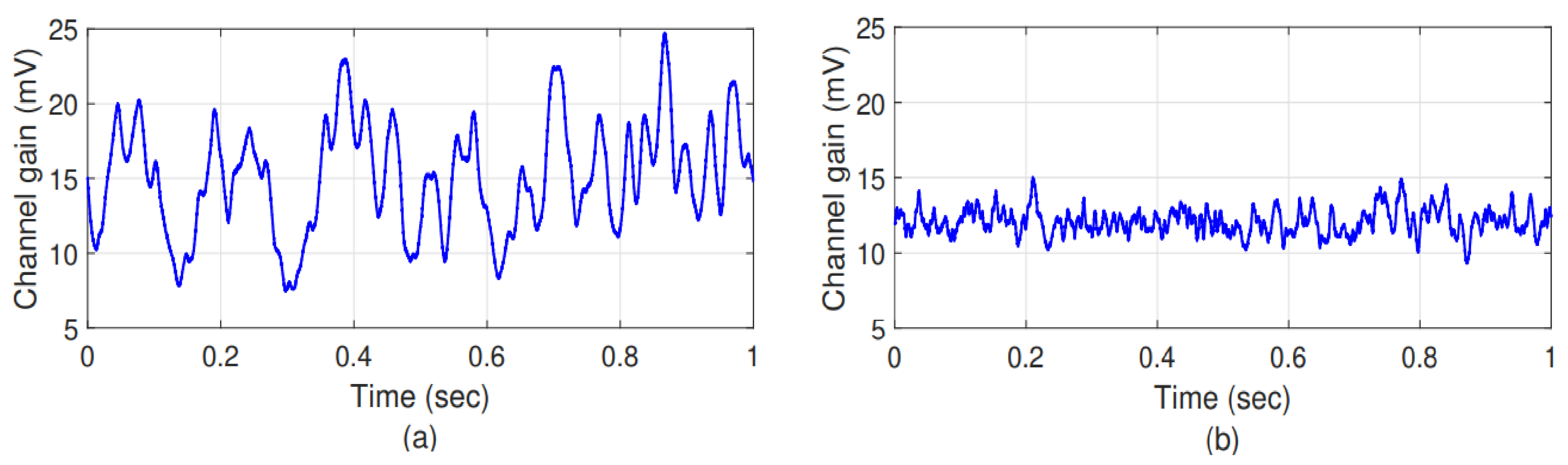

Fig. 2. The channel data for (a) SI = 0.0594 (high SI) and (b) SI = 0.0051 (low SI).

Scintillation index (SI) indicates the strength of atmospheric turbulence
➔ *Higher SI values, more uncertainty of FSO channels*

3.2. ESN Model

- The ESN model consists of three layers, an input layer $[1; \boldsymbol{u}(n)]$ with $(M+1)$ neurons, a hidden layer (reservoir) $\boldsymbol{x}(n)$ with N neurons, and a single-neuron output layer $y(n)$. $\boldsymbol{W}_{in}$ and $\boldsymbol{W}$ are the input weight and internal weight matrixes, respectively.

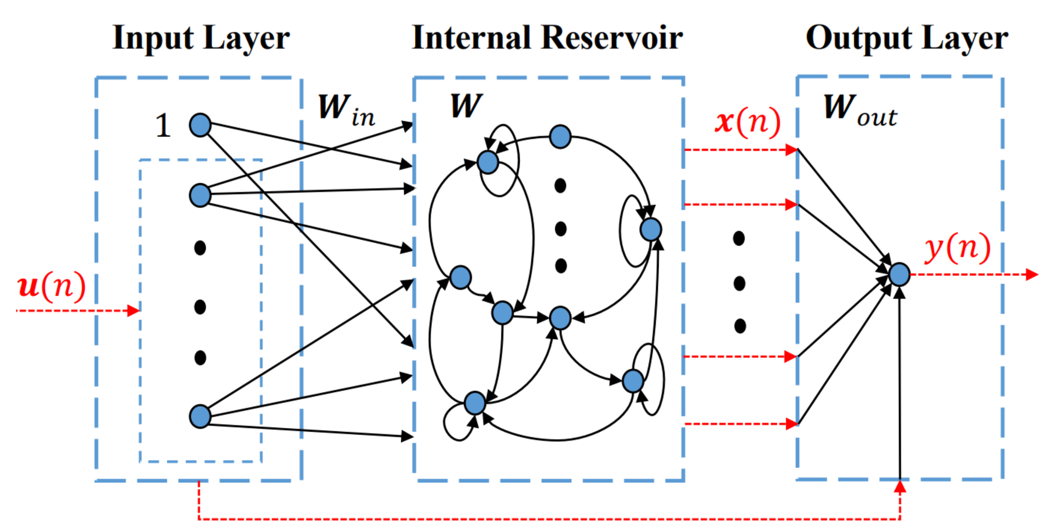

Fig. 3. A multiple input/single output ESN model.

- At discrete time n, M channel gain samples are regarded as input data, while output is the predicted channel gain at the next time period.
- The $\boldsymbol{W}_{in}$ and $\boldsymbol{W}$ are randomly generated. The readout weights $\boldsymbol{W}_{out}$ can be trained and obtained by using ridge regression.

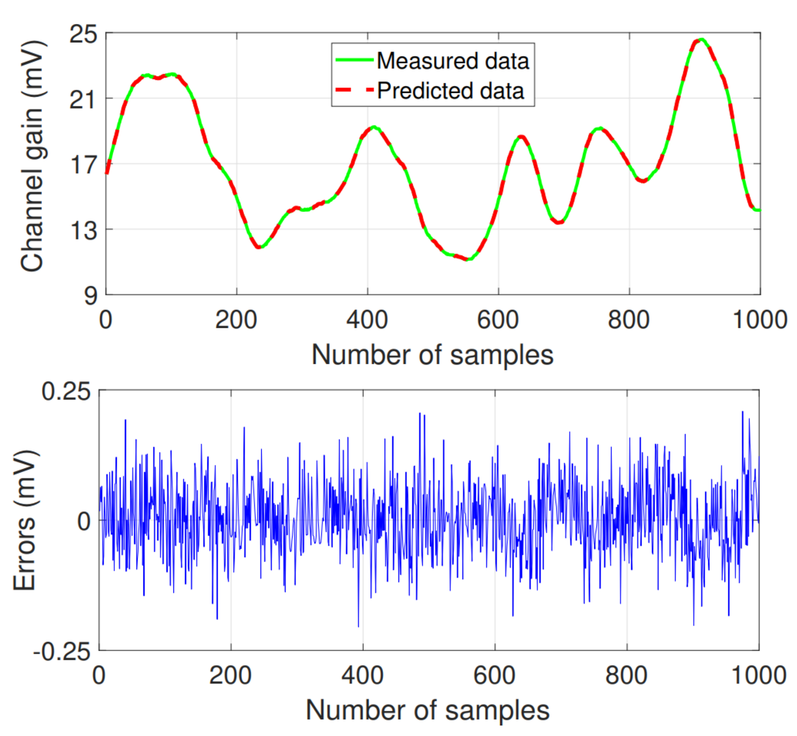

Fig. 4. Prediction performance of ESN.

The predicted curve follows the ideal one closely with low errors

3.3. Simulation Results

Data	Model	RMSE	NRMSE	MAPE	SMAPE
SI = 0.0051	AR	0.69571	0.59710	0.04522	0.04525
	SVM	0.11548	0.09885	0.00673	0.00670
	ESN	0.03686	0.03171	0.00242	0.00242
SI = 0.0594	AR	0.98256	0.24908	0.05947	0.05828
	SVM	0.38435	0.10955	0.00694	0.00706
	ESN	0.06843	0.01948	0.00334	0.00334

Table 2. Prediction performance comparison.

The ESN achieves the highest accuracy, which decreases when the SI gets higher

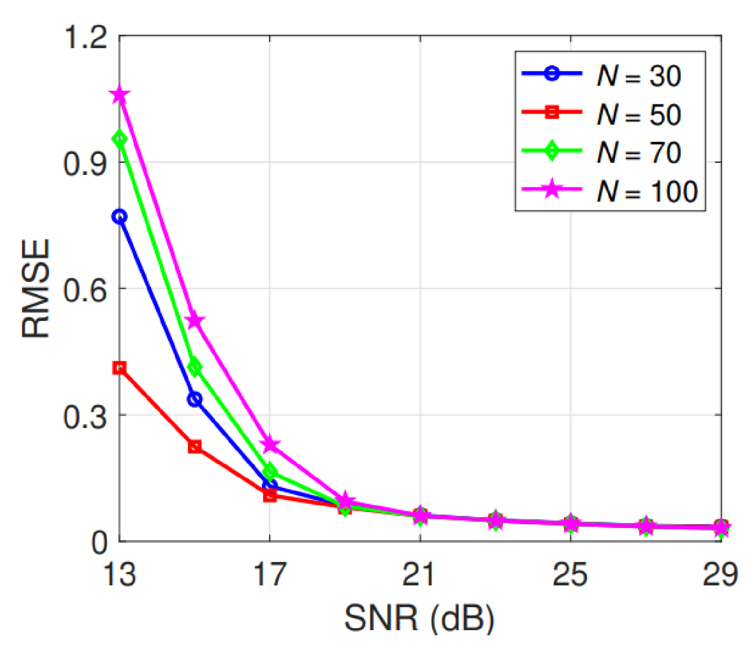

Fig. 5. RMSE for different reservoir sizes.

The reservoir size affects greatly on prediction performance

3.4. Concluding Remarks

- The ESN model offers excellent prediction performance in FSO systems.
- Also, the ESN model outperforms the classical AR and SVM models in terms of computational complexity and accuracy.

3.5. References

[1]. A. Mostafa and S. Hranilovic, "Channel measurement and Markov modeling of an urban free-space optical link," *IEEE/OSA J. Optical Commun. Netw.*, vol. 4, no. 10, pp. 836 – 846, Oct. 2012.