Performance Study of Hybrid DS/FFH Spread-Spectrum Systems in the Presence of Multipath Fading and Multiple-Access Interference

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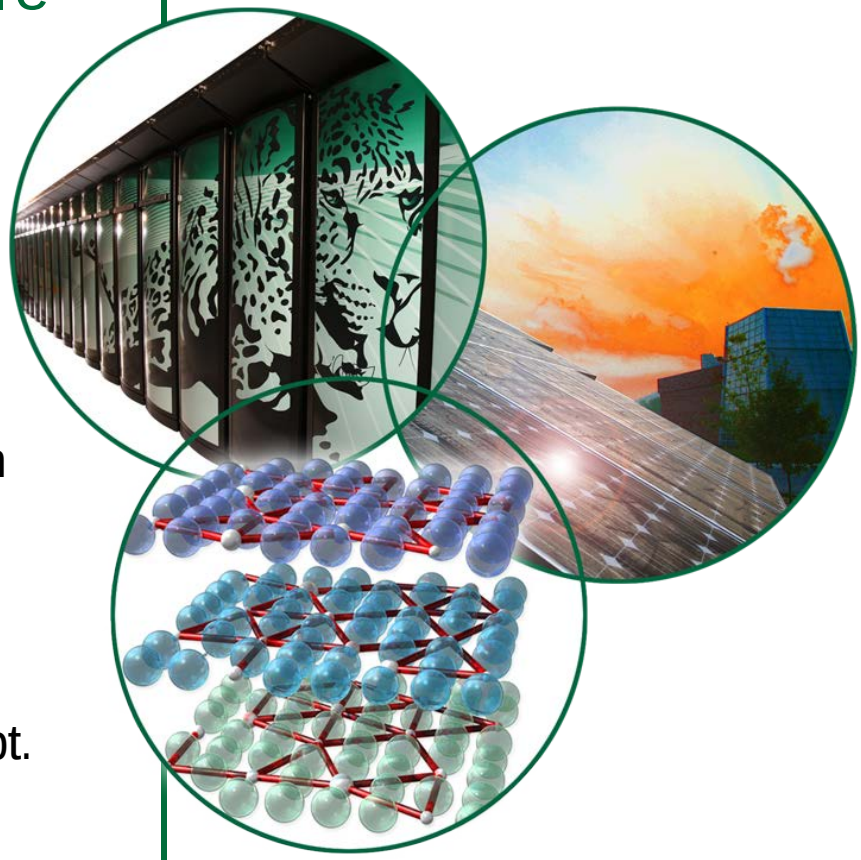

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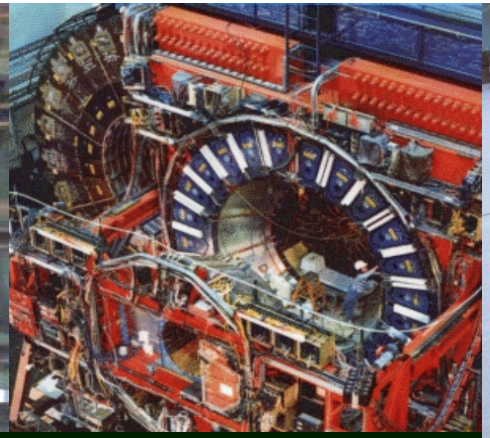
Outline

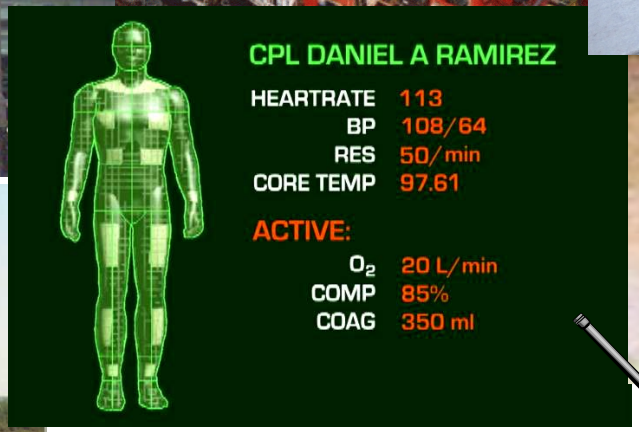
- **Introduction**
- **Types of SS Systems**
- **Multipath Fading Channel**
- **Direct Digital Synthesizers (DDS)**
- **Performance Evaluation of DS/FFH**
- **Numerical Results**
- **Conclusion**

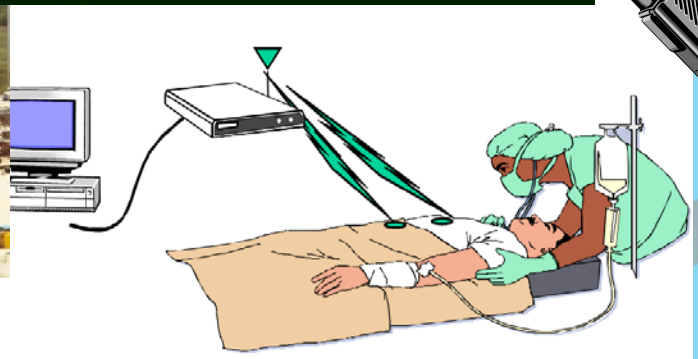
ORNL's Solution: Hybrid Spread Spectrum

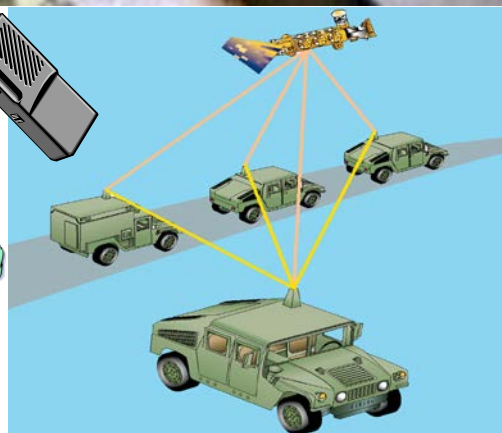
- **Novel technique (3 Patents); adaptive, programmable.**
- **HSS: a synergistic combination of DS, FH, and TH.**
- **Advantages:**
  - **Adaptive Hybrid Spread-Spectrum (HSS) modulation format *combines* DSSS and frequency/time hopping in a multi-dimensional, orthogonal signaling scheme.**
  - **Capable of excellent LPI, LPD & security properties (programmable).**
  - **Adaptive, robust protocol for high QoS applications.**
  - **Can be operated in burst mode for very low power drain.**
  - **Superior resistance to multipath and jamming (high process gain).**
  - **Easily deployed with modern chip technology.**
  - **Compliant with existing FCC/NTIA/ETSI rules for ISM bands.**
  - **Ideally implemented via modern FPGA-based electronics, ASICs, and SDR techniques.**

Typical HSS Applications

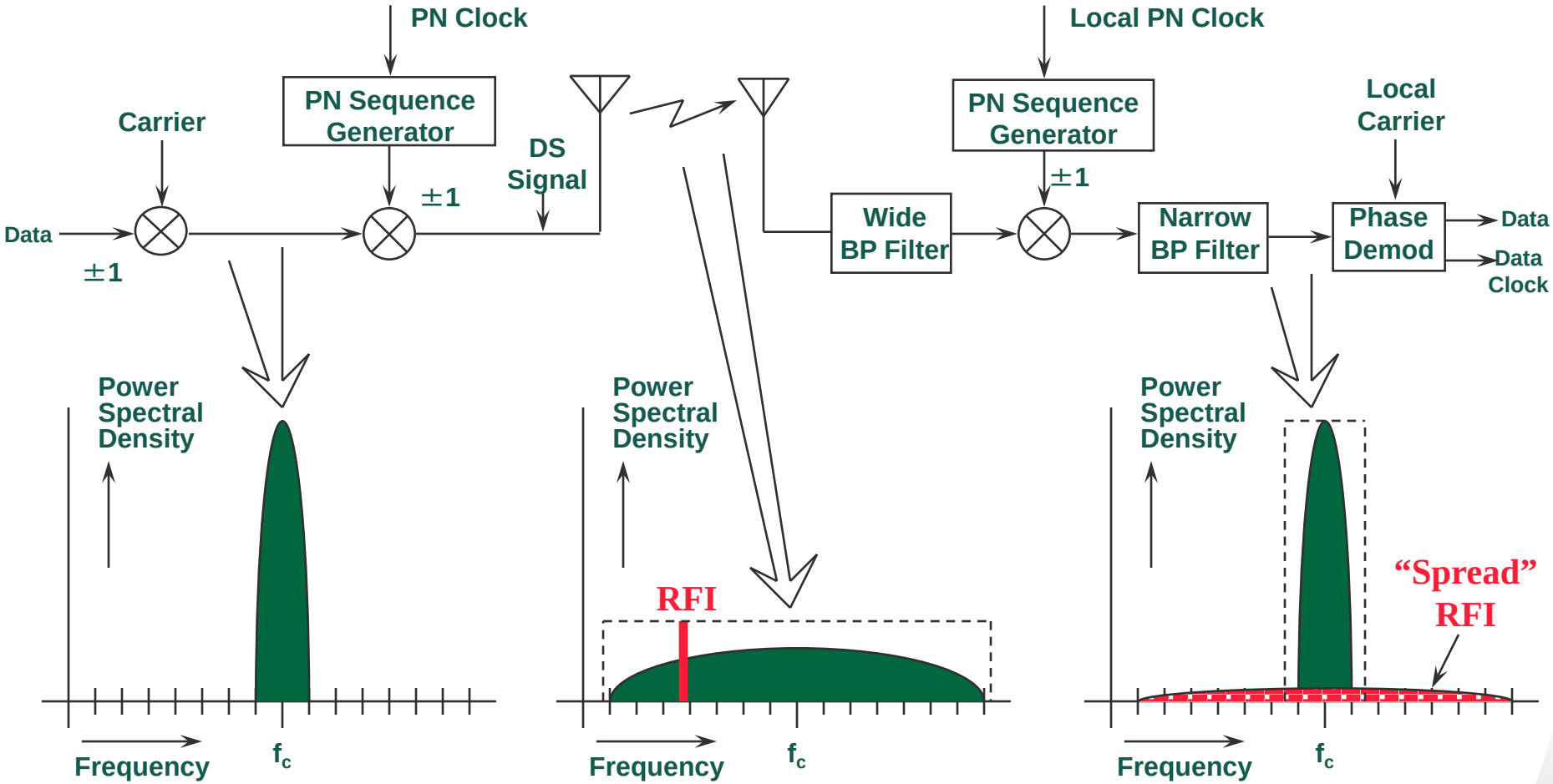








DIRECT-SEQUENCE SPREAD-SPECTRUM

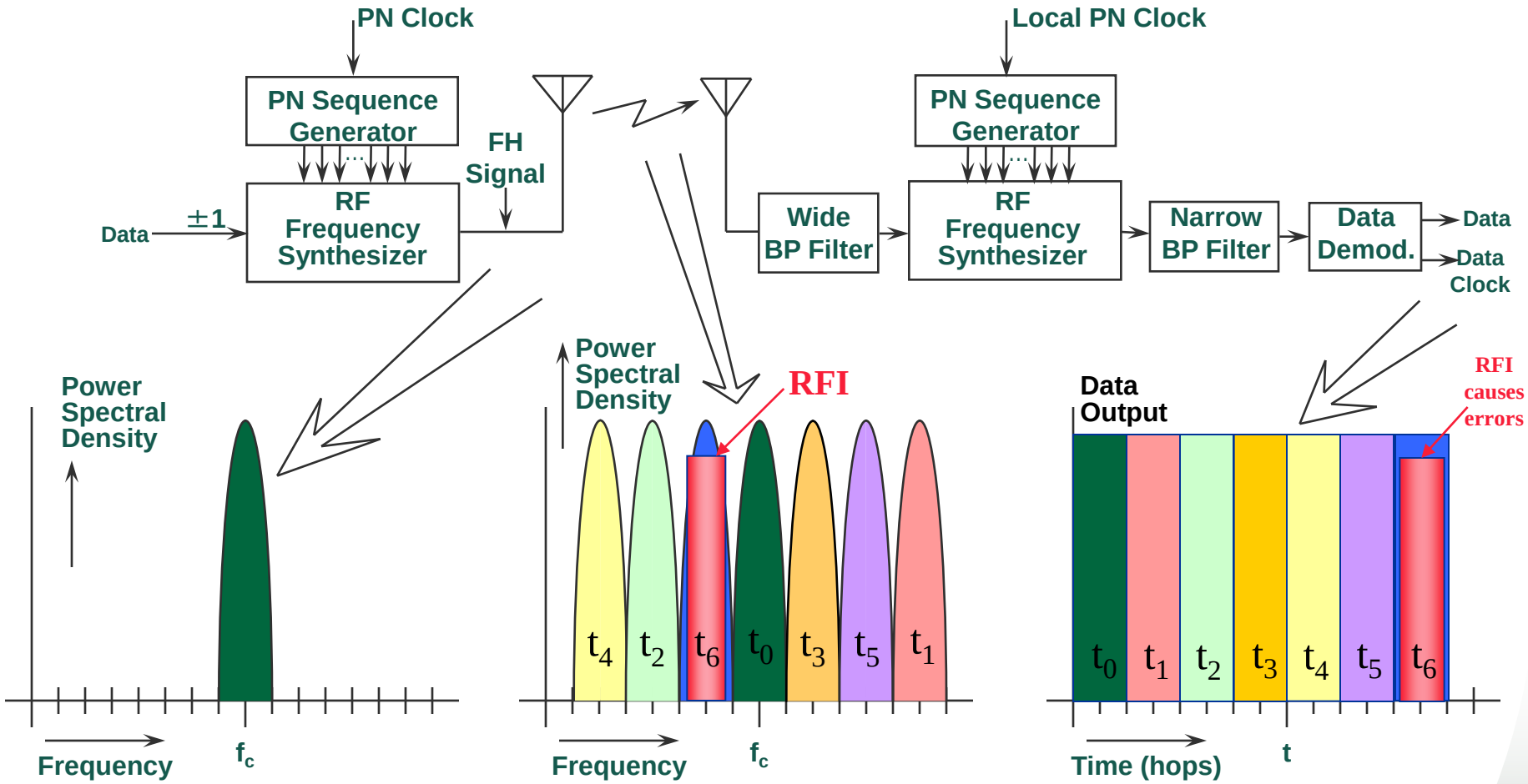


Narrow spectrum at output of modulator before spreading

Spectrum has wider bandwidth and lower power density after spreading with PN sequence (PN Rate >> Data Rate)

Original narrowband, high power density spectrum is restored if local PN sequence is same as and lined up with received PN sequence

FREQUENCY-HOPPING SPREAD-SPECTRUM

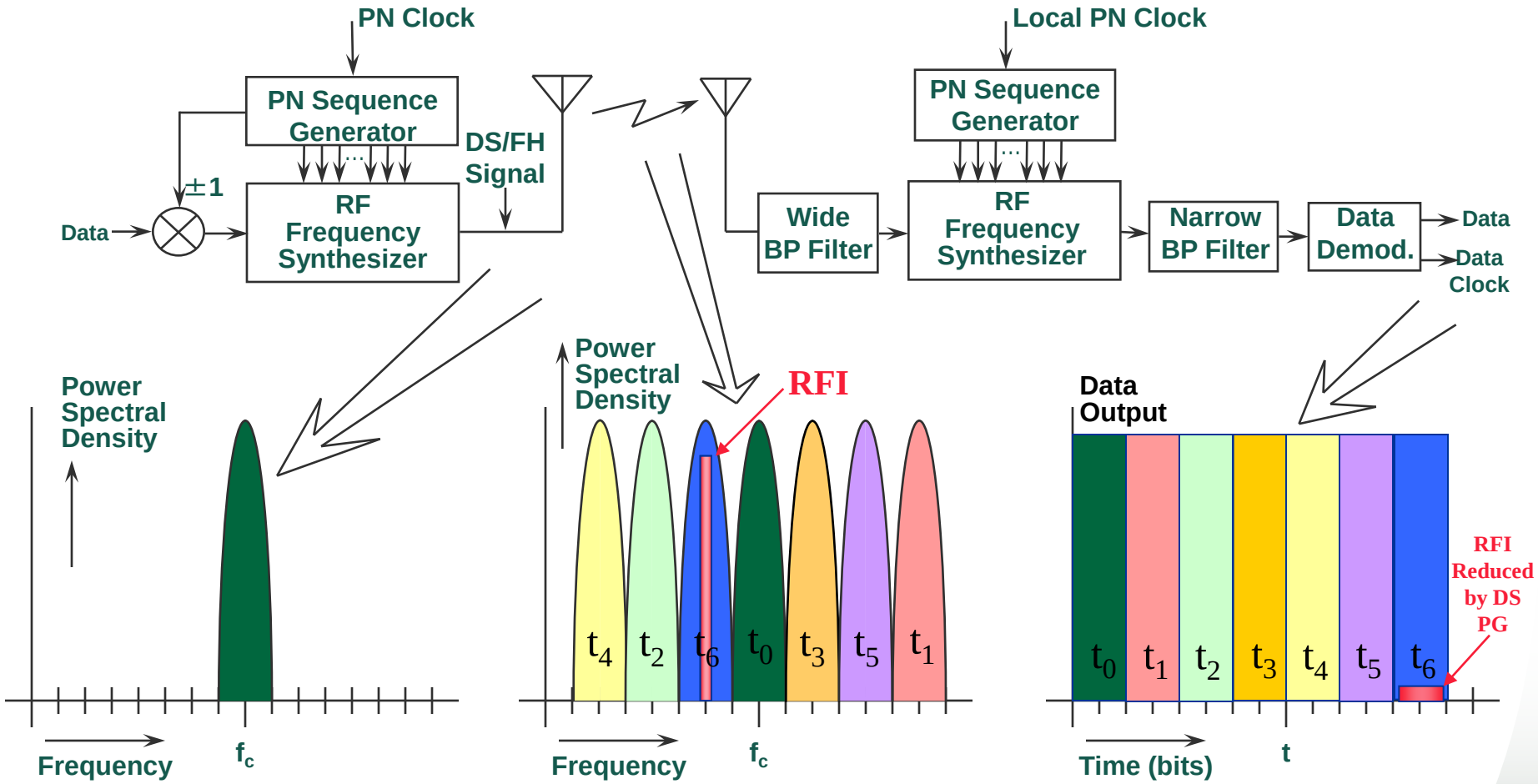


Narrow spectrum at output of modulator while hopping

Spectrum has same bandwidth and power density after hopping with PN sequence (PN Rate << Data Rate for standard FHSS)

Original narrowband, high power data stream is restored if local PN sequence is same as and lined up with received PN sequence

SLOW HYBRID SPREAD-SPECTRUM (DS/SFH)

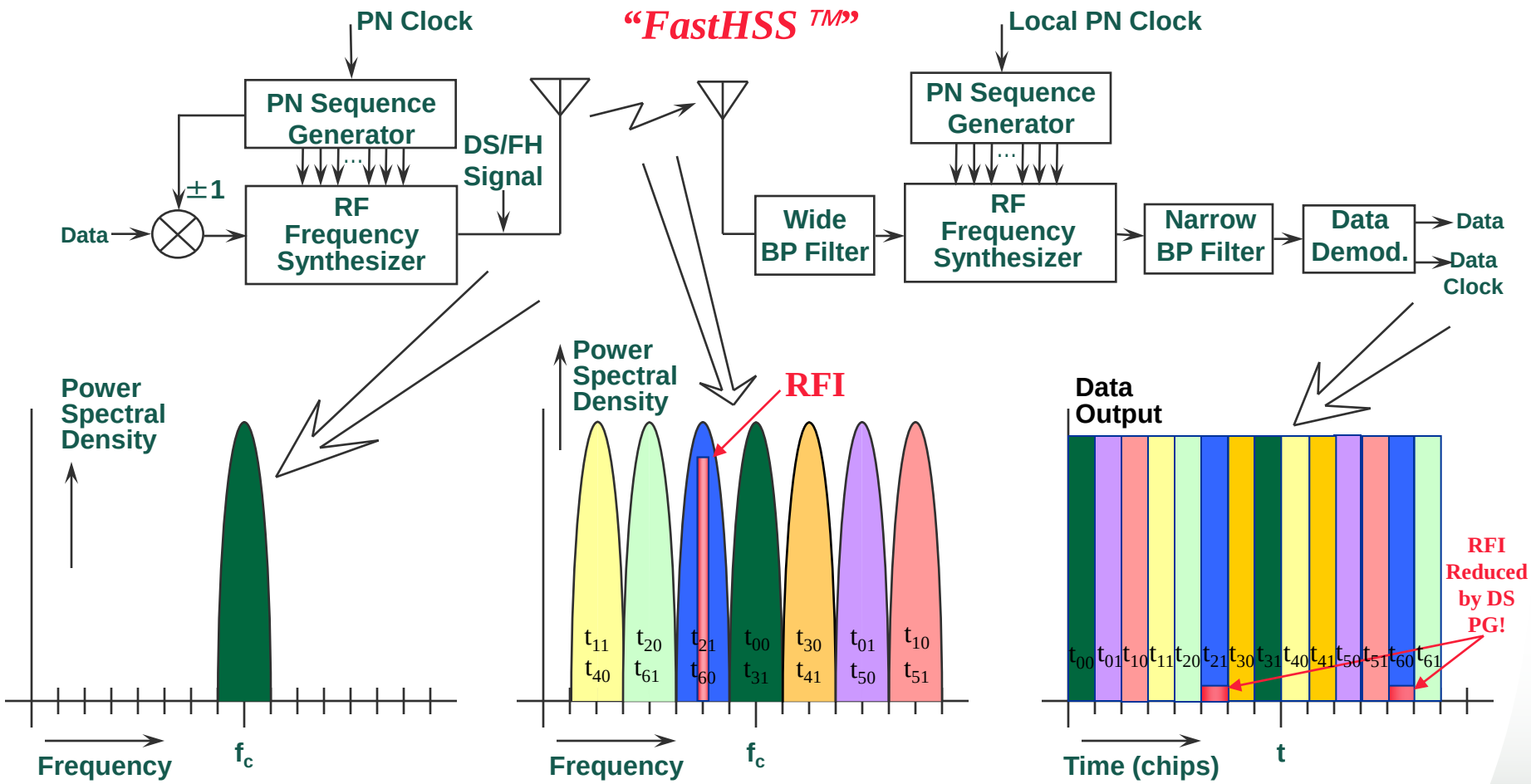


DS (wide) spectrum at output of modulator while hopping

Spectrum has same bandwidth and power density after hopping with PN sequence (PN Rate << Data Rate for standard HSS; >> for FastHSS™)

Original narrowband, high power data stream is restored if local PN sequence is same as and lined up with received PN sequence

FAST HYBRID SPREAD-SPECTRUM (DS/FFH)



DS (wide) spectrum at output of modulator while hopping

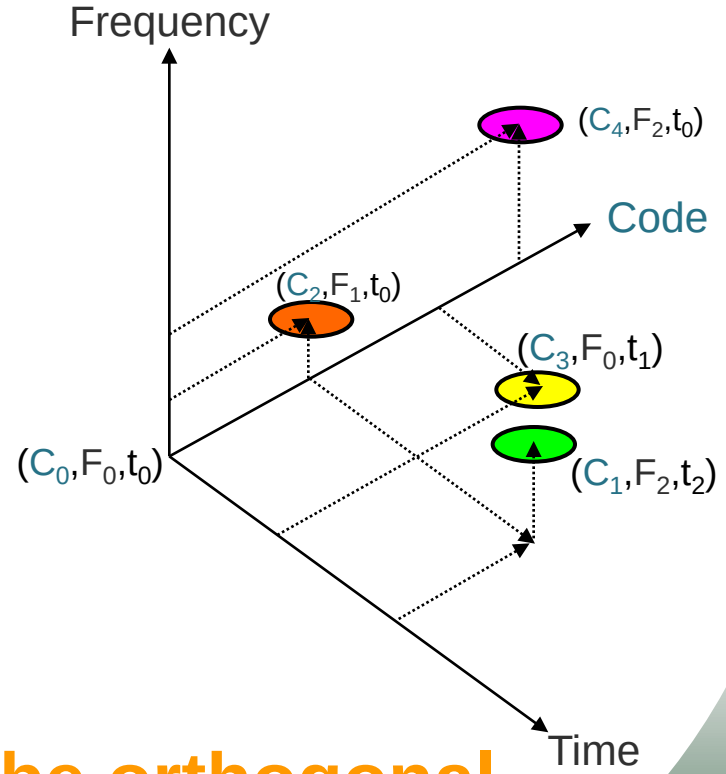
Spectrum has same bandwidth and power density after hopping with PN sequence (PN Rate >> Data Rate for FastHSS™; e.g., as above, 2 hops per bit).

Original narrowband, high power data stream is restored if local PN sequence is same as and lined up with received PN sequence

$$G_{p(FH/DS)\,dB} = G_{p(FH)\,dB} + G_{p(DS)dB} = 10 \log (\text{no. of hopping channels}) + 10 \log (BW_{DS}/R_{info})$$

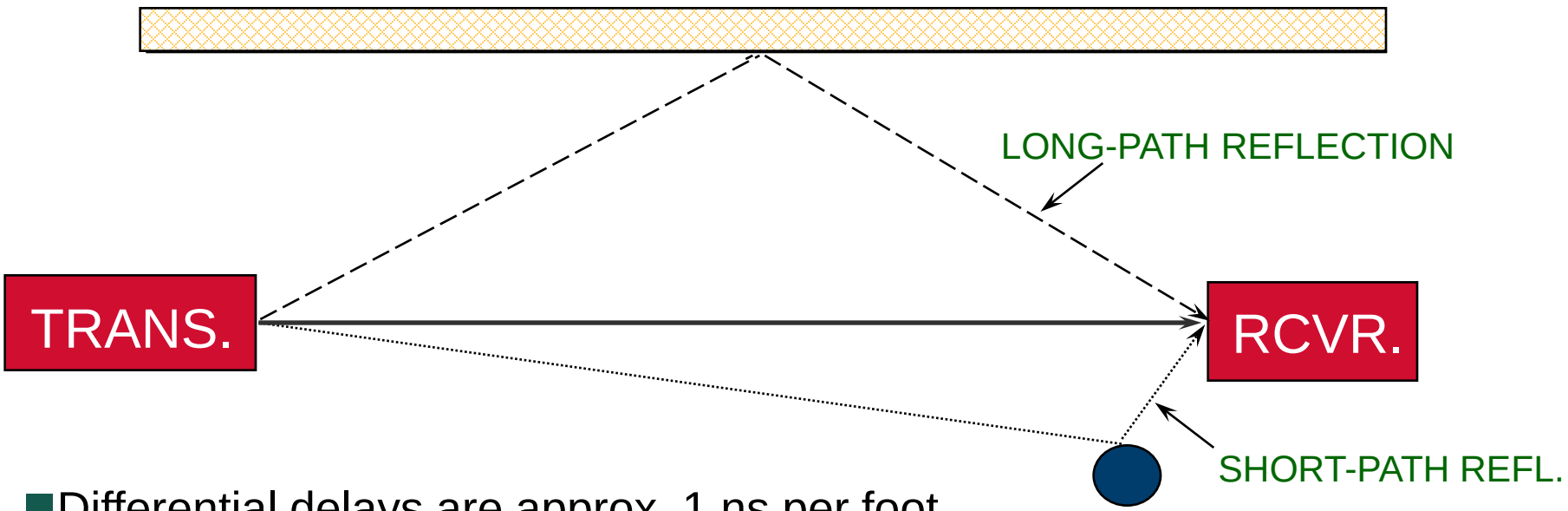
HSS is a Multidimensional Signal

- **HSS can be defined in 3 axes (code, frequency, and time).**
  - **Each dimension is orthogonal with the others.**
  - **Permissible signal spaces along an axis may also be ~ orthogonal.**
    - **Codes**
    - **Frequencies**
    - **Time slots**



- **Easily adaptable to exploit many degrees of freedom to meet system requirements.**
- **Some signal overlaps may be orthogonal.**

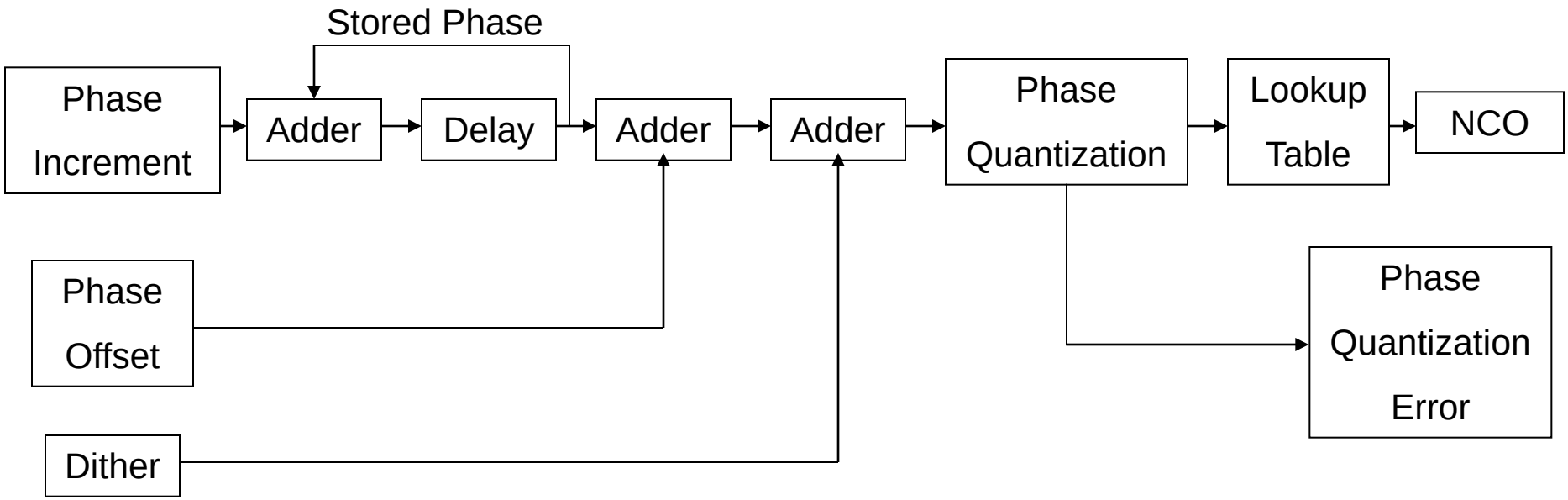
MULTIPATH PROPAGATION



- Differential delays are approx. 1 ns per foot
- Short-path delays (indoors) are typically $< 0.1\mu s$
- Spread-spectrum modulation can largely cancel long-path effects

ORNL is developing new techniques to mitigate short-path degradations!

Direct Digital Synthesizers (DDS)



- **The implementation of a DDS has two distinct parts:**
  - **A phase accumulator accumulates the phase increment and adds in the phase offset.**
  - **The DDS output is then calculated by quantizing the results of the phase accumulator section and using them to select values from a lookup table.**

RF Coexistence – Multi-User, Jamming, and Multipath Fading Performance

The error probability of one hop is:

K Number of users

M Number of FH channels

L Number of hops per bit

$T = \frac{T_b}{L}$ Duration of each hop

$T_c = \frac{T_b}{NL}$ Chip duration for PN sequence

N Period of the PN sequence

W_{DS} Bandwidth of DS waveform

W_J Bandwidth of the wideband jamming

W Number of hopping channels corrupted by jamming

W_J^p Part of the bandwidth of the channel partially corrupted by jamming

$$
\begin{aligned}
P_h &= \sum_{j=0}^{K-1} P_\varepsilon^k(j\ users) \\
&= \sum_{j=0}^{K-1} \{P_\varepsilon^k(j\ users,\ no\ jam) + P_\varepsilon^k(j\ users,\ ful\ jam) + P_\varepsilon^k(j\ users,\ partial\ jam)\} \\
&= \sum_{j=0}^{K-1} \{P(j\ users,\ no\ jam)P^k(\varepsilon \mid j\ users,\ no\ jam) \\
&\quad + P(j\ users,\ ful\ jam)P^k(\varepsilon \mid j\ users,\ ful\ jam) \\
&\quad + P(j\ users,\ partial\ jam)P^k(\varepsilon \mid j\ users,\ partial\ jam)\}
\end{aligned}
$$

The error probability of one bit is:

$$
P_b = \sum_{d=\frac{L+1}{2}}^{L} \binom{L}{d} (P_h)^d (1-P_h)^{L-d}
$$

RF Coexistence – Multi-User, Jamming, and Multipath Fading Performance

P Transmitted signal power

M Number of FH channels

L Number of hops per bit

$T = \frac{T_b}{L}$ Duration of each hop

$T_c = \frac{T_b}{NL}$ Chip duration for PN sequence

N Period of the PN sequence

W_{DS} Bandwidth of DS waveform

W_J Bandwidth of the wideband jamming

W Number of hopping channels corrupted by jamming

W_J^p Part of the bandwidth of the channel partially corrupted by jamming

$NSR = N_0 / 2PT$ Noise-to-signal ratio

$JSR = N_J / 2PT$ Jamming-to-signal ratio

I_j^k Interference to signal ratio introduced by the other users hopping in user *k*'s channel

$q = W_J^p / W_{DS}$ Fraction of the channel jammed

From the problem formulation, we have

$$P(j\ users,\ no\ jam) = \binom{K-1}{j}\left(\frac{1}{M}\right)^j\left(1-\frac{1}{M}\right)^{K-1-j}\left(\frac{M-W-1}{M}\right)$$

$$P(j\ users,\ full\ jam) = \binom{K-1}{j}\left(\frac{1}{M}\right)^j\left(1-\frac{1}{M}\right)^{K-1-j}\left(\frac{W}{M}\right)$$

$$P(j\ users,\ partial\ jam) = \binom{K-1}{j}\left(\frac{1}{M}\right)^j\left(1-\frac{1}{M}\right)^{K-1-j}\left(\frac{1}{M}\right)$$

No Jamming

$$P^k(\varepsilon \mid j\ users,\ no\ jam) = Q\left(\frac{1}{\sqrt{NSR/2 + I_j^k}}\right)$$

Full Jamming

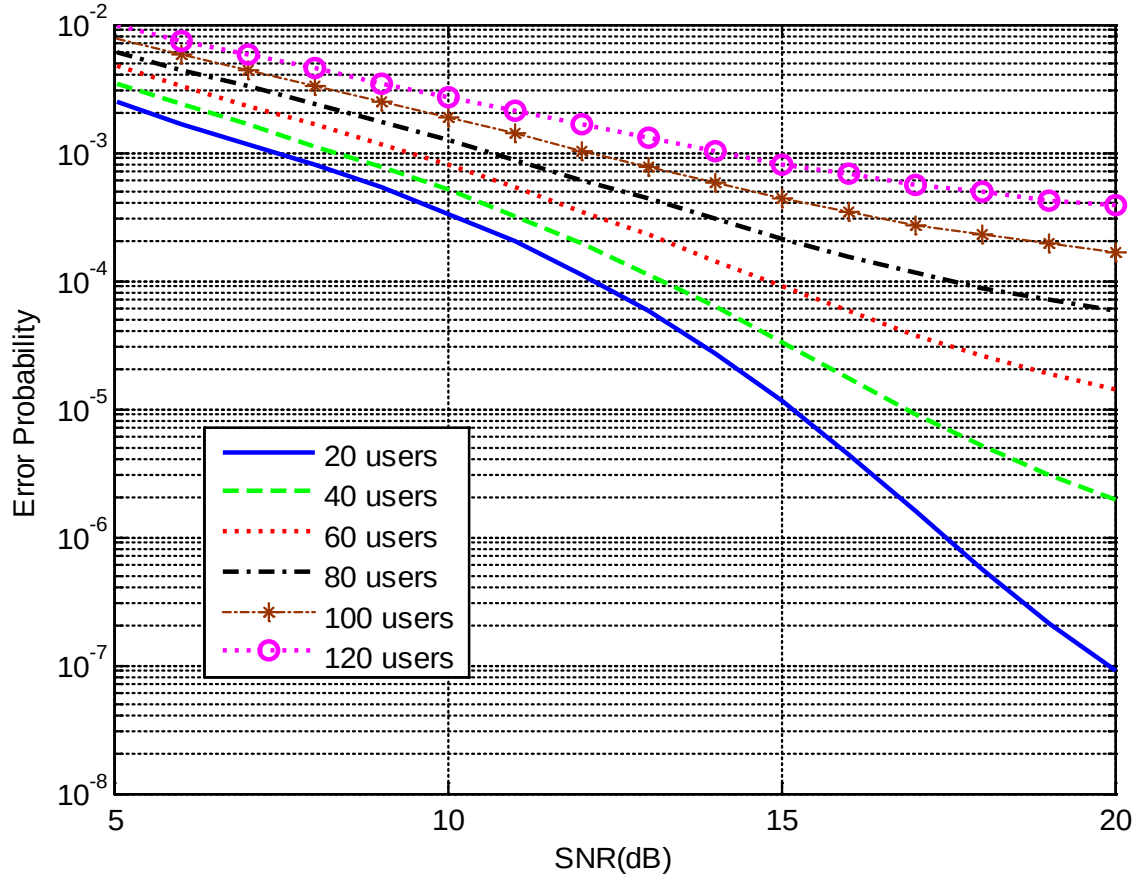
$$P^k(\varepsilon \mid j\ users,\ full\ jam) = Q\left(\frac{1}{\sqrt{NSR/2 + JSR/2 + I_j^k}}\right)$$

Partial Jamming

$$P^k(\varepsilon \mid j\ users,\ partial\ jam) = q\,P^k(\varepsilon \mid j\ users,\ partial\ jam,\ corrupted\ portion) + (1-q)P^k(\varepsilon \mid j\ users,\ partial\ jam,\ uncorrupted\ portion)$$

Hybrid DS/FFH Multi-user Simulation

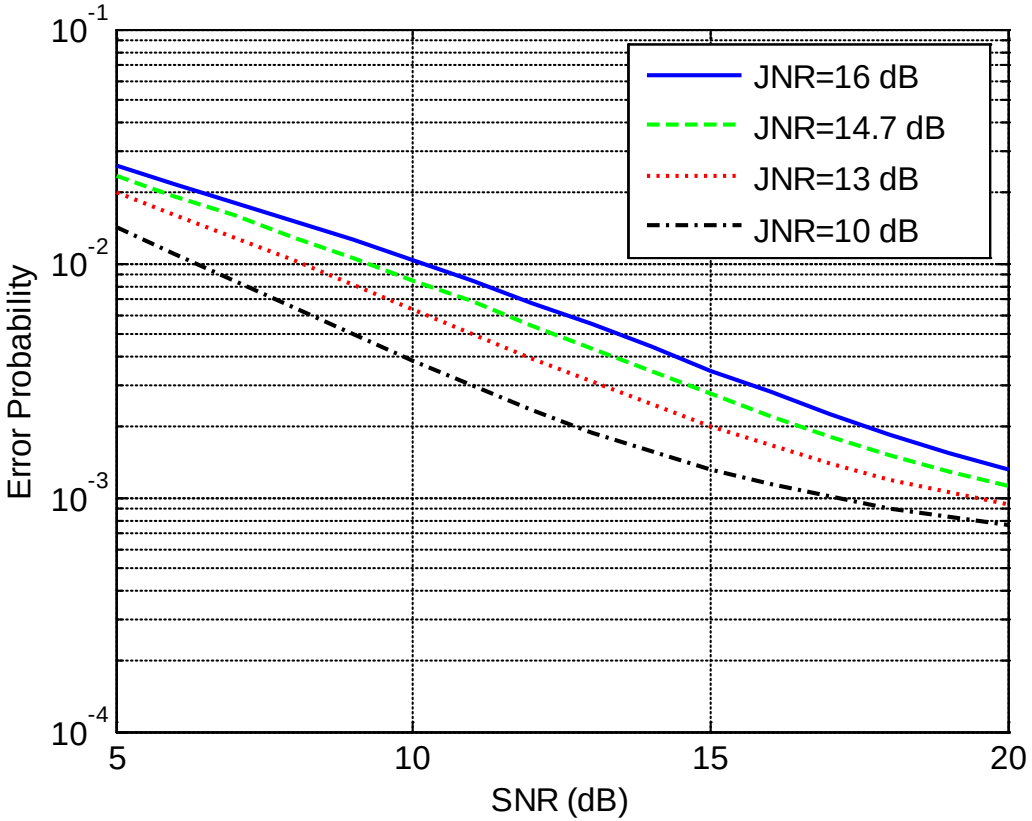
- **Severe (~worst-case) channel conditions:**
  - **K = 20-120 users, 100% duty cycle**
  - **L = 5 hops/bit**
  - **M = 20 channels**
  - **N = 127 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 13 dB**
  - **Rician coeff. γ = 0.1**
  - **Chan. covariance λ = 1**
  - **Jammed chan. = 5**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain.**



Performance of a hybrid DS/FFH system: Effect of different number of users (multi-user interference).

Hybrid DS/FFH Multi-user Simulation

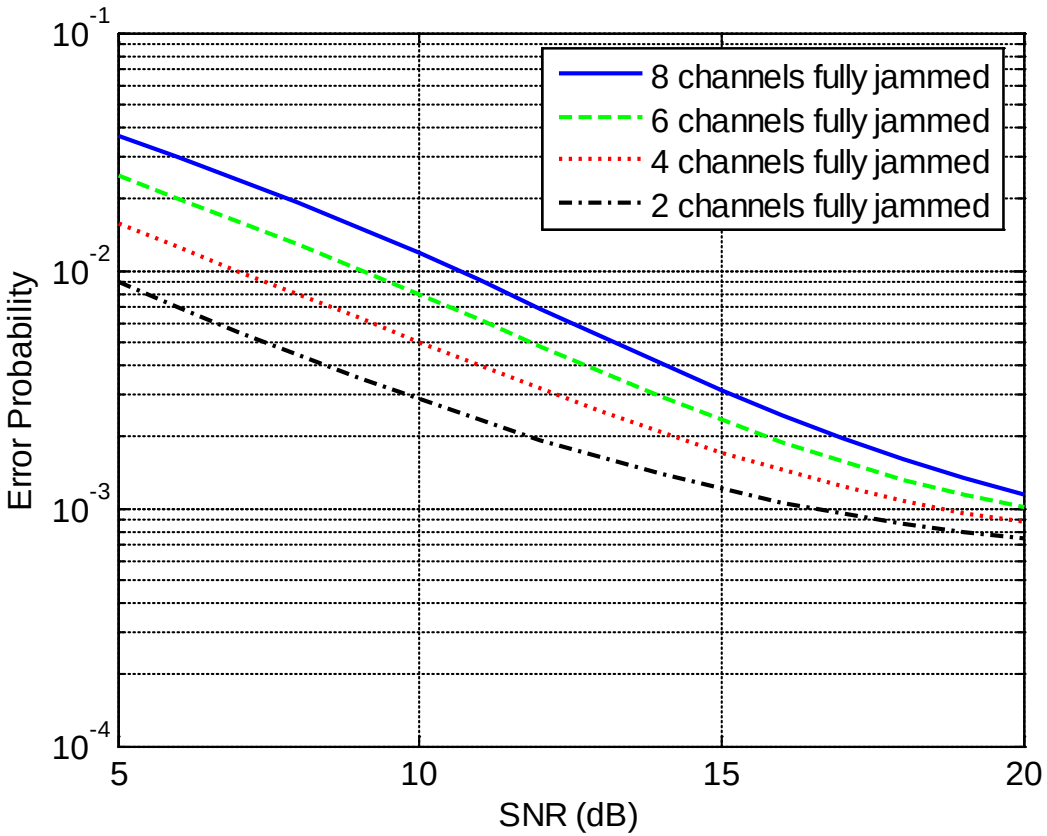
- **Severe (~worst-case) channel conditions:**
  - **K = 100 users, 100% duty cycle**
  - **L = 5 hops/bit**
  - **M = 20 channels**
  - **N = 127 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 10-16 dB**
  - **Rician coeff. γ = 0.1**
  - **Chan. covariance λ = 10**
  - **Jammed chan. = 5**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain.**



Performance of a hybrid DS/FFH system: Effect of different jamming-to-noise ratios (JNRs).

Hybrid DS/FFH Multi-user Simulation

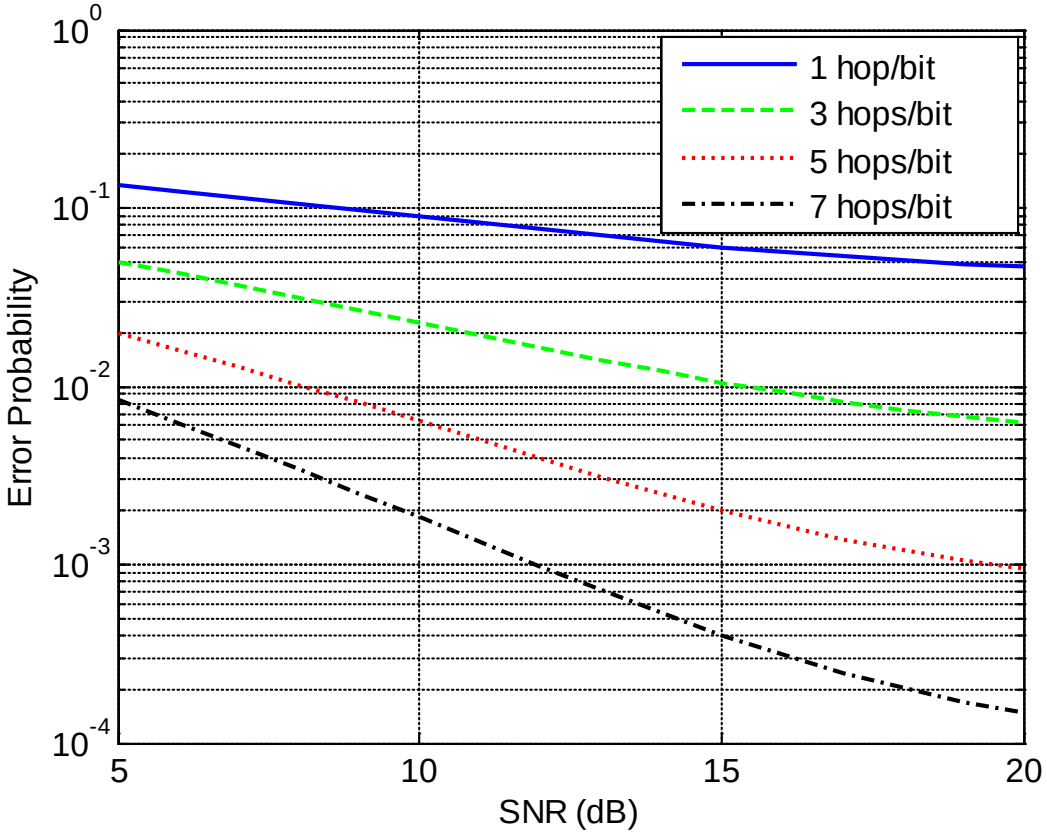
- **Severe (~worst-case) channel conditions:**
  - **K = 100 users, 100% duty cycle**
  - **L = 5 hops/bit**
  - **M = 20 channels**
  - **N = 127 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 13 dB**
  - **Rician coeff. γ = 0.1**
  - **Chan. covariance λ = 1**
  - **Jammed chan. = 2-8**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain.**



Performance of a hybrid DS/FFH system: Effect of different number of fully-jammed channels.

Hybrid DS/FFH Multi-user Simulation

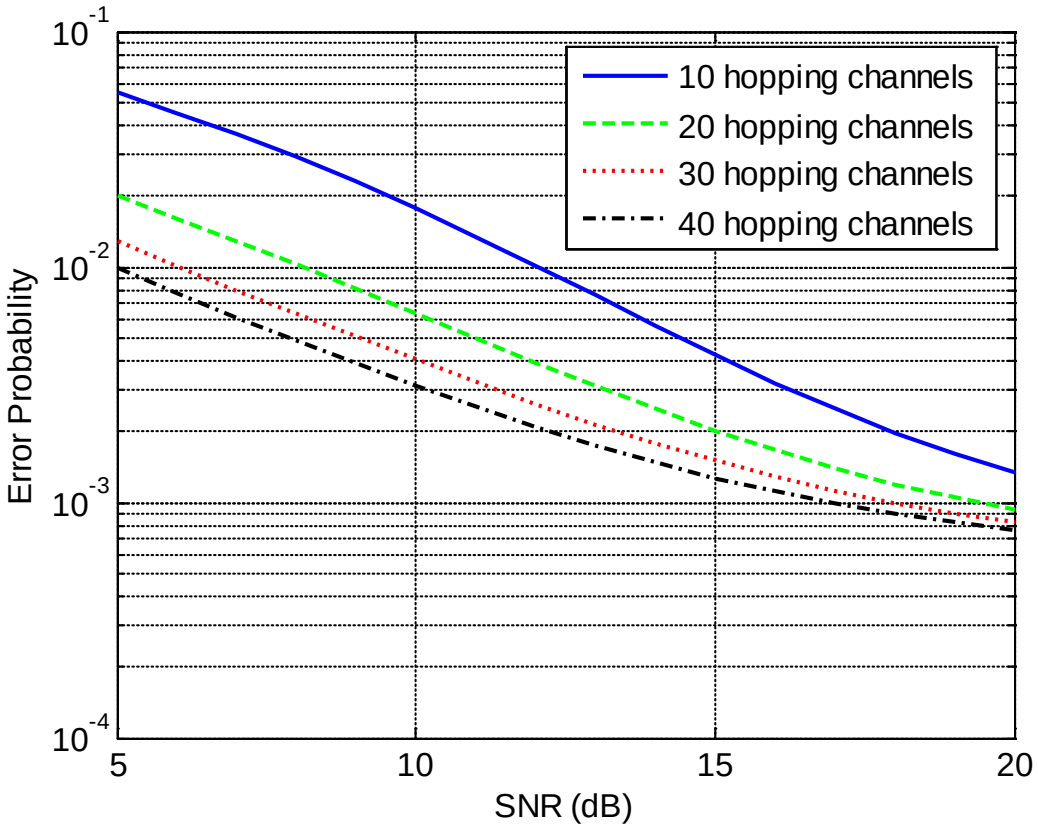
- **Severe (~worst-case) channel conditions:**
  - **K = 100 users, 100% duty cycle**
  - **L = 1-7 hops/bit**
  - **M = 20 channels**
  - **N = 127 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 13 dB**
  - **Rician coeff. γ = 0.1**
  - **Chan. covariance λ = 1**
  - **Jammed chan. = 5**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain.**



Performance of a hybrid DS/FFH system: Effect of different numbers of frequency hops per bit.

Hybrid DS/FFH Multi-user Simulation

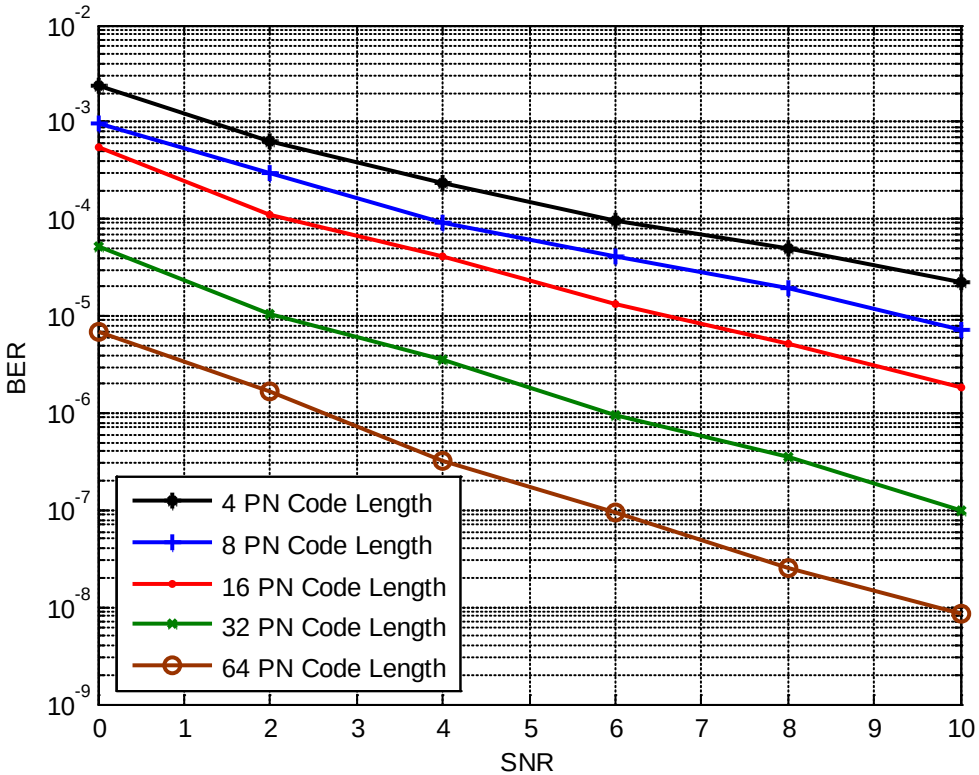
- **Severe (~worst-case) channel conditions:**
  - **K = 100 users, 100% duty cycle**
  - **L = 5 hops/bit**
  - **M = 10-40 channels**
  - **N = 127 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 13 dB**
  - **Rician coeff. γ = 0.1**
  - **Chan. covariance λ = 1(**
  - **Jammed chan. = 5**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain.**



Performance of a hybrid DS/FFH system: Effect of different numbers of available hopping channels.

Hybrid DS/FFH Multi-user Simulation

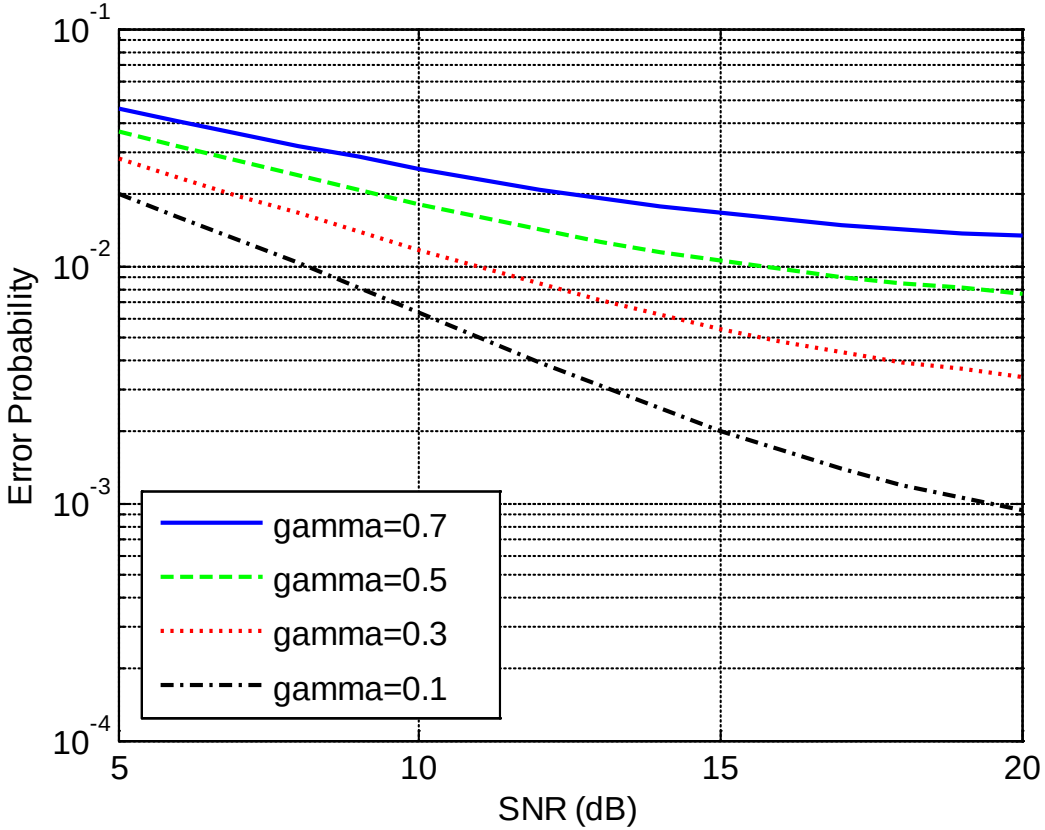
- **Severe (~worst-case) channel conditions:**
  - **K = 100 users, 100% duty cycle**
  - **L = 5 hops/bit**
  - **M = 20 channels**
  - **N = 4-64 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 13 dB**
  - **Rician coeff. γ = 0.1**
  - **Chan. covariance λ = 10**
  - **Jammed chan. = 5**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain.**



Performance of a hybrid DS/FFH system: Effect of different DS PN code lengths.

Hybrid DS/FFH Multi-user Simulation

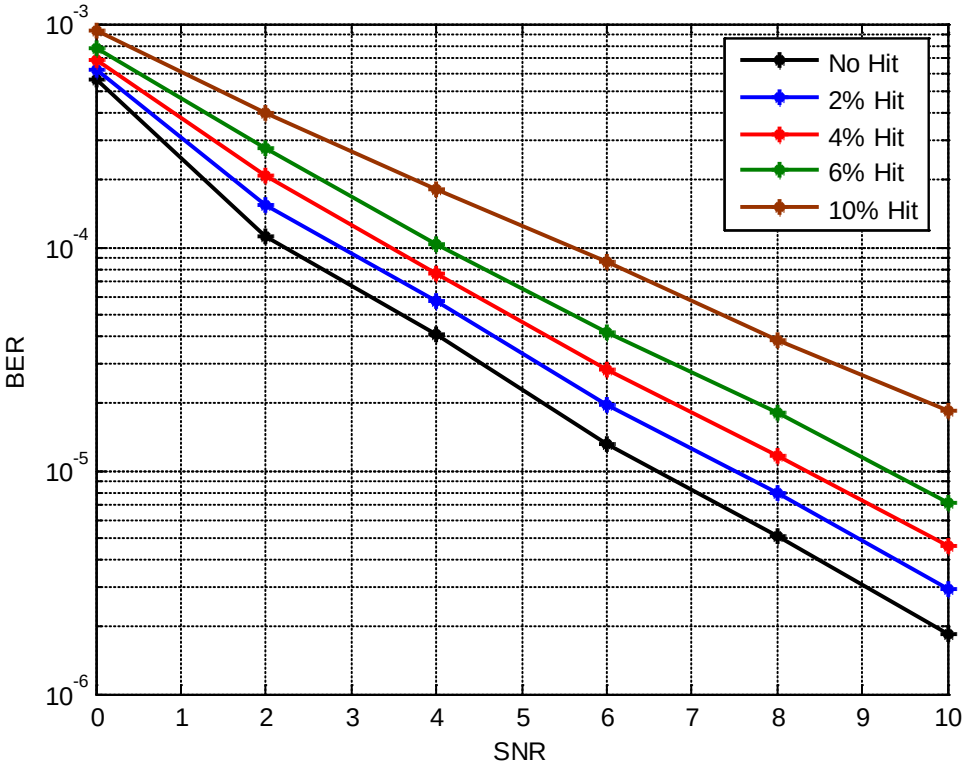
- **Severe (~worst-case) channel conditions:**
  - **K = 100 users, 100% duty cycle**
  - **L = 5 hops/bit**
  - **M = 20 channels**
  - **N = 127 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 13 dB**
  - **Rician coeff. γ = 0.1-0.7**
  - **Chan. covariance λ = 1**
  - **Jammed chan. = 5**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain**



Performance of a hybrid DS/FFH system: Effect of different Rician fading channel parameters.

Hybrid DS/FFH Multi-user Simulation

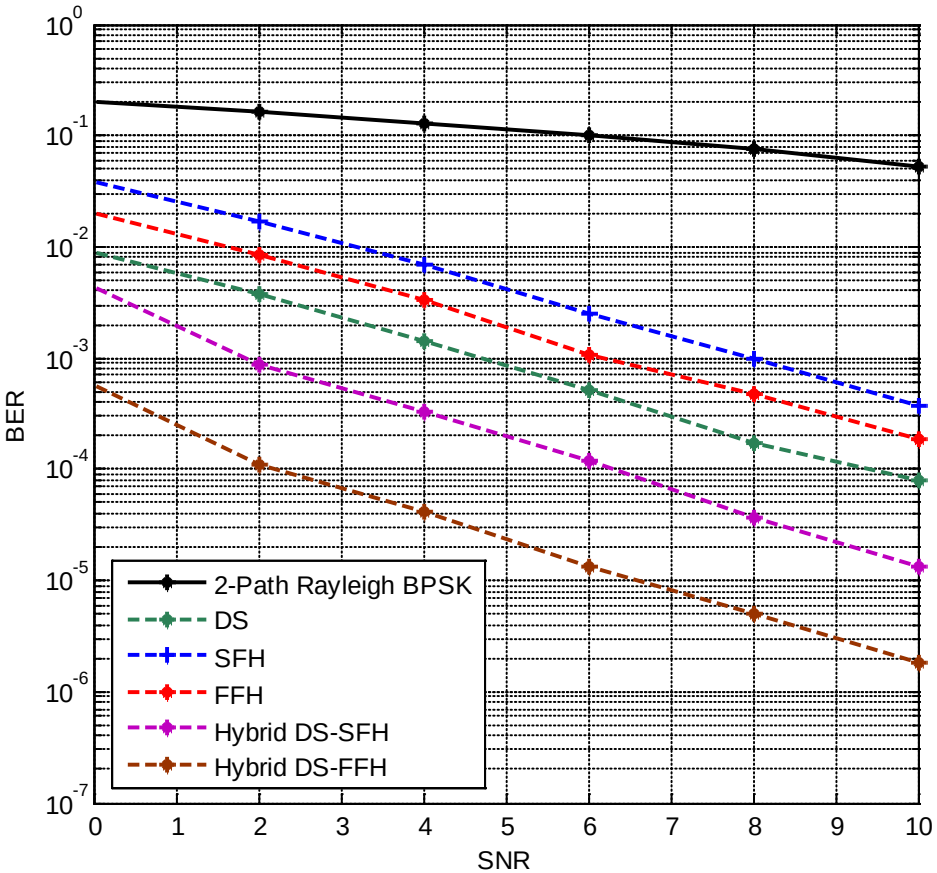
- **Severe (~worst-case) channel conditions:**
  - **K = 100 users, 100% duty cycle**
  - **L = 5 hops/bit**
  - **M = 20 channels**
  - **N = 127 PN code length**
  - **DS PG = 21 dB**
  - **JNR = 13 dB**
  - **Rician coeff. γ = 0.1**
  - **Chan. covariance λ = 10**
  - **Jammed chan. = 5**
  - **Channel portion partially corrupted = 0.4**
- **Represents user flooding in rough terrain.**



Performance of a hybrid DS/FFH system: Effect of different hitting rates.

Hybrid DS/FFH Comparative Simulation

- **Severe (~worst-case) channel conditions:**
  - **Two-path Rayleigh chan.**
  - **P1: Δ = 0, gain = 0.7**
  - **P2: Δ = 0.3 μs, gain = 0.4**
  - **Equal-bandwidth cases**
  - **DS SF = 16**
  - **FH: 16 ch., 4 b/hop**
  - **DS/FH: SF = 16, 4 hopping freqs.**
- **Represents the fixed-bandwidth advantage of DS/FFH format over other modulations.**



Comparative performance of a hybrid DS/FFH versus other forms in Rayleigh fading.

Conclusions

- **The performance of a hybrid DS/FFH system was analytically evaluated in a worst-case use scenario.**
- **We derived the average BER for a hybrid DS/FFH system that includes the effects from wide-band and partial-band jamming, multi-user interference and/or varying degrees of Rician/Rayleigh fading.**
- **Numerical results exploring the parameter space of the HSS system have been presented to demonstrate its effectiveness under different conditions and scenarios.**
- **The detailed performance and security aspects of HSS signals will be further analyzed in a future paper.**

Questions?