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machine learning for science and humanities   postdoctoral program

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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

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

subarea "**1.3 Beyond Supervised Learning**"

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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**

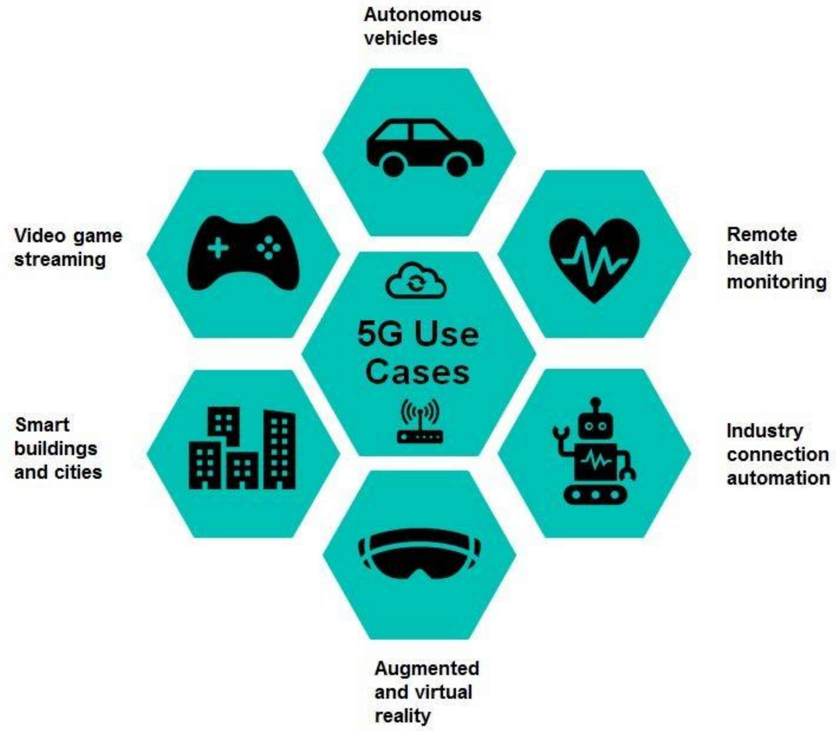


Figure. 1 5G Use Cases [1]

Introduction - 6G

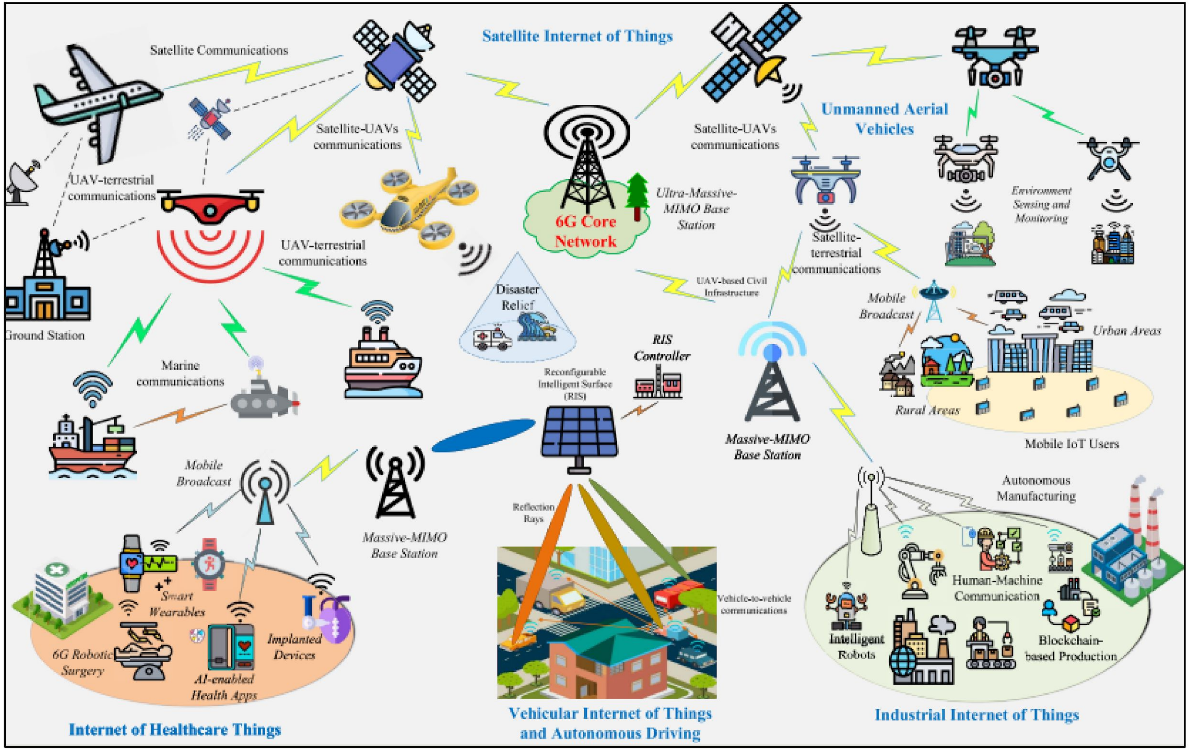


Figure. 2 6G Applications [2]

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.

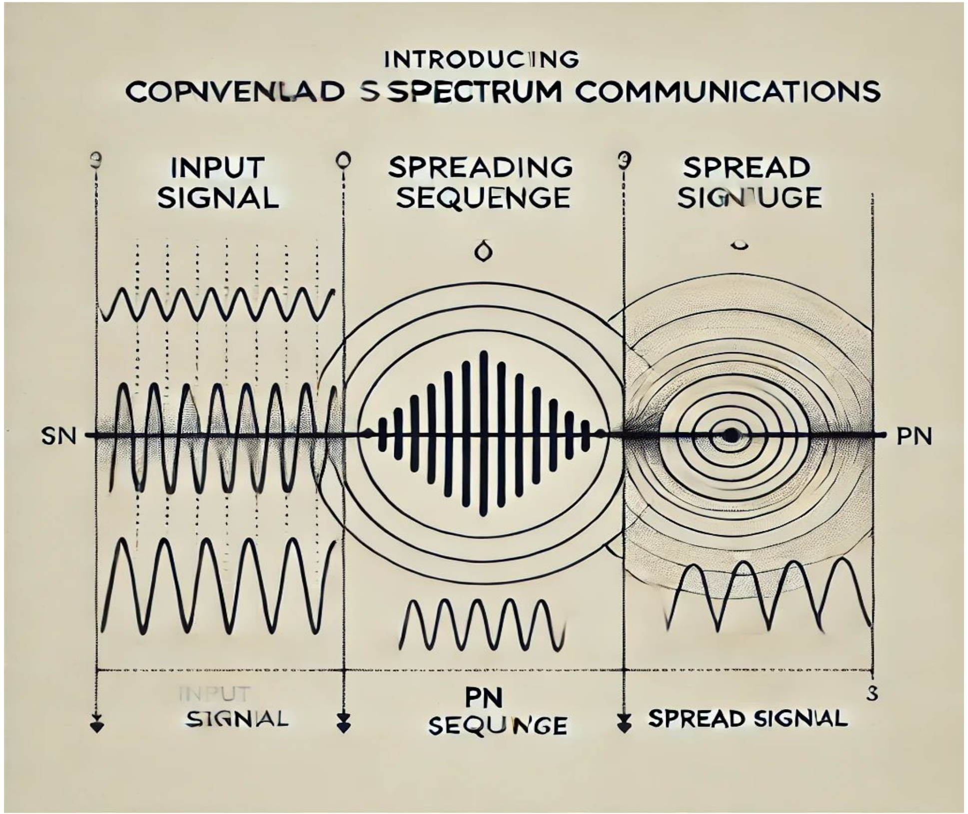
Security and Surveillance:

- **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]

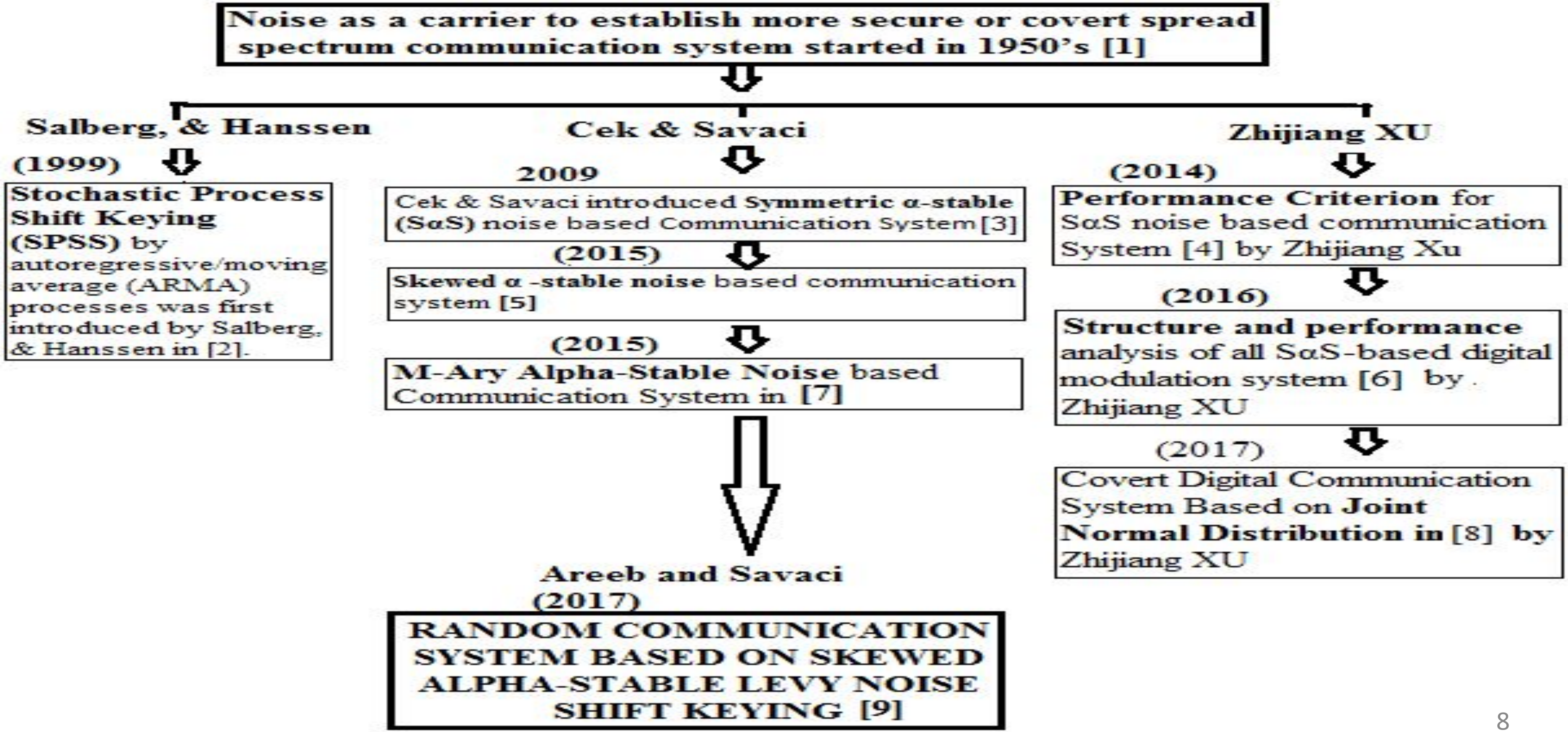
Types of Spread Spectrum:

- 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:

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

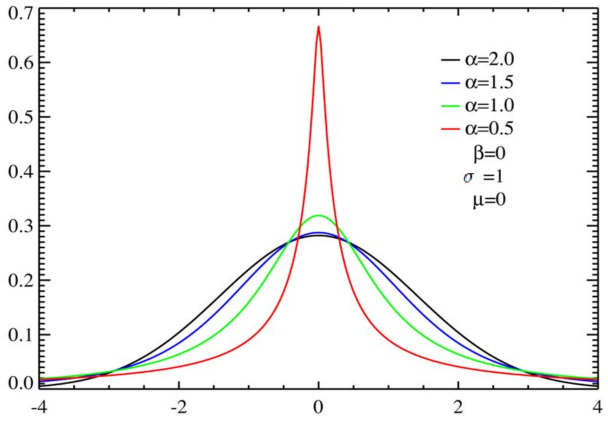
$$= \begin{cases} \exp\left(i\mu t - |\sigma t|^{\alpha}\left(1 - i\beta(\operatorname{sign} t)\tan\frac{\pi\alpha}{2}\right)\right) & \alpha \neq 1 \\ \exp\left(i\mu t - \sigma|t|\left(1 + i\beta\frac{2}{\pi}(\operatorname{sign} t)\ln|t|\right)\right) & \alpha = 1 \end{cases}$$

where

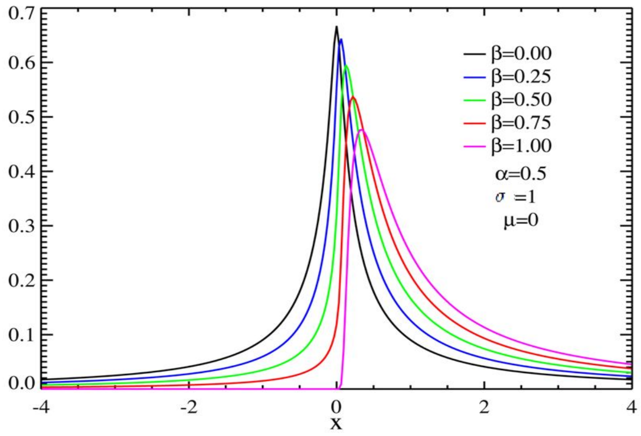
$$\operatorname{sign} t = \begin{cases} 1, & t > 0 \\ 0, & t = 0 \\ -1, & t < 0 \end{cases}$$

Four related parameters are:

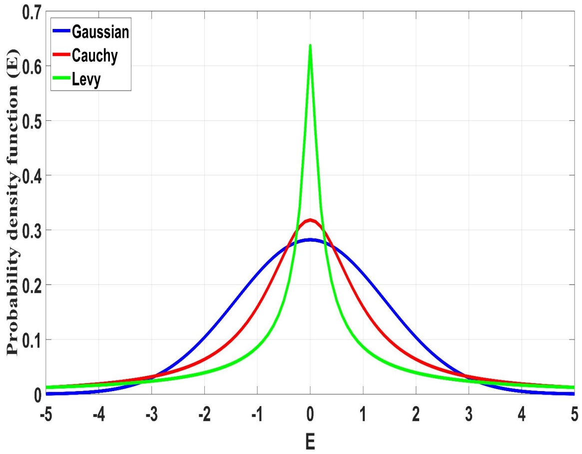
- α: the index of stability or the shape parameter, $\alpha \in (0,2)$
- β: the skewness parameter, $\beta \in [-1,1]$
- σ: the scale parameter, $\sigma \in (0,+\infty)$
- μ: the location parameter, $\mu \in (-\infty,+\infty)$



a) Symmetric α-stable distributions



b) Skewed centered stable distributions



c) Special Noises Cases [12]

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

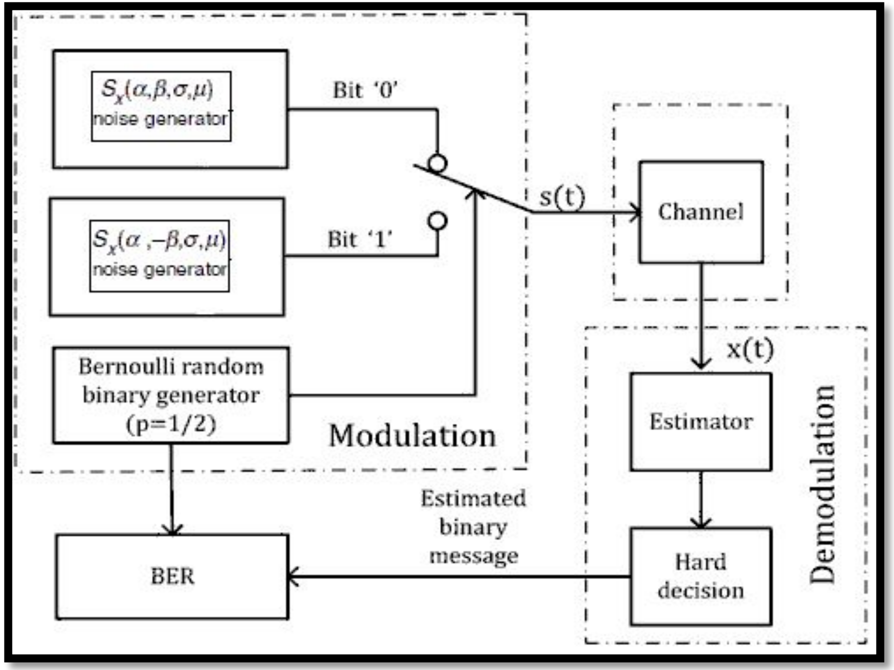
Proposed RCS Model

The random variable

X_0 ~ $S\alpha\ (\beta_0, \gamma, \mu)$ is used to code message signal '**0**' and

X_1 ~ $S\alpha\ (\beta_1, \gamma, \mu)$ 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.

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

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

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

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

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

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

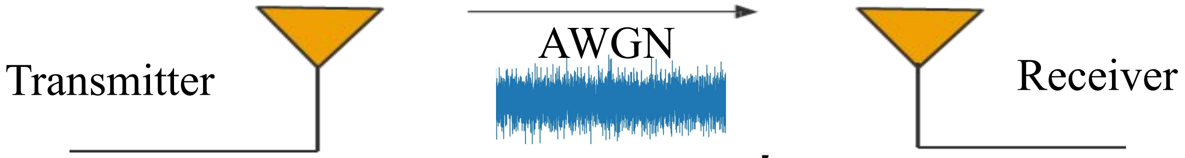
$$\hat{\beta} = 1 - \frac{2}{\exp(\hat{\alpha}(S_{max} - S_{min}))}$$

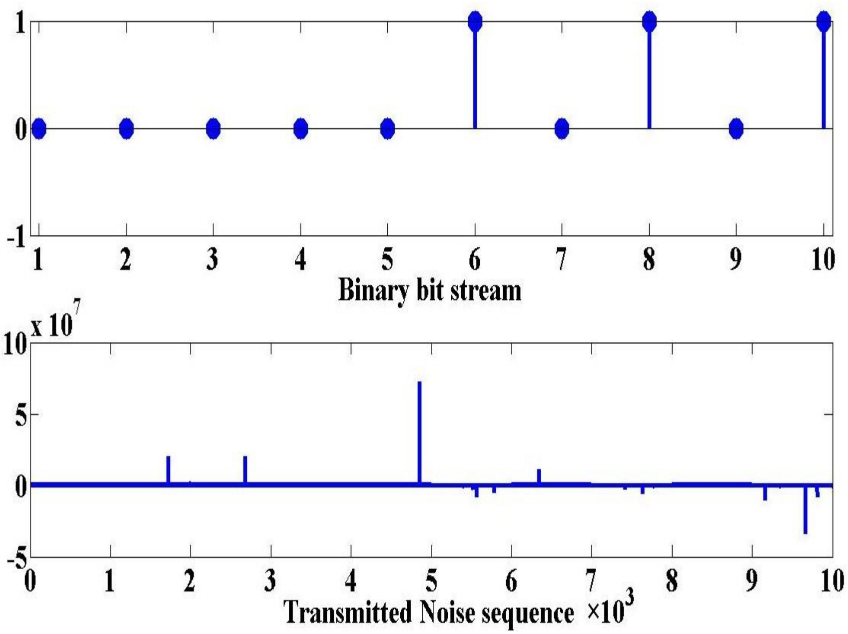
Where $\hat{\alpha} = \frac{\pi}{2\sqrt{6}}\left(\frac{1}{Y_{max}} + \frac{1}{Y_{min}}\right)$

Receiver

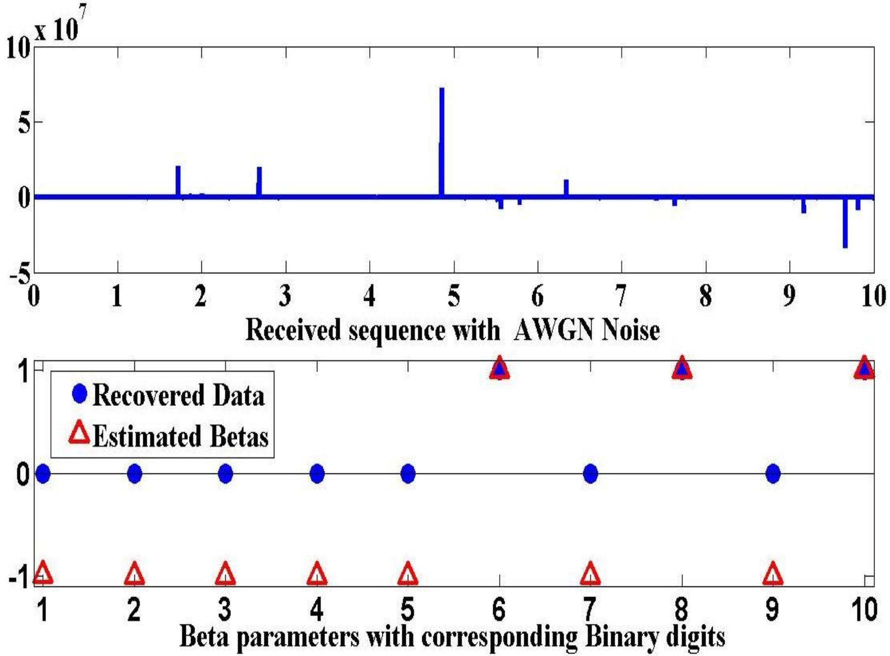
Random Communication System (RCS) based on Alpha-stable Noise

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]



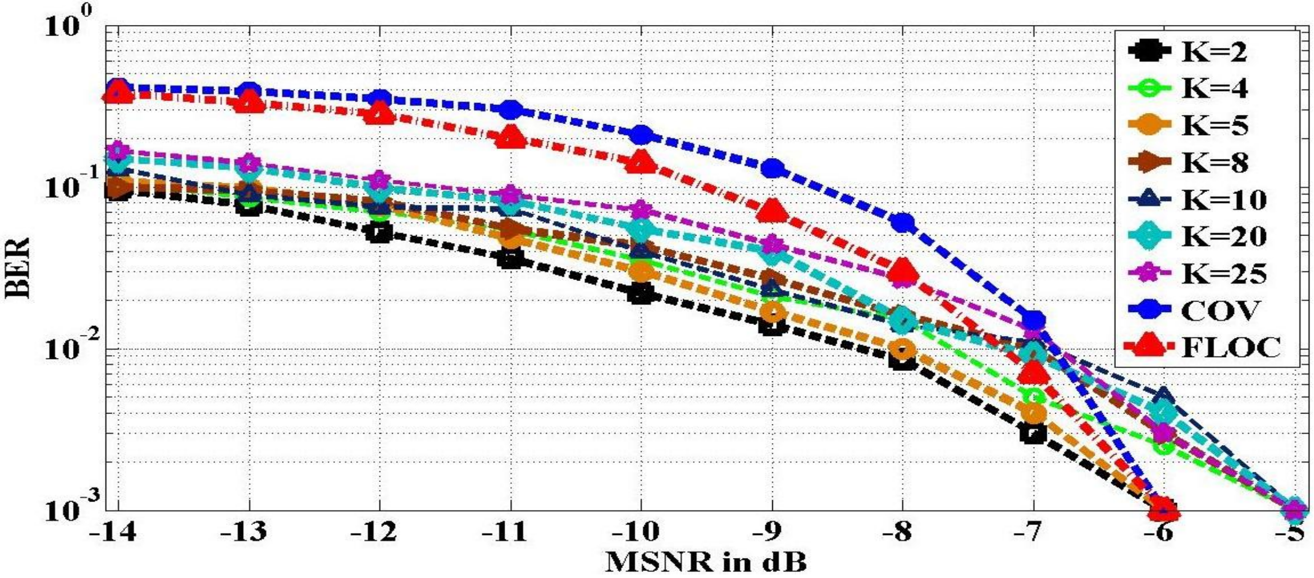
Received Signal from AWGN Channel in time Domain (Top), Estimated Beta parameters and recovered binary message (bottom); Bit length =1, N = 1000 noise samples per information bit, =1× 10^3 bit [12]

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

Performance Analysis

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

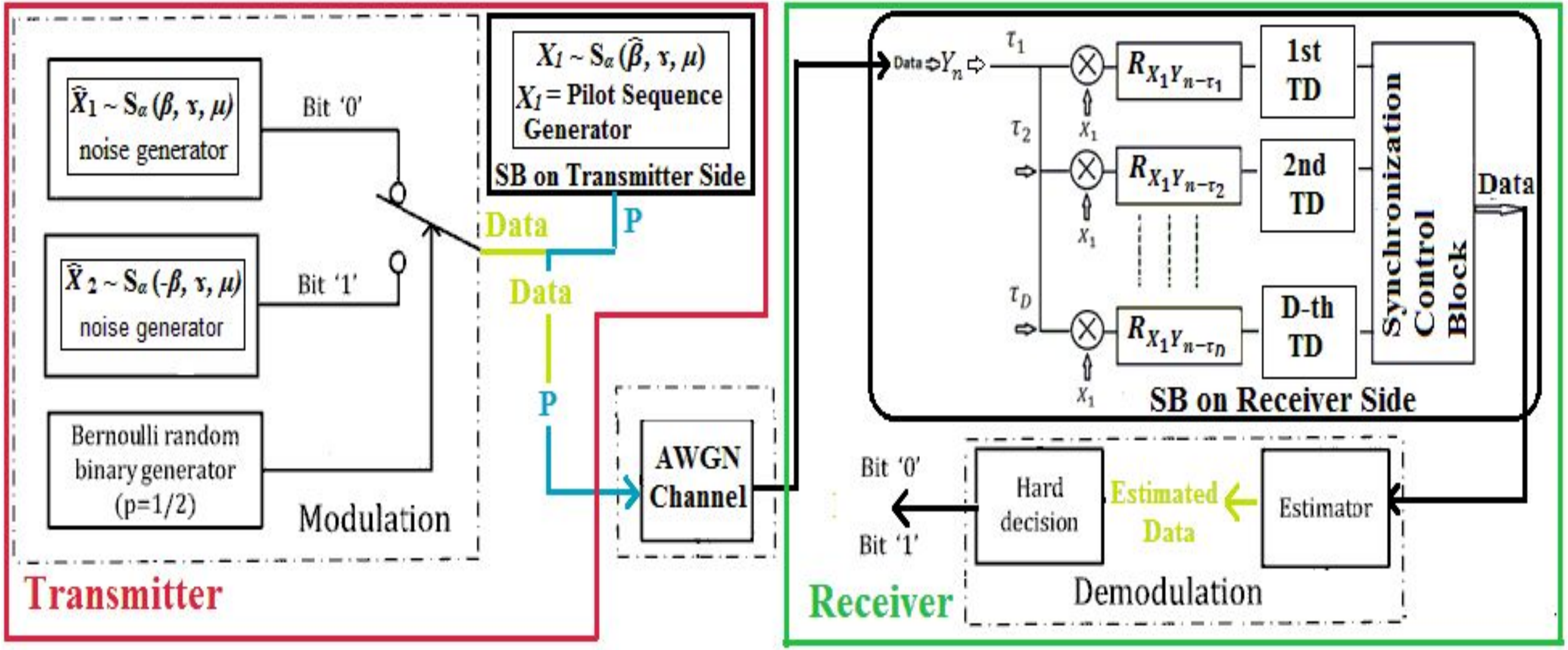
Where ɣ and ɣ_G are the dispersion parameters of the information bearing α-stable random signal and channel noise [7].



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

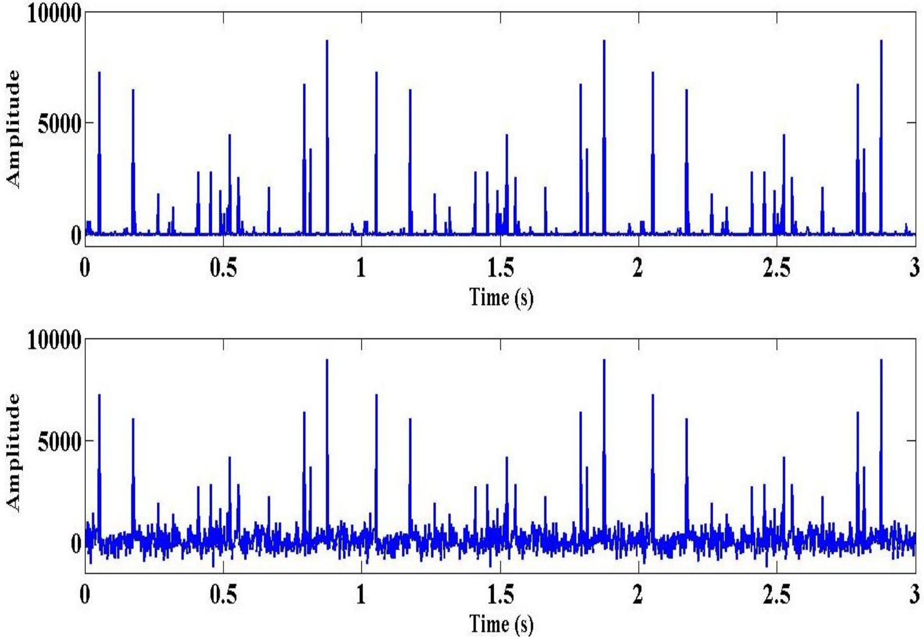
Synchronized Random Communication System (RCS) Noise

Proposed RCS Model



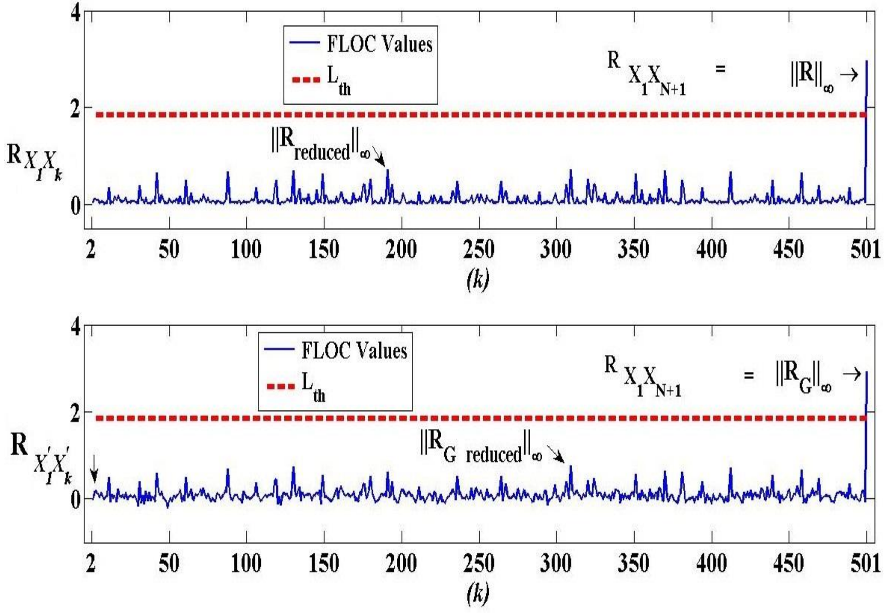
Block diagram of the RCS based on α-stable Levy noise along with the proposed Synchronization Blocks on Transmitter and Receiver side [13]

Synchronized Random Communication System (RCS) Noise



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

Transmitter Testing

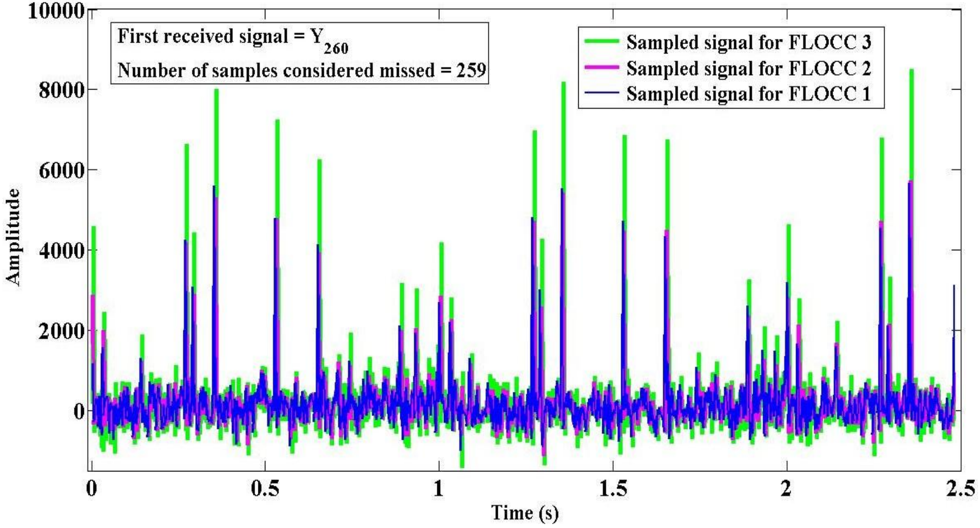


a) FLOCs of X_1X_k *b) FLOCs of* $X'_1X'_k$ *[13]*

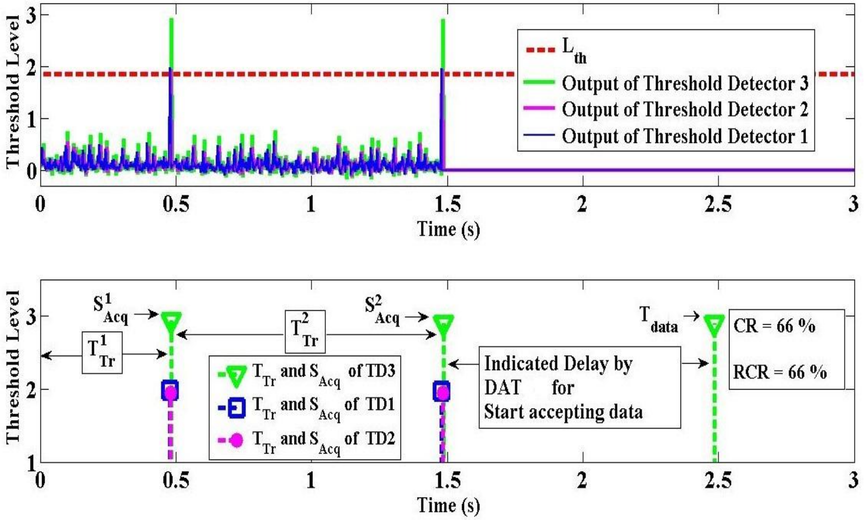
Y

Synchronized Random Communication System (RCS) Noise

Receiver Testing



Received signals Y_n through AWGN channel [13].

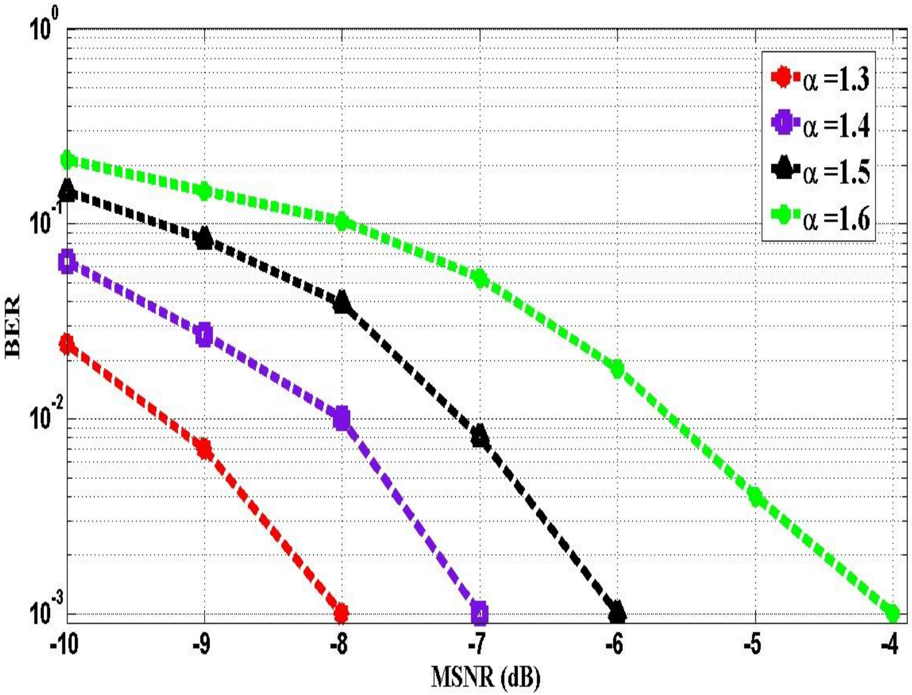


a) Output of Threshold Detectors

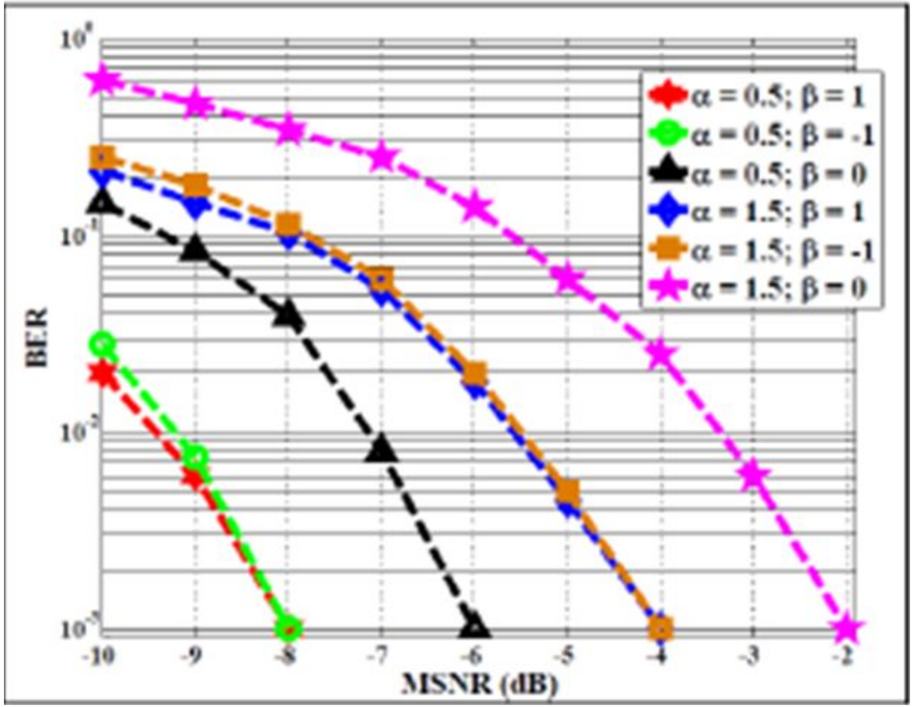
b) Output of Synchronization Control block [13]

Synchronized Random Communication System (RCS) Noise

Performance Analysis

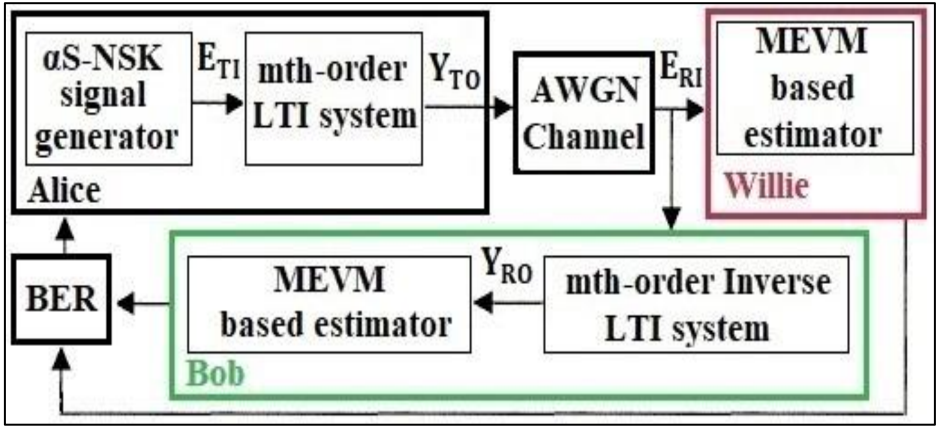


BER vs. MSNR for different characteristic exponents ***'α'*** *[13]*



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

Inverse System Approach to design Secure RCS



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

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

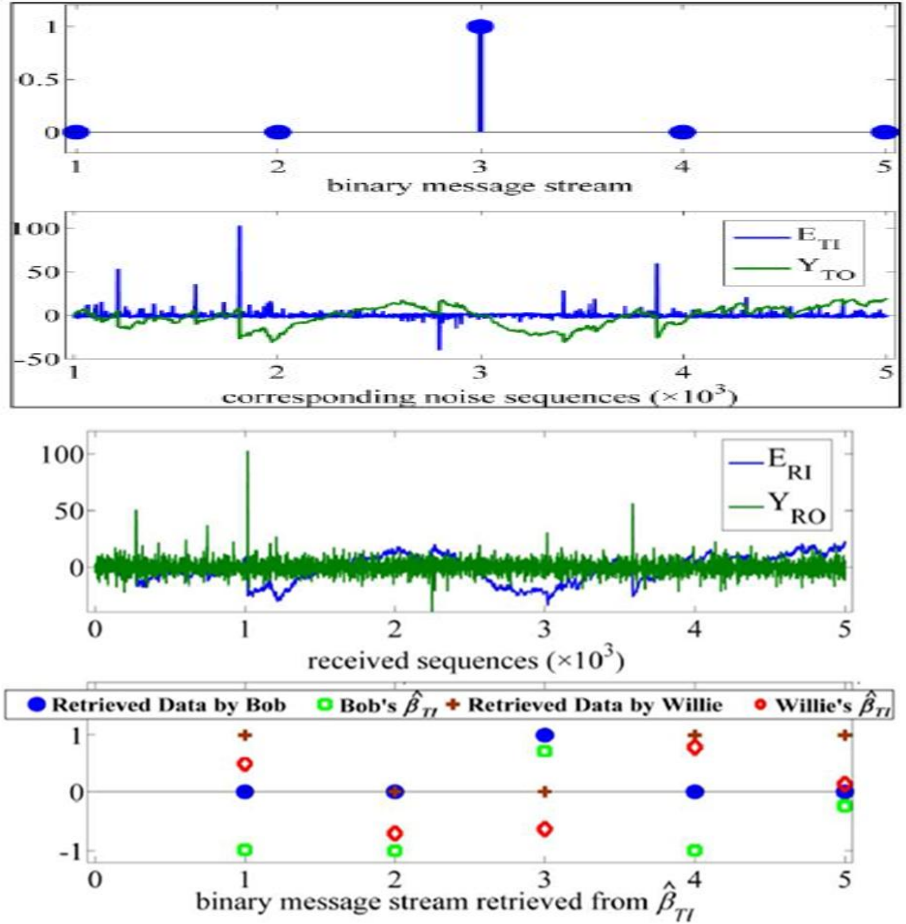
$$A = \begin{bmatrix} 0.98 & -0.01 \\ -0.01 & 0.98 \end{bmatrix}, B = \begin{bmatrix} -0.06 \\ 2.19 \end{bmatrix},$$

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

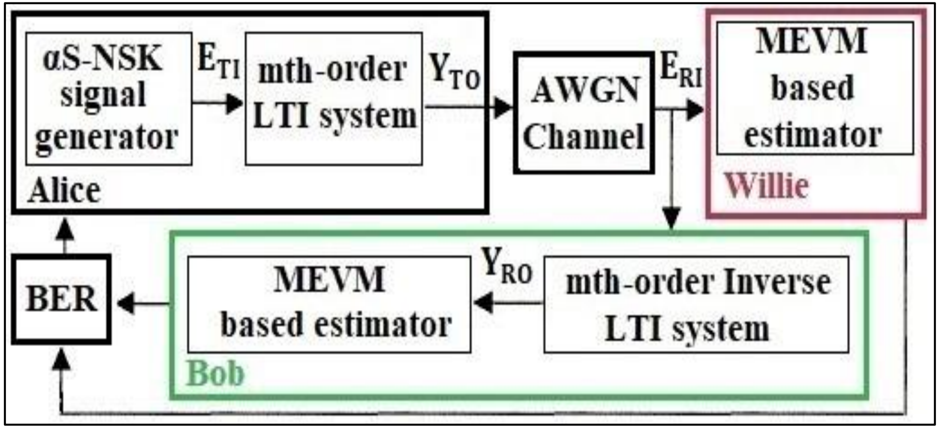
$$\mathcal{R}_I = [A - BD^{-1}C \quad BD^{-1} \quad -D^{-1}C \quad D^{-1}].$$

[14]

Model and Initial Testing



Inverse System Approach to design Secure RCS



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

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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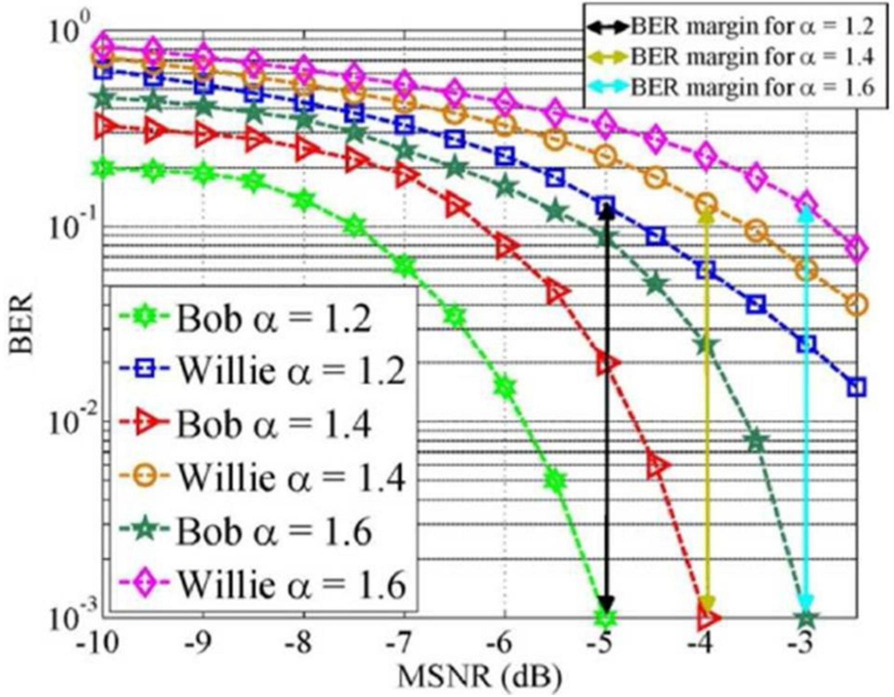
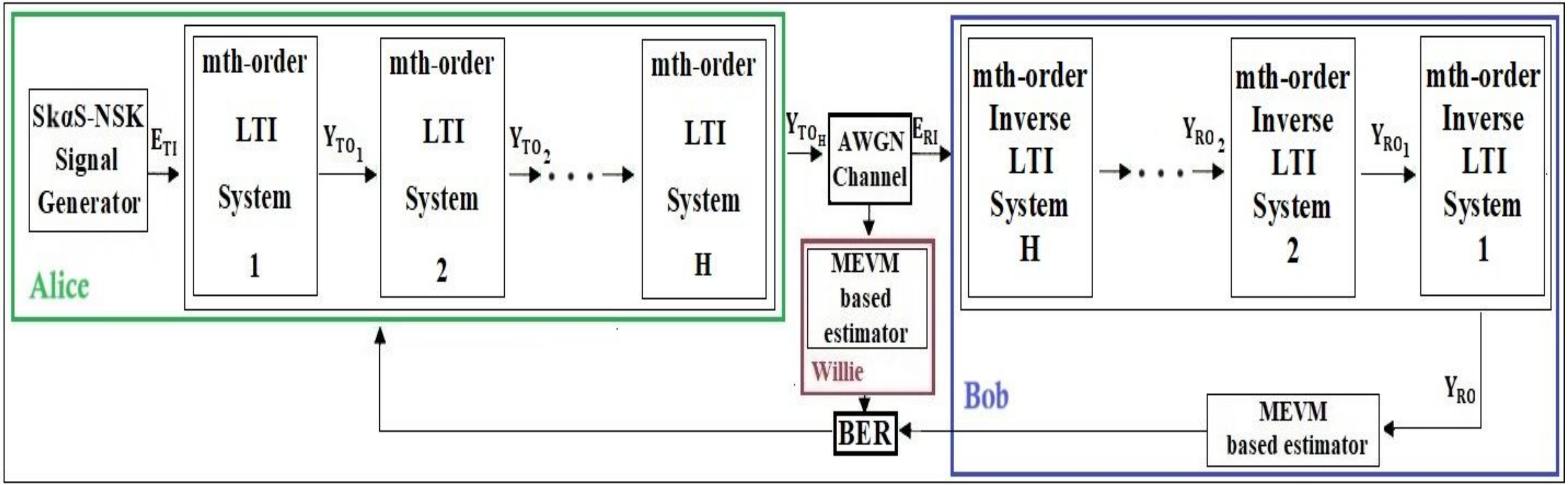
Performance Analysis



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

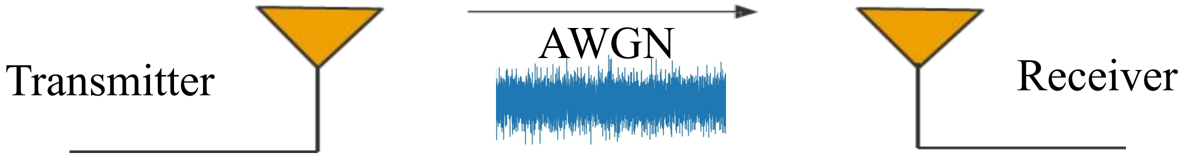
Proposed Model

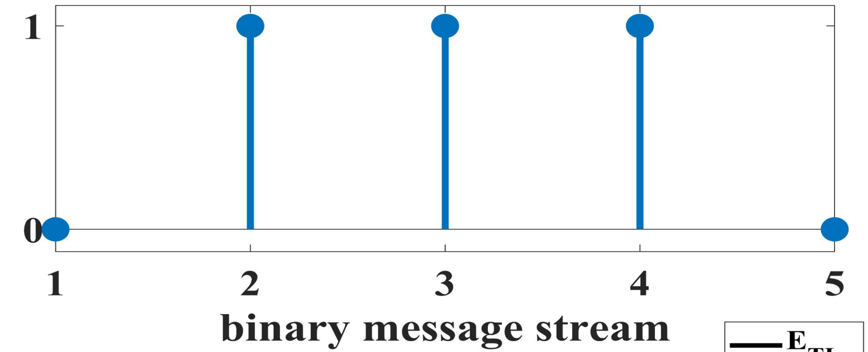


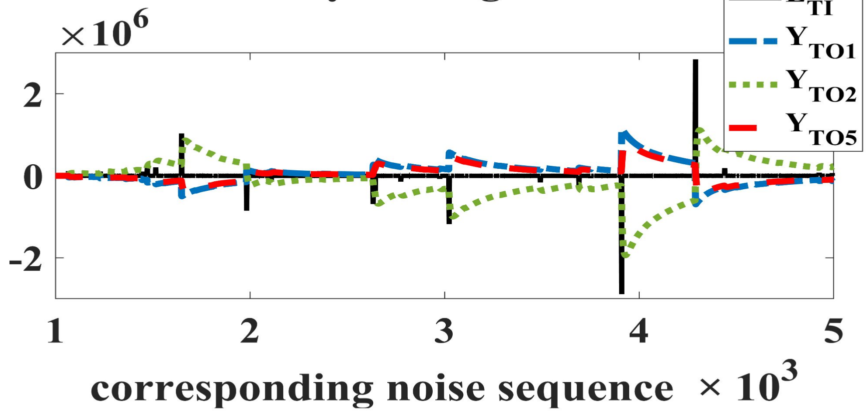
System model of the proposed ERCS based on the multiple inverse systems

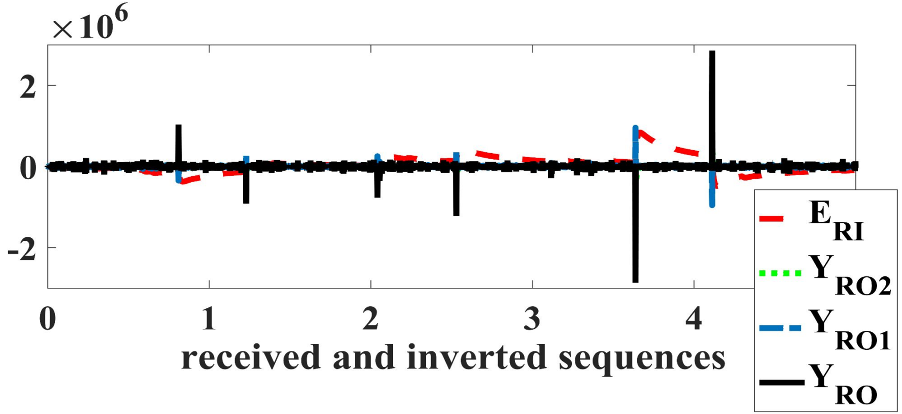
Multiple Inverse System Approach for Secure RCS in Terahertz Band

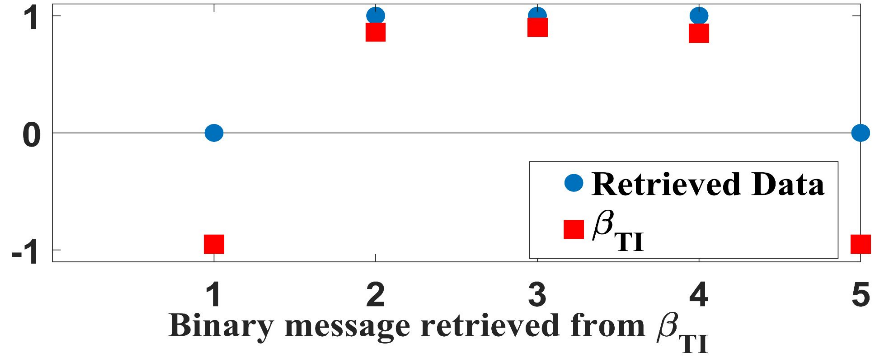
Initial Results





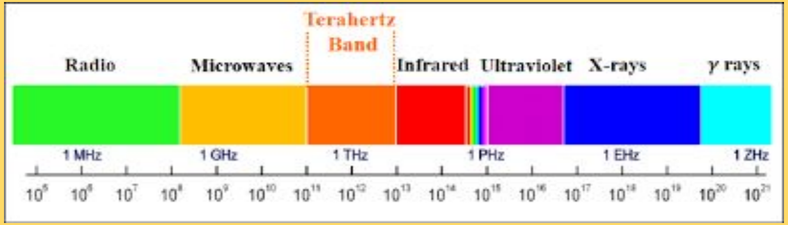






Currently in Lab

- 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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