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Inverse systems approach to design Secure Random Communication Systems

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AI and ML for scientific applications through secure communications for 5G/6G

Areeb Ahmed

SMASH's research area "**1. Data Science - Machine Learning for Scientific Applications**"

subarea "**1.3 Beyond Supervised Learning**"

under the supervision of

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Introduction 5G

- **Fifth Generation (5G) Overview:**
  - Current generation wireless technology.
  - Massive machine type of communications (mMTC)
  - Ultra-reliable low-latency communications (URLLC)
- **Internet of Things (IoT)**
  - Communication of connected devices.
  - Facilitates smart homes.
- **Augmented and Virtual Reality (AR/VR)**
  - Enhances user experiences with immersive technologies.
  - AR/VR applications.
- **Autonomous Vehicles**
- **Enhanced Mobile Broadband**

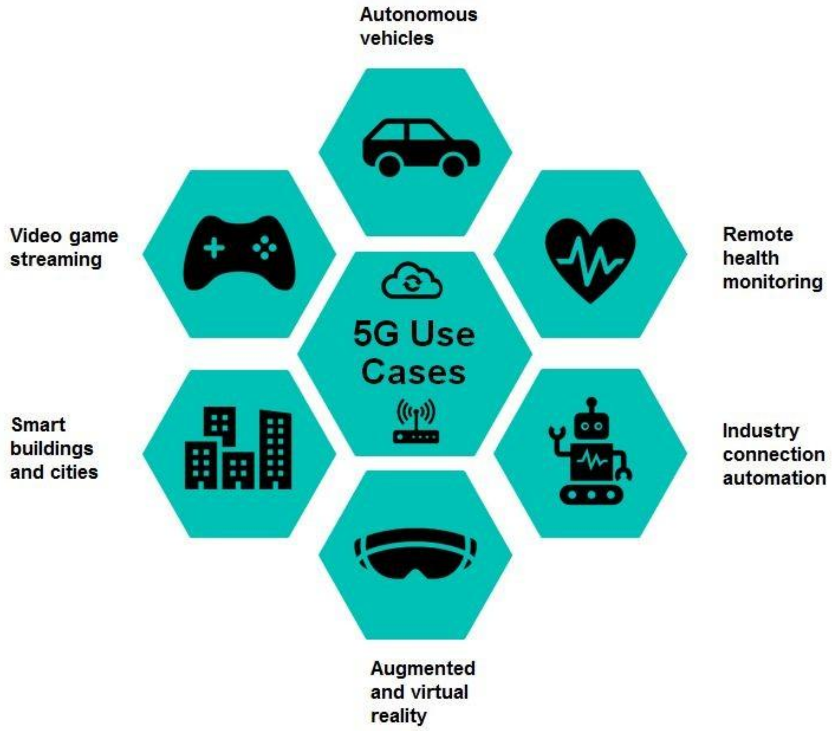


Figure. 1 5G Use Cases [1]

Introduction - 6G

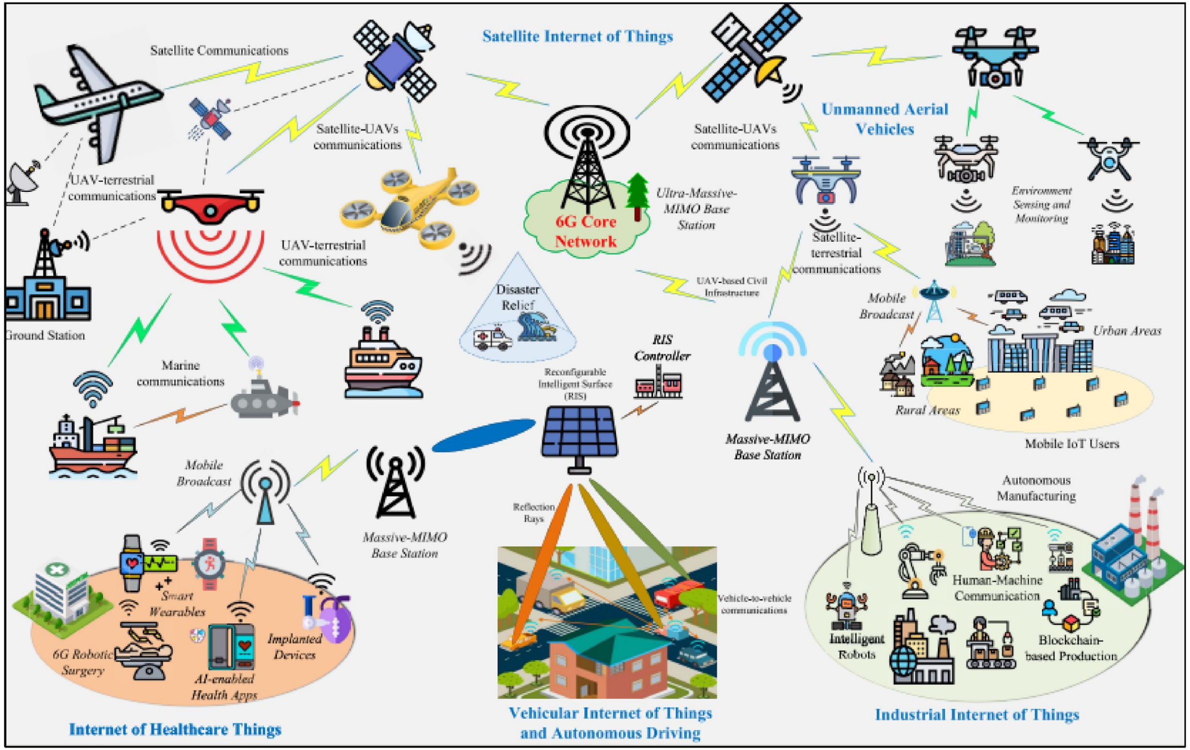


Figure. 2 6G Applications [2]

Not just about connectivity -
but about fostering deeper, more meaningful and intelligent interactions in an increasingly Digital world

Introduction – 6G Applications and Security

Communication Revolution with 6G (IoNT) speed and connectivity.

Personalized Medicine & Healthcare Advancements :

- **Health Monitoring:** real-time health monitoring through high-speed, low-latency connections.
- **Improved telemedicine and remote patient monitoring**
- **Remote Healthcare:** Patient monitoring and virtual consultations, transforming healthcare delivery.
- **Data Precision** for personalized treatment plans.

Autonomous Systems:

- **Empowering autonomous vehicles**, drones, robots
- **Precision** navigation and coordination

Smart Cities and Infrastructure:

- **Smart city applications**, energy and traffic
- **Intelligent infrastructure**

Climate Research & Environmental Monitoring:

- **Advanced environmental monitoring**, climate change research and disaster management.
- **Real-time data collection** for proactive measures in preserving and sustaining the environment.

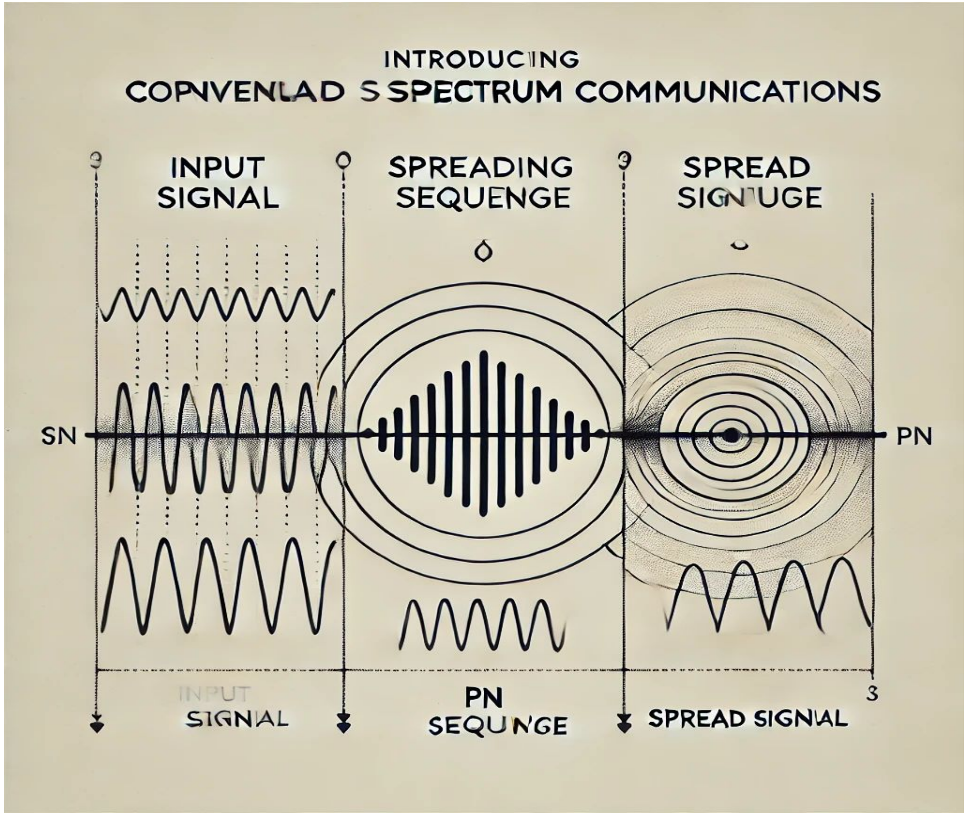
Security and Surveillance:

- **Enhanced security systems** with real-time data analytics and monitoring.
- **Improved surveillance**

Innovations in Agriculture:

- **Precision agriculture** IoNT devices and sensors connected via 6G.
- **Monitoring and controlling** agricultural processes

Current Conventional Security Mechanisms



Spread Spectrum is a technique where the signal is spread across a wider bandwidth using a spreading code [3]

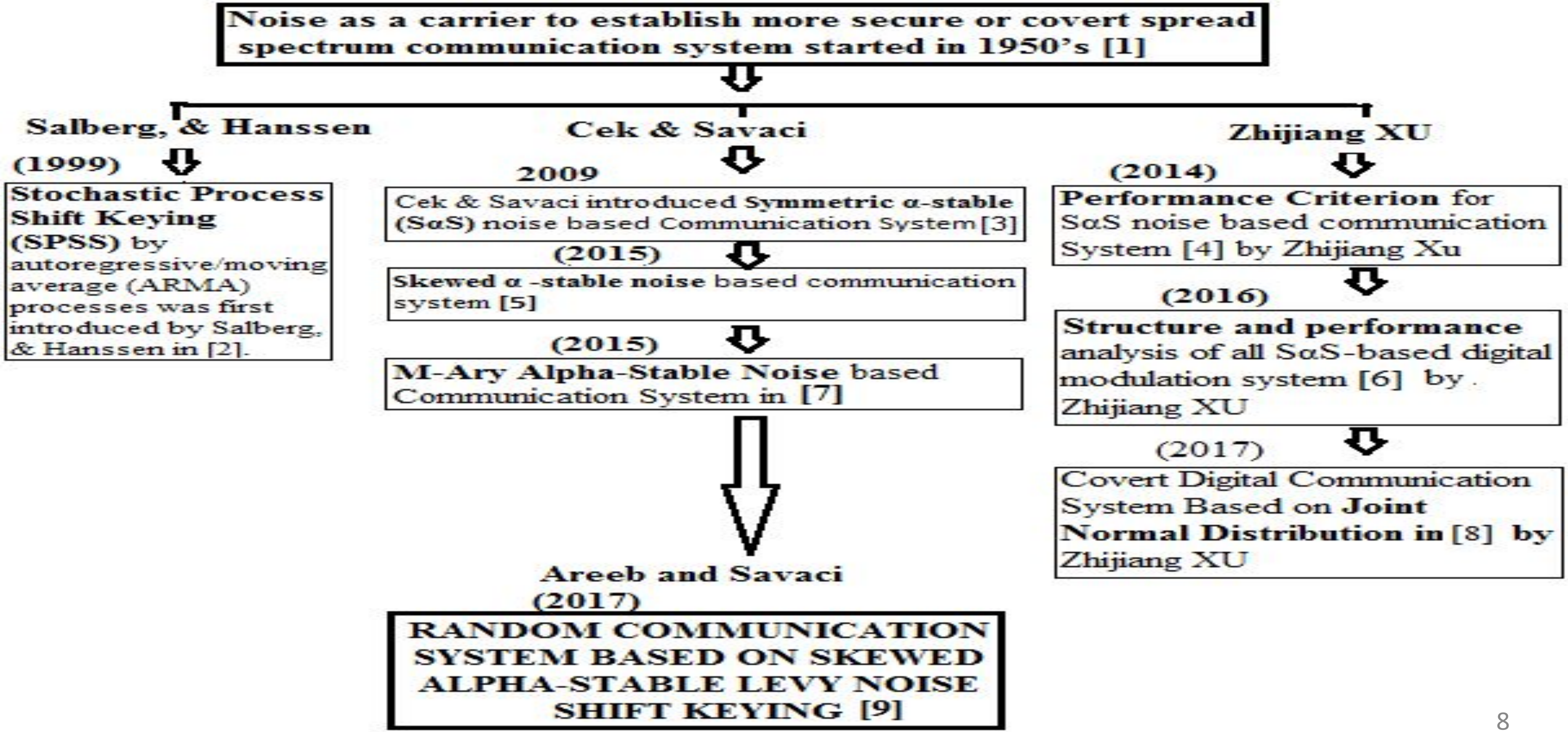
Types of Spread Spectrum:

- Direct Sequence Spread Spectrum (DSSS)
- Frequency Hopping Spread Spectrum (FHSS)

Key Benefits:

- Resistance to interference
- Improved security
- Multipath fading mitigation

Unconventional Security Mechanisms



Random Communication System (RCS) based on Alpha-stable Noise

Alpha-stable distribution

α-Stable distribution does not have closed form density function and is expressed by characteristic function:

$$\phi_{stable}(t;\alpha,\sigma,\beta,\mu) = E\left[e^{itX}\right]$$

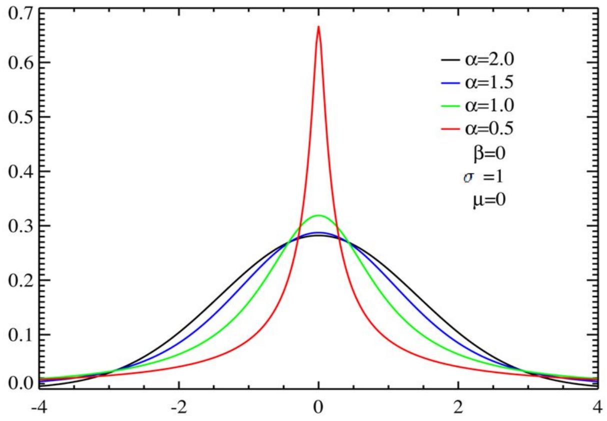
$$= \begin{cases} \exp\left(i\mu t - |\sigma t|^{\alpha}\left(1 - i\beta(\operatorname{sign} t)\tan\frac{\pi\alpha}{2}\right)\right) & \alpha \neq 1 \\ \exp\left(i\mu t - \sigma|t|\left(1 + i\beta\frac{2}{\pi}(\operatorname{sign} t)\ln|t|\right)\right) & \alpha = 1 \end{cases}$$

where

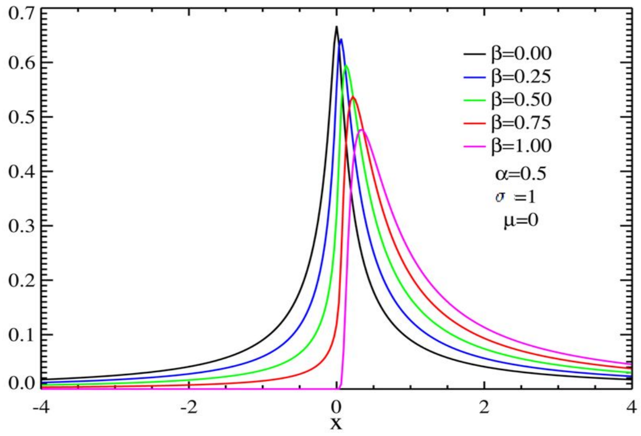
$$\operatorname{sign} t = \begin{cases} 1, & t > 0 \\ 0, & t = 0 \\ -1, & t < 0 \end{cases}$$

Four related parameters are:

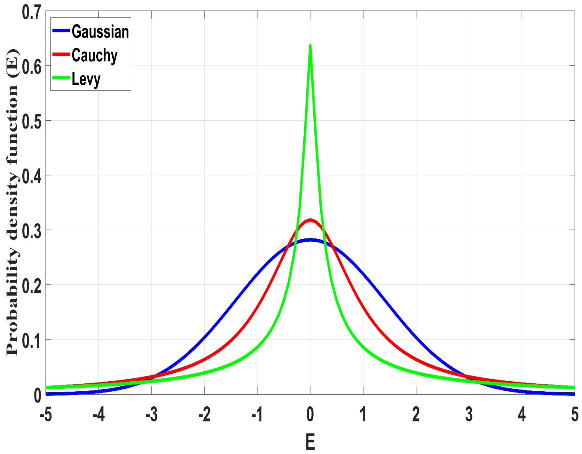
- α: the index of stability or the shape parameter, $\alpha \in (0,2)$
- β: the skewness parameter, $\beta \in [-1,1]$
- σ: the scale parameter, $\sigma \in (0,+\infty)$
- μ: the location parameter, $\mu \in (-\infty,+\infty)$



a) Symmetric α-stable distributions



b) Skewed centered stable distributions



c) Special Noises Cases [12]

Random Communication System (RCS) based on Alpha-stable Noise

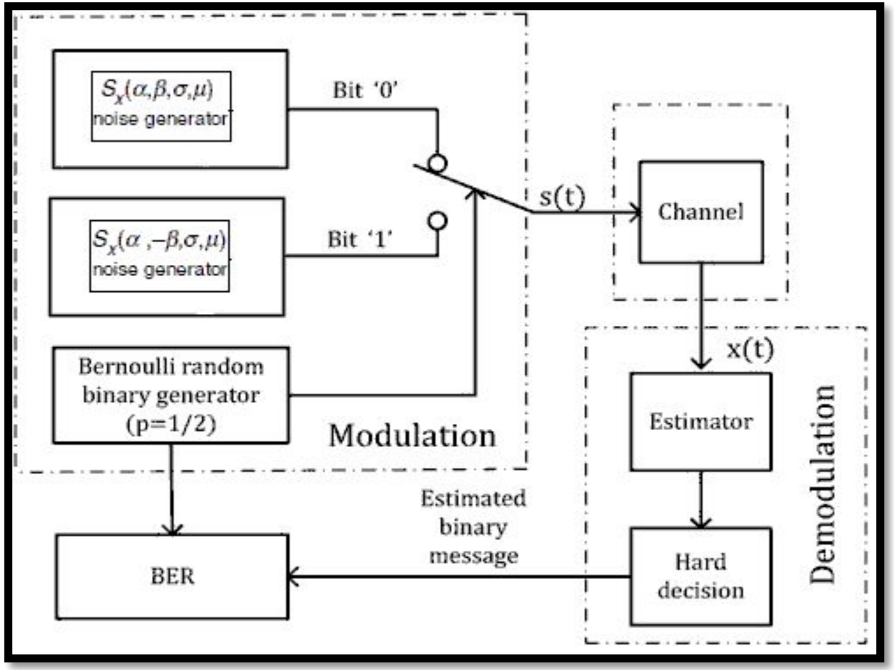
Proposed RCS Model

The random variable

$\mathbf{X_0} \sim \boldsymbol{S\alpha\ (\beta_0,\ \gamma,\ \mu)}$ is used to code message signal '**0**' and

$\mathbf{X_1} \sim \boldsymbol{S\alpha\ (\beta_1,\ \gamma,\ \mu)}$ where $\beta_1 = -\beta_0$ is used for code message signal '**1**'

Transmitter



Most Optimised Model [12]

The method proceeds by subdividing the received data $\{x_1, x_2, \ldots, x_N\}$ in duration consisting of N samples into L non overlapping segments of length K.

$$Y_{lmax} = log\,\{max(x_{lK-K+i} | \, i \in 1,2,\ldots,K)\}$$

$$Y_{lmin} = log\,\{-min(x_{lK-K+i} | \, i \in 1,2,\ldots,K)\}$$

$$Y_{max} = \frac{1}{L} \sum_{l=1}^{L} Y_{lmax} \; ;$$

$$Y_{min} = \frac{1}{L} \sum_{l=1}^{L} Y_{lmin} \; ;$$

$$s_{max}^2 = \frac{1}{L-1} \sum_{l=1}^{L} (Y_{lmax} - Y_{max})^2$$

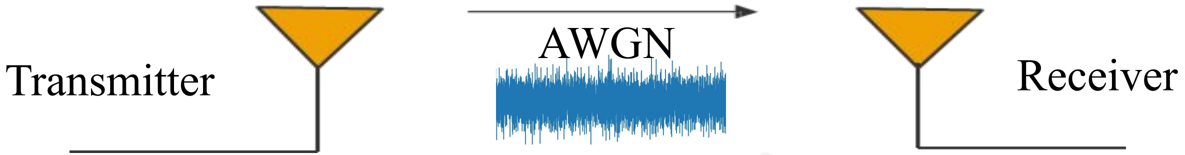
$$s_{min}^2 = \frac{1}{L-1} \sum_{l=1}^{L} (Y_{lmin} - Y_{min})^2$$

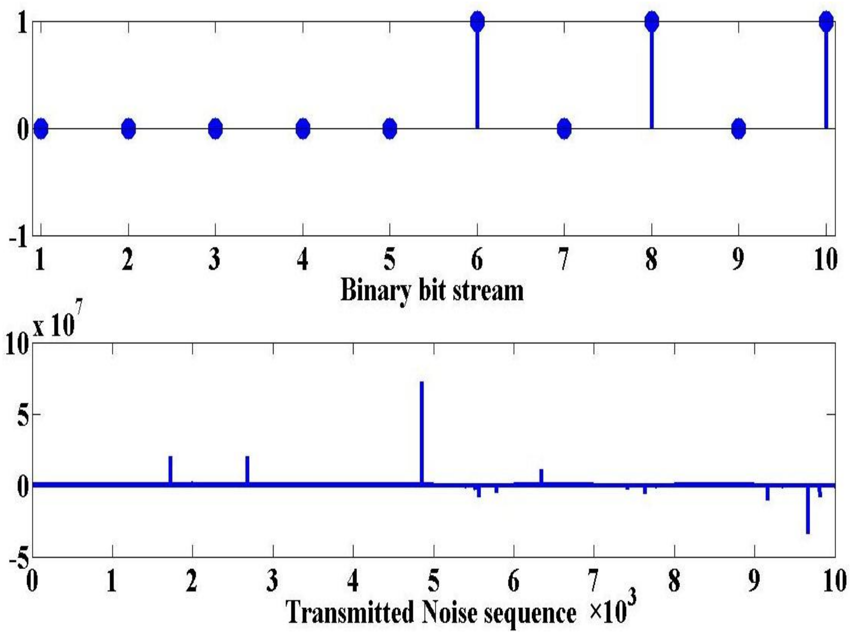
$$\hat{\beta} = 1 - \frac{2}{\exp\left(\hat{\alpha}(S_{max} - S_{min})\right)} \qquad \text{Where } \hat{\alpha} = \frac{\pi}{2\sqrt{6}}\left(\frac{1}{Y_{max}} + \frac{1}{Y_{min}}\right)$$

Receiver

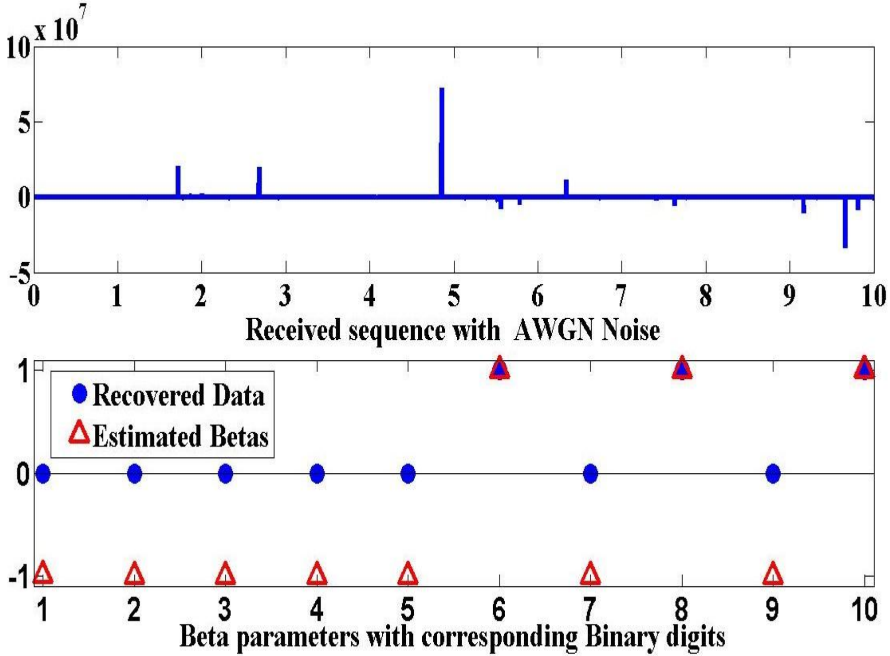
Random Communication System (RCS) based on Alpha-stable Noise

Transmission Testing





Binary Message sequence (Top), Transmitted Signal In time Domain (Bottom); Bit length =1, N = 1000 noise samples per information bit, =1× 10^3 [12]



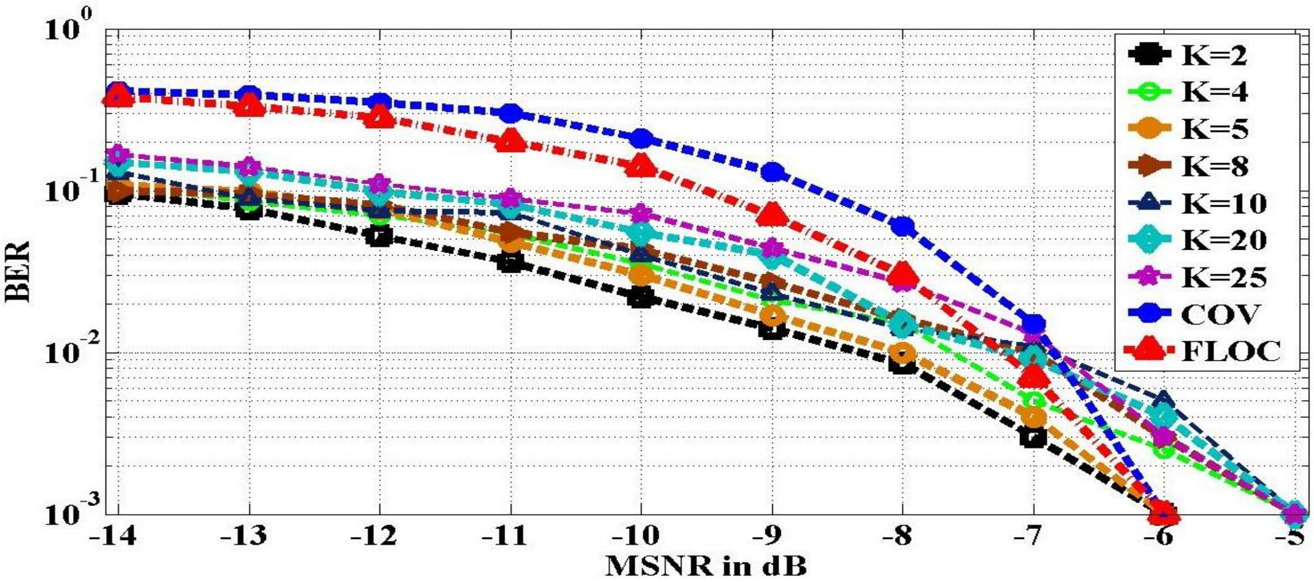
Received Signal from AWGN Channel in time Domain (Top), Estimated Beta parameters and recovered binary message (bottom); Bit length =1, N = 1000 noise samples per information bit, =1× 10^3 bit [12]

Random Communication System (RCS) based on Alpha-stable Noise

Performance Analysis

$$MSNR_{dB} = 10\log\frac{\gamma}{\gamma_G}$$

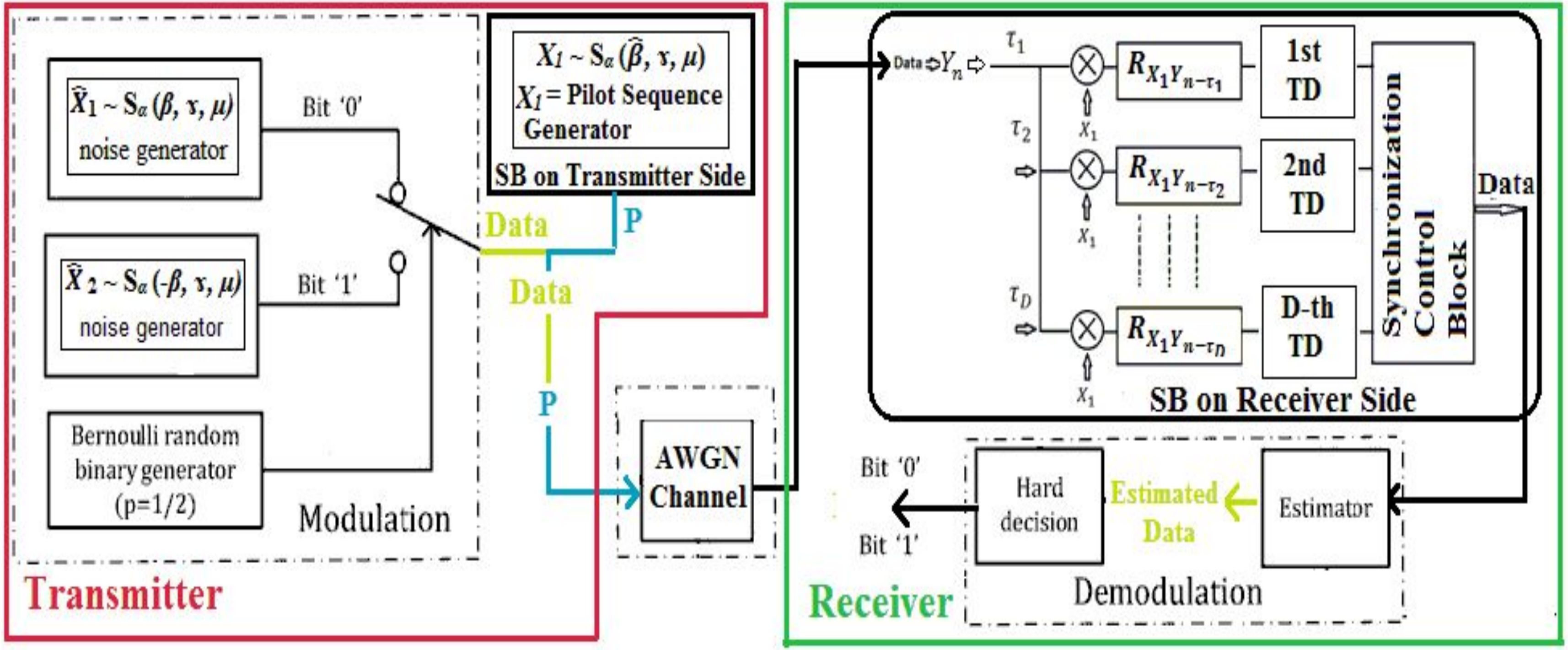
Where γ and γ_G are the dispersion parameters of the information bearing α-stable random signal and channel noise [7].



BER vs. MSNR (dB) with different 'L and K' of estimator in AWGN channel; where = 1.5; (Where $\beta_1 = -\beta_0 = 1$) [12]

Synchronized Random Communication System (RCS) Noise

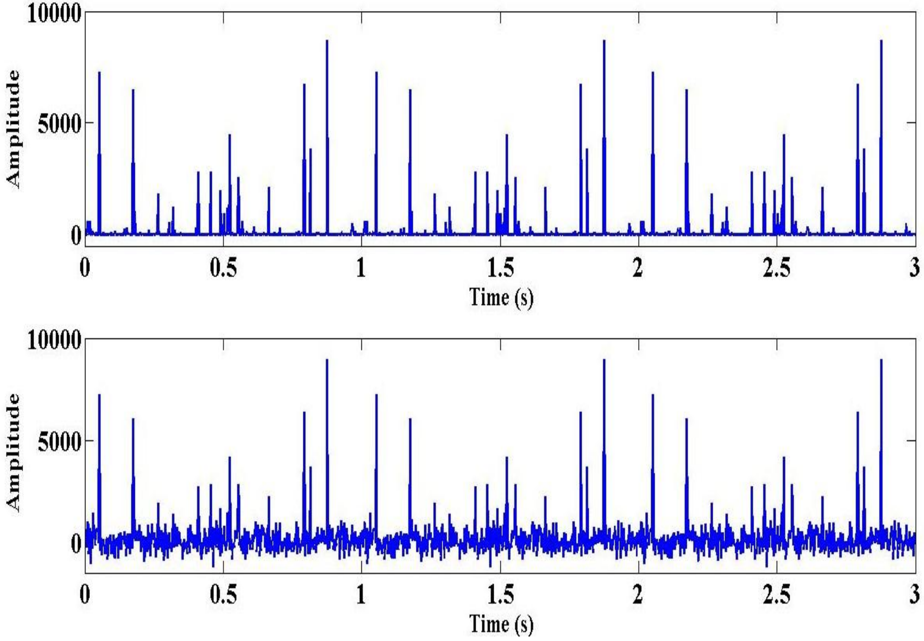
Proposed RCS Model



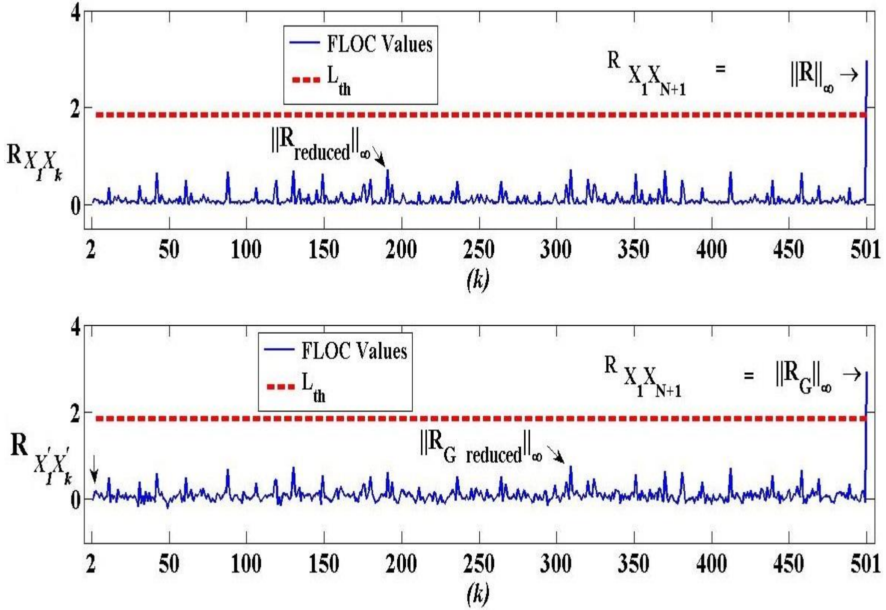
Block diagram of the RCS based on α-stable Levy noise along with the proposed Synchronization Blocks on Transmitter and Receiver side [13]

Synchronized Random Communication System (RCS) Noise

Transmitter Testing



a) Pilot Sequence b) Noisy Pilot Sequence [13]

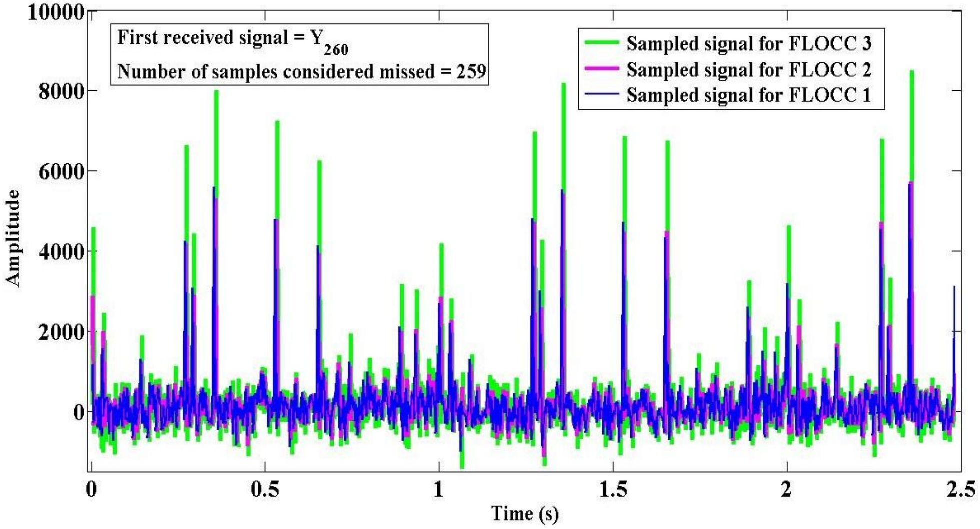


a) FLOCs of X_1X_k *b) FLOCs of* $X_1'X_k'$ *[13]*

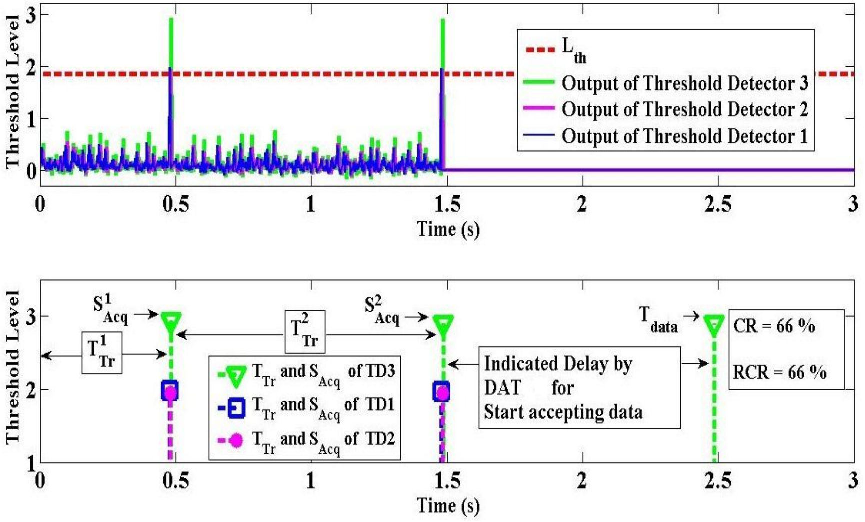
Y

Synchronized Random Communication System (RCS) Noise

Receiver Testing



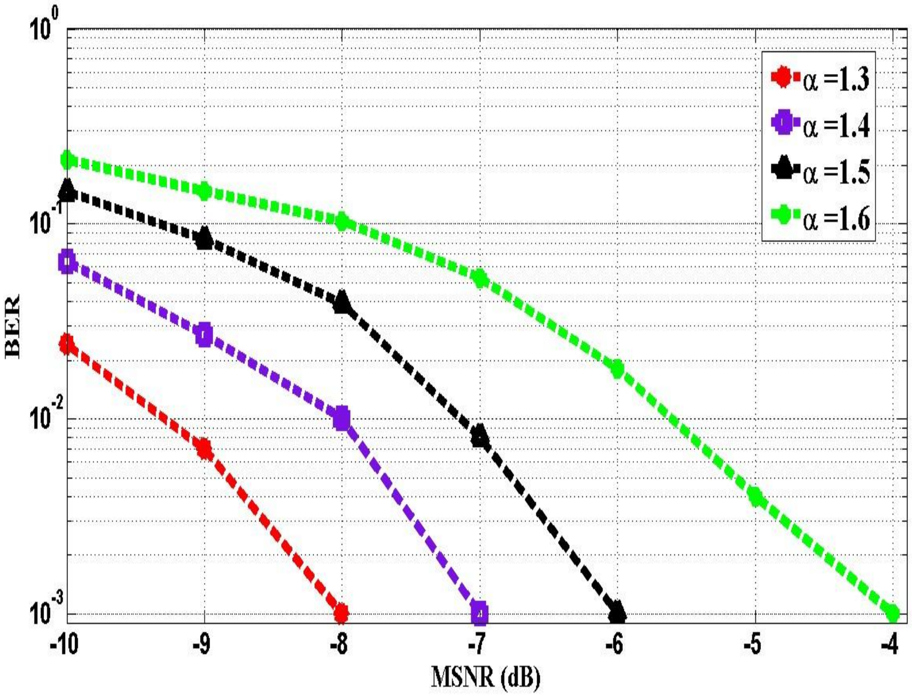
Received signals Y_n through AWGN channel [13].



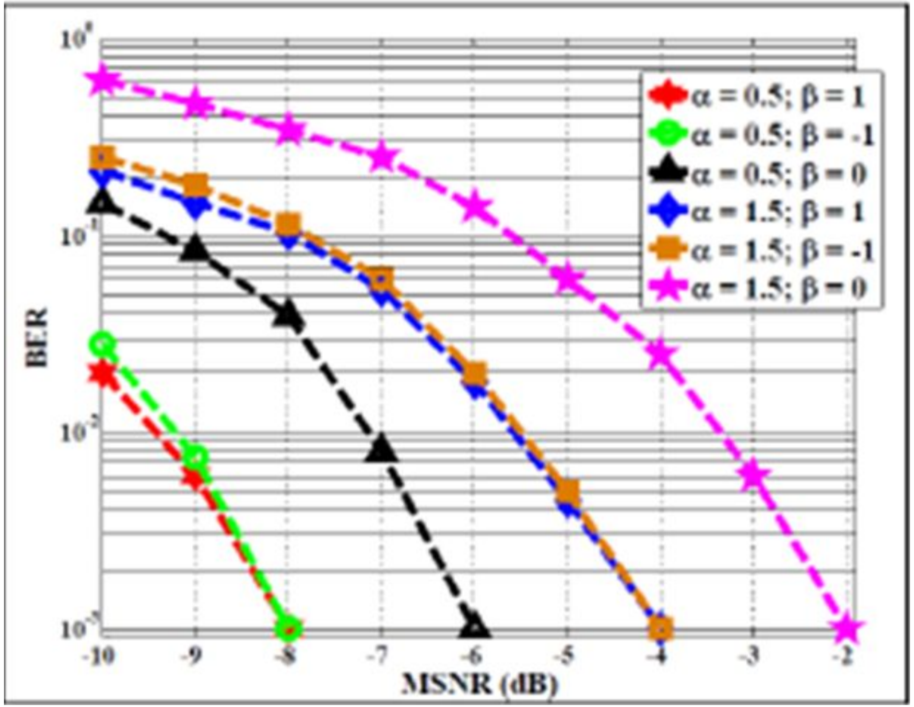
a) Output of Threshold Detectors
b) Output of Synchronization Control block [13]

Synchronized Random Communication System (RCS) Noise

Performance Analysis

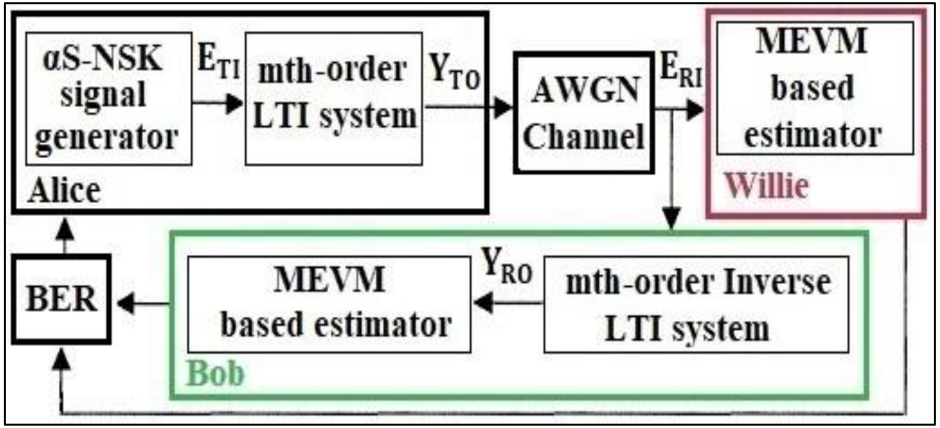


*BER vs. MSNR for different characteristic exponents **'α'** [13]*



*BER vs. MSNR for different characteristic exponents **'α' & 'β'** [13]*

Inverse System Approach to design Secure RCS



$$\mathcal{R} = [A\ B\ C\ D];$$

where $A \in R^{m\times m}$, $B \in R^{m\times p}$, $C \in R^{q\times m}$ and $D \in R^{q\times p}$. In the proposed RCS, we have chosen the representation

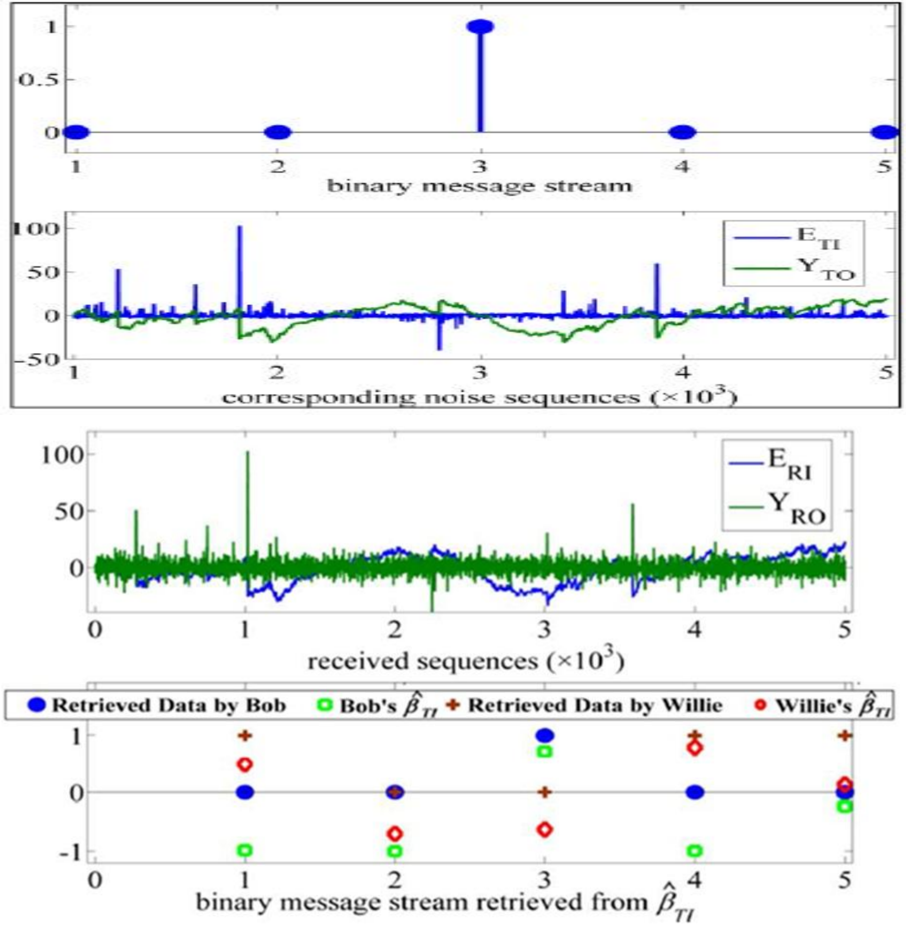
$$A = \begin{bmatrix} 0.98 & -0.01 \\ -0.01 & 0.98 \end{bmatrix}, B = \begin{bmatrix} -0.06 \\ 2.19 \end{bmatrix},$$

$$C = [0 \quad -0.16], \text{ and } D = [-0.33]$$

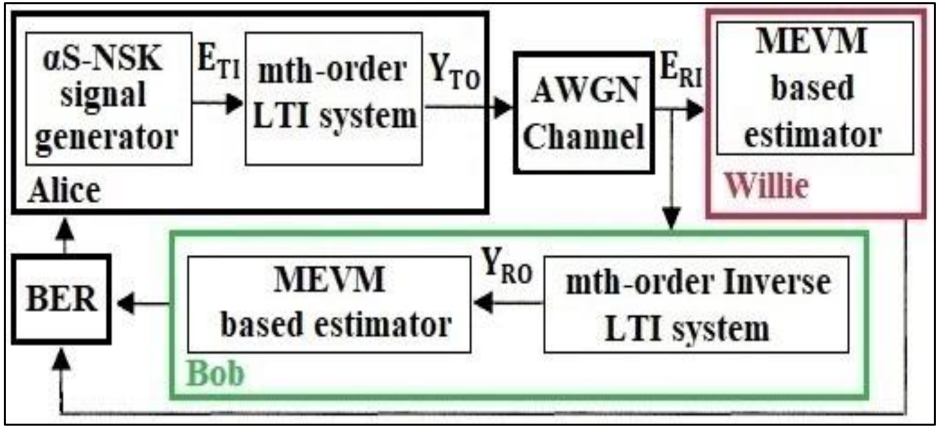
$$\mathcal{R}_I = [A - BD^{-1}C \quad BD^{-1} \quad -D^{-1}C \quad D^{-1}].$$

[14]

Model and Initial Testing



Inverse System Approach to design Secure RCS



$$\mathcal{R} = [\mathrm{A\ B\ C\ D}];$$

where $A \in R^{m \times m}$, $B \in R^{m \times p}$, $C \in R^{q \times m}$ and $D \in R^{q \times p}$. In the proposed RCS, we have chosen the representation

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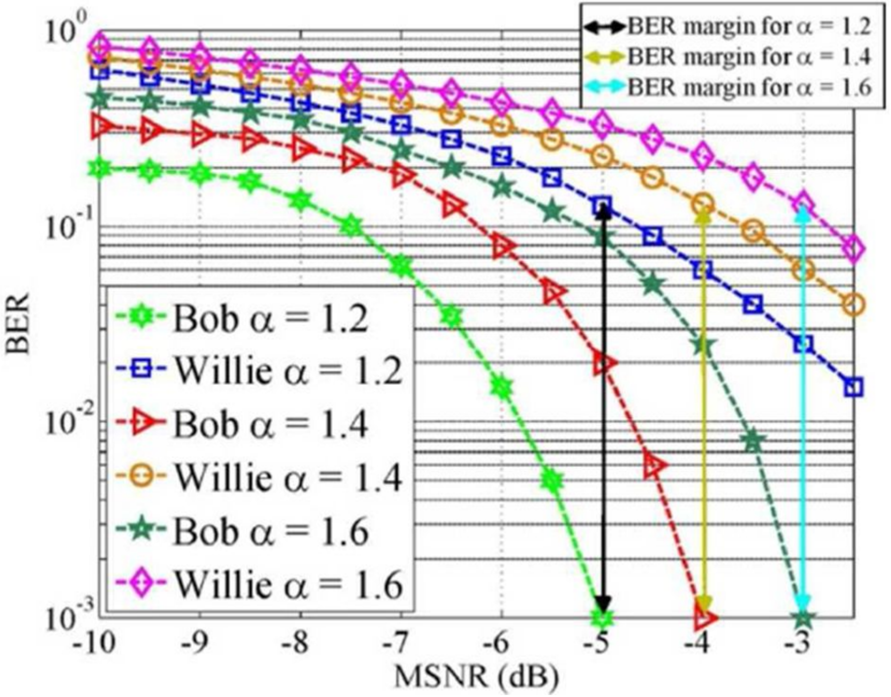
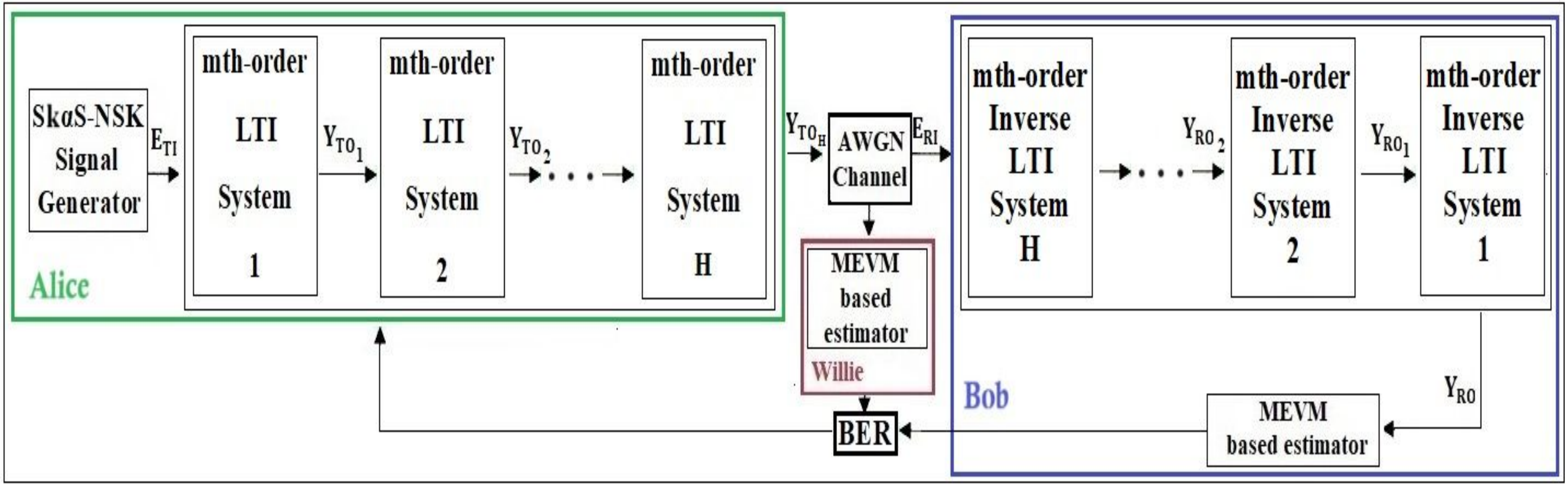
Performance Analysis



BER vs. MSNR (dB) performances of Bob and Willie for the different 's utilized by Alice; number of transmitted bits=1000

Multiple Inverse System Approach for Secure RCS in Terahertz Band

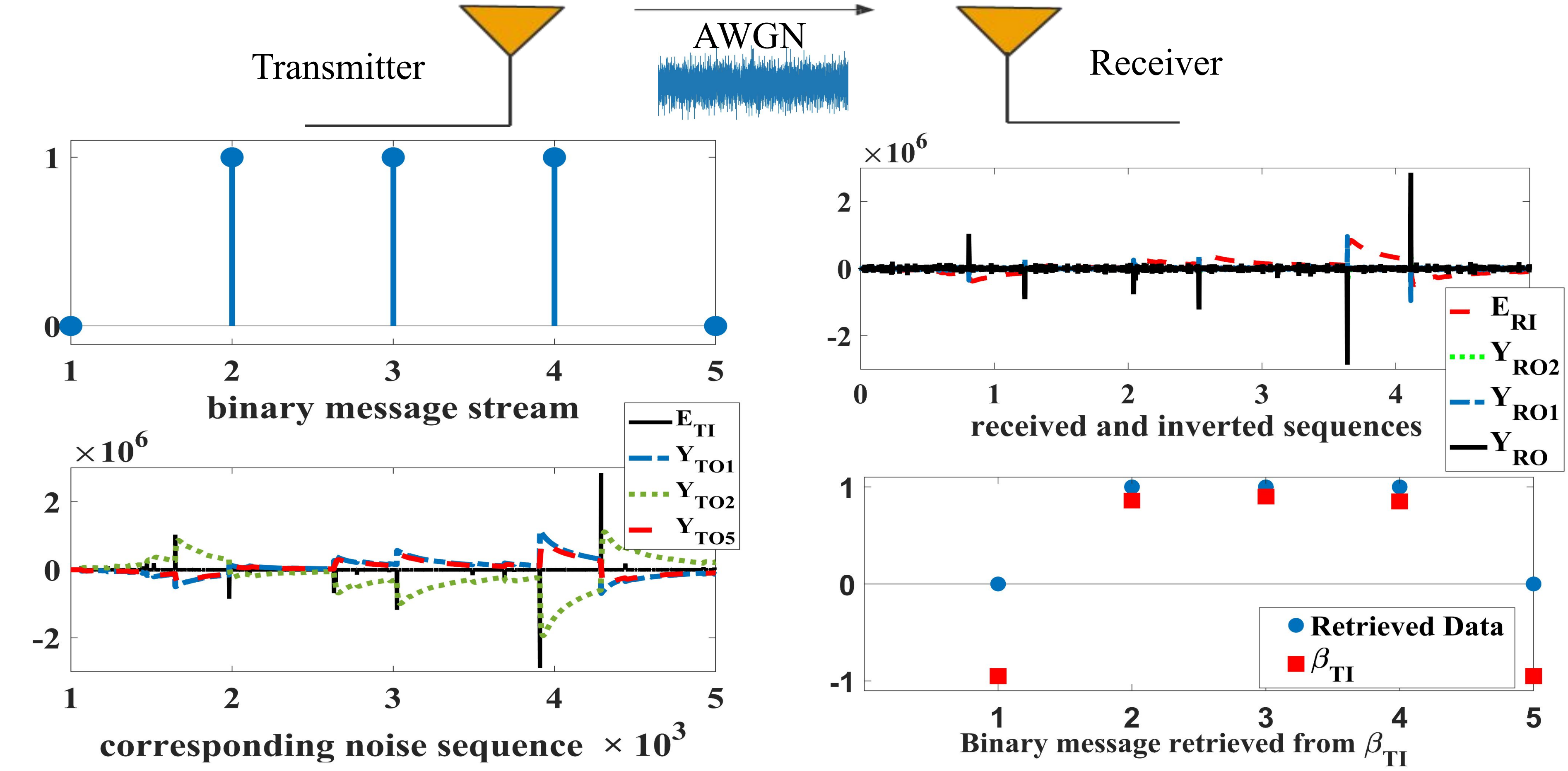
Proposed Model



System model of the proposed ERCS based on the multiple inverse systems

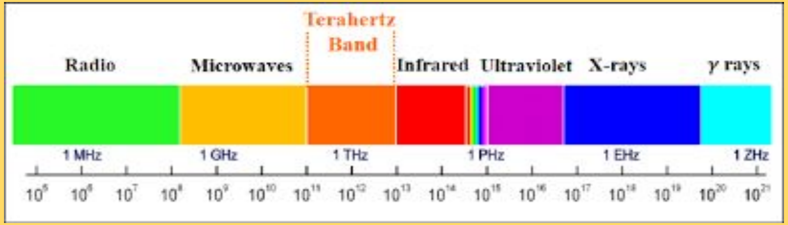
Multiple Inverse System Approach for Secure RCS in Terahertz Band

Initial Results



Currently in Lab

- The research proposal aims to leverage **AI and ML techniques to enhance the security of wireless communications in the Terahertz (THz) band for future scientific applications**.
  - THz band offers immense bandwidth and potential for high-speed data transfer.
  - Unique security challenges, such as vulnerability to eavesdropping and signal attenuation.



- The proposal addresses these challenges by developing **ML and data-driven solutions with Random Communication Systems (RCSs),** such as
  - Intrusion detection
  - Encryption, authentication,
  - Adaptive modulation
  - Coding, and channel modeling.

Conclusion – Beyond State of the Art

Expected Outcomes:

- **Comprehensive data collection** and analysis framework for THz communication.
- **ML-driven** intrusion detection, encryption, authentication, and adaptive modulation **techniques for THz communication**.
- **Data-driven channel models** for THz communication evaluation.
- **Testing and evaluation results** of the AI-driven secure communication solutions.

Beyond State of the Art:

- **Advancing the state-of-the-art** in machine learning and wireless communication research.
- **Enhancing the security and efficiency** of wireless communication systems for 5G/6G applications.
- **Supporting scientific applications** that require high-speed and secure data transmission, such as multidisciplinary communications, healthcare and climate operations.
- **Contributing to the development** of a sustainable and secure future.

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