ELECTRICAL & COMPUTER ENGINEERING W

EESM-log-AR:

An Efficient Error Model for OFDM MIMO Systems over Time-Varying Channels

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University of Washington

Fundamentals of Networking Lab

2021 Workshop on ns-3

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Outline

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1. **Motivation**: Fast ns-3 error models for increasingly complex Wi-Fi physical layer scenarios
2. **Approach**: Take link-to-system mapping approach a step further
    - **EESM-log-AR** based error model for ns-3
3. **Results**: A link-to-system mapping with **constant run-time** and **modest storage requirement**

What Is an Error Model?

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- An error model represents packet error rate (PER) as a function of

Channel type   MCS   Bandwidth   MIMO dimension   RX SNR

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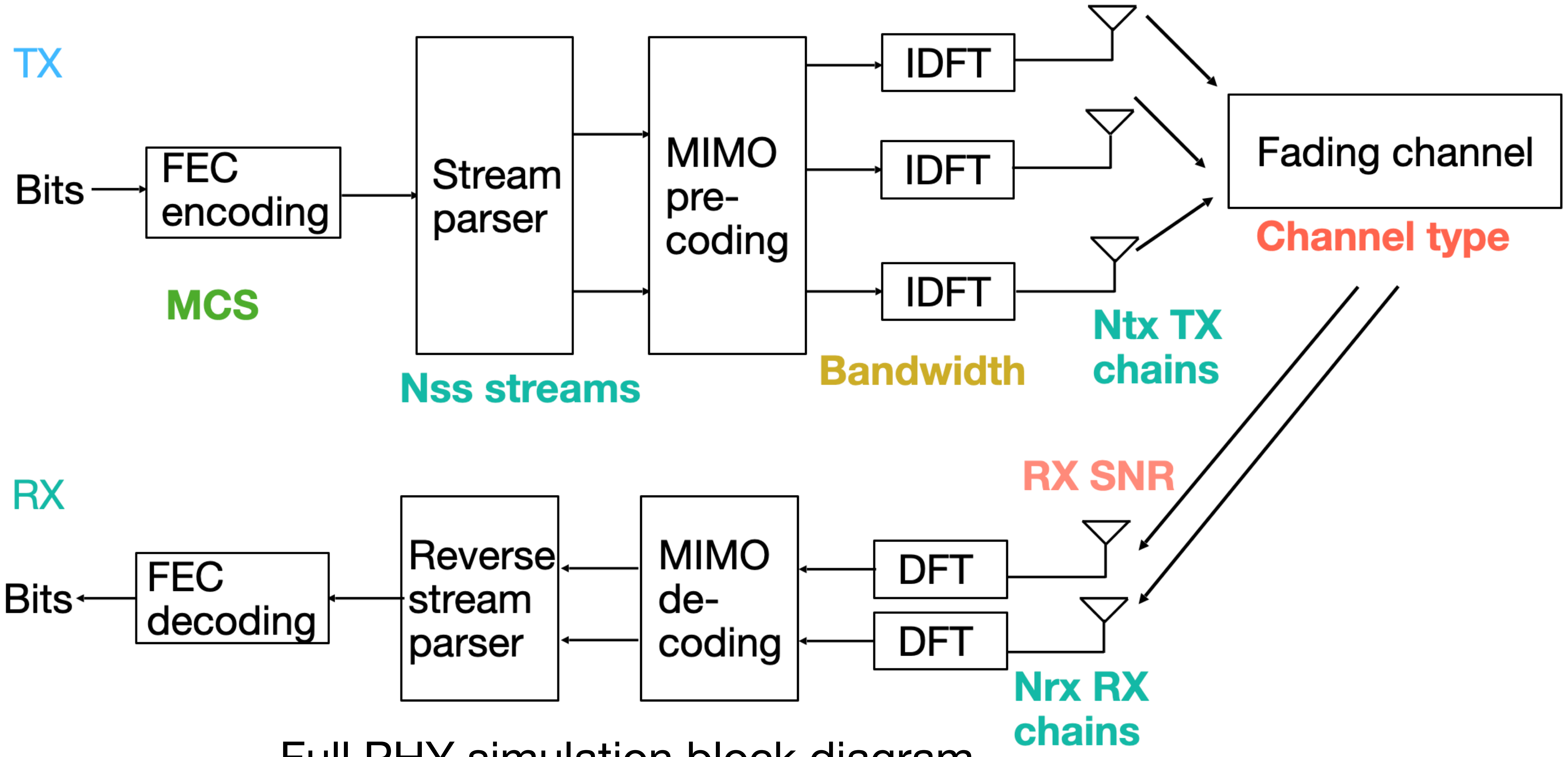

Full PHY simulation block diagram

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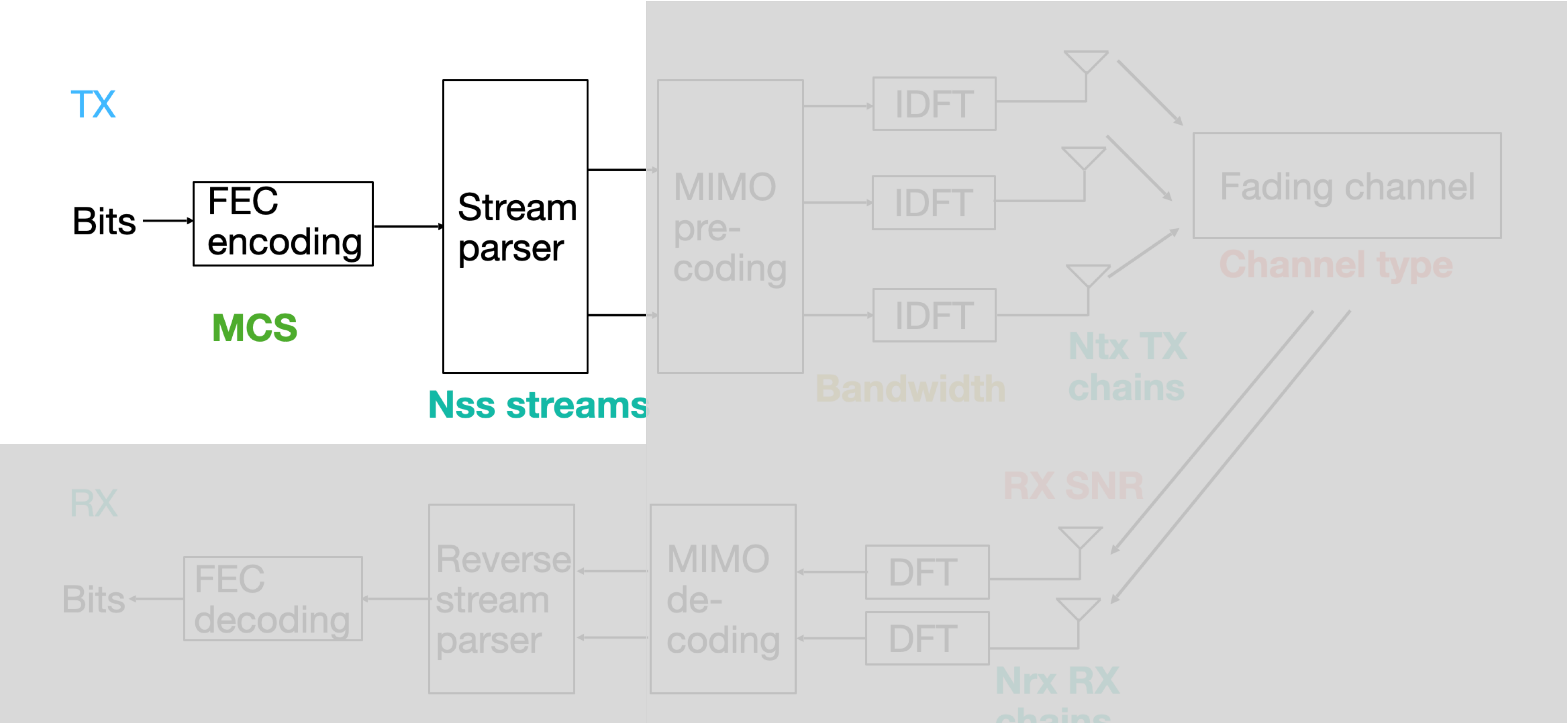

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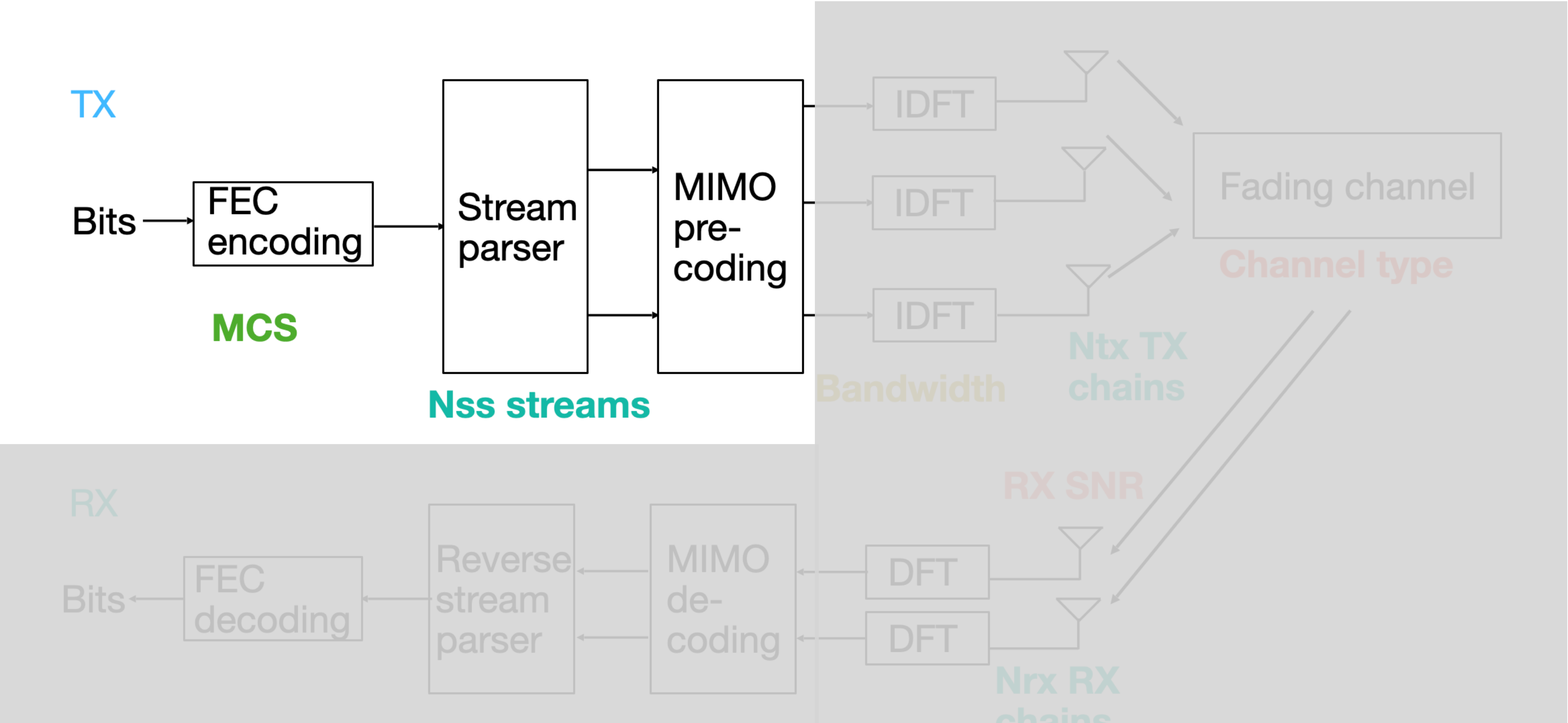

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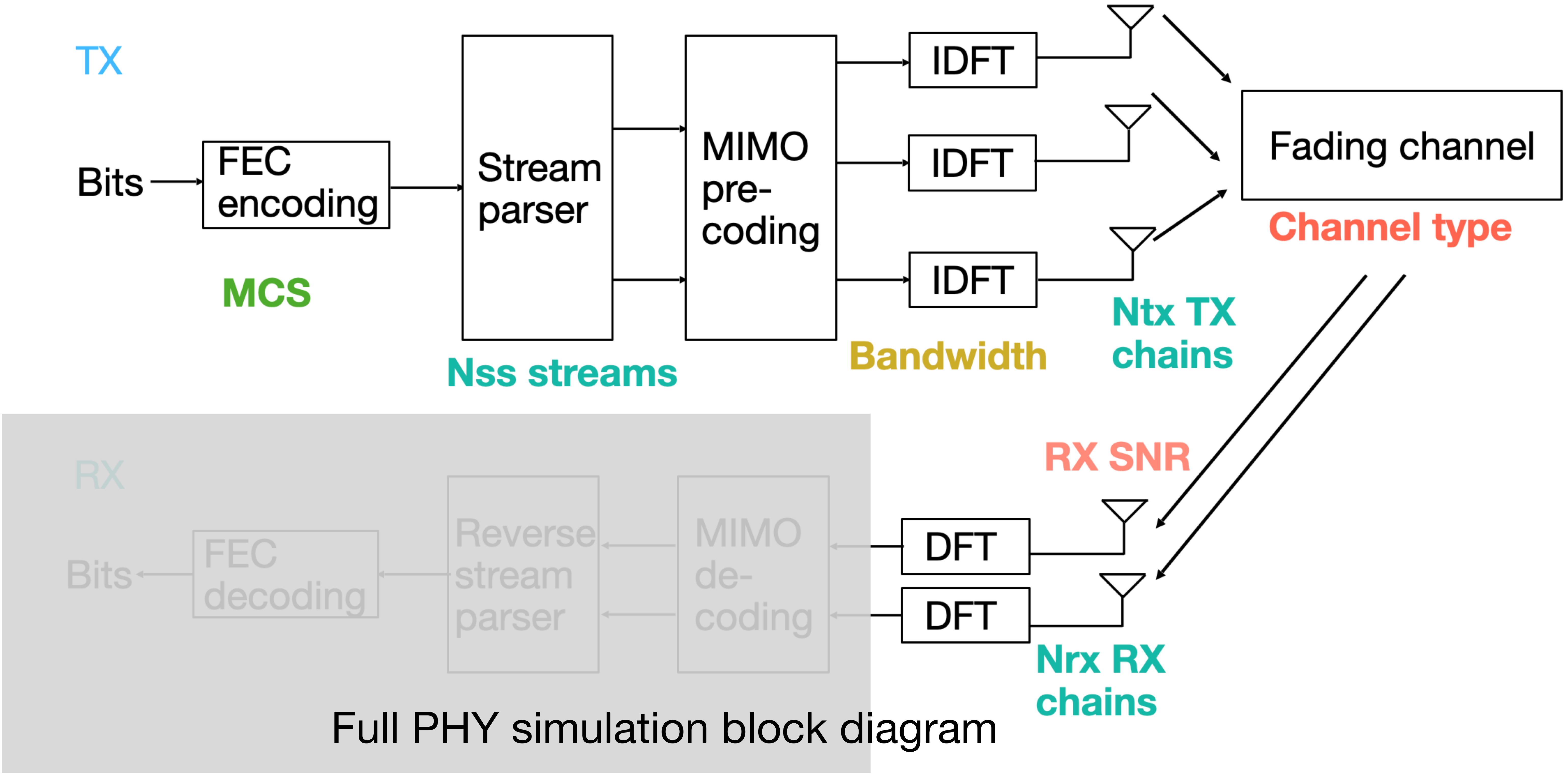

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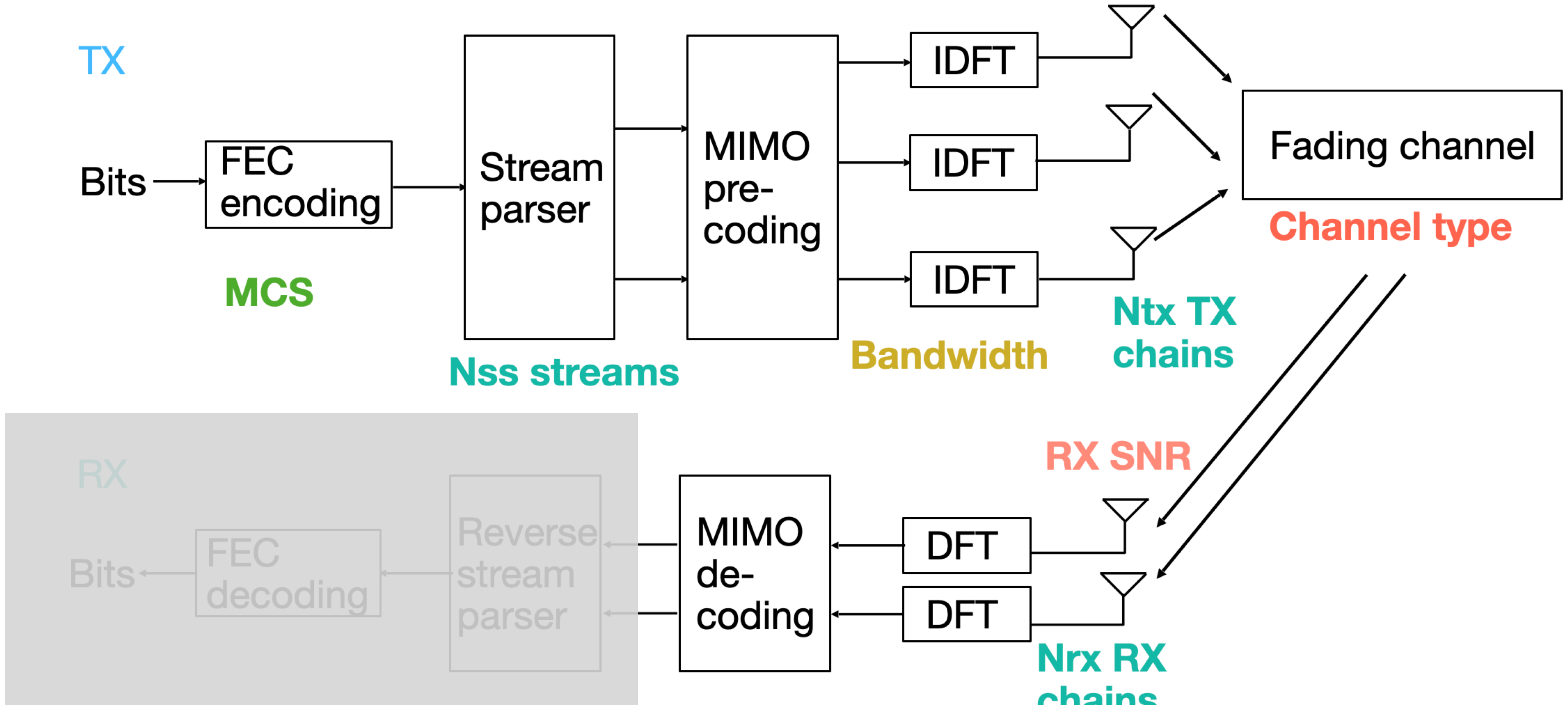

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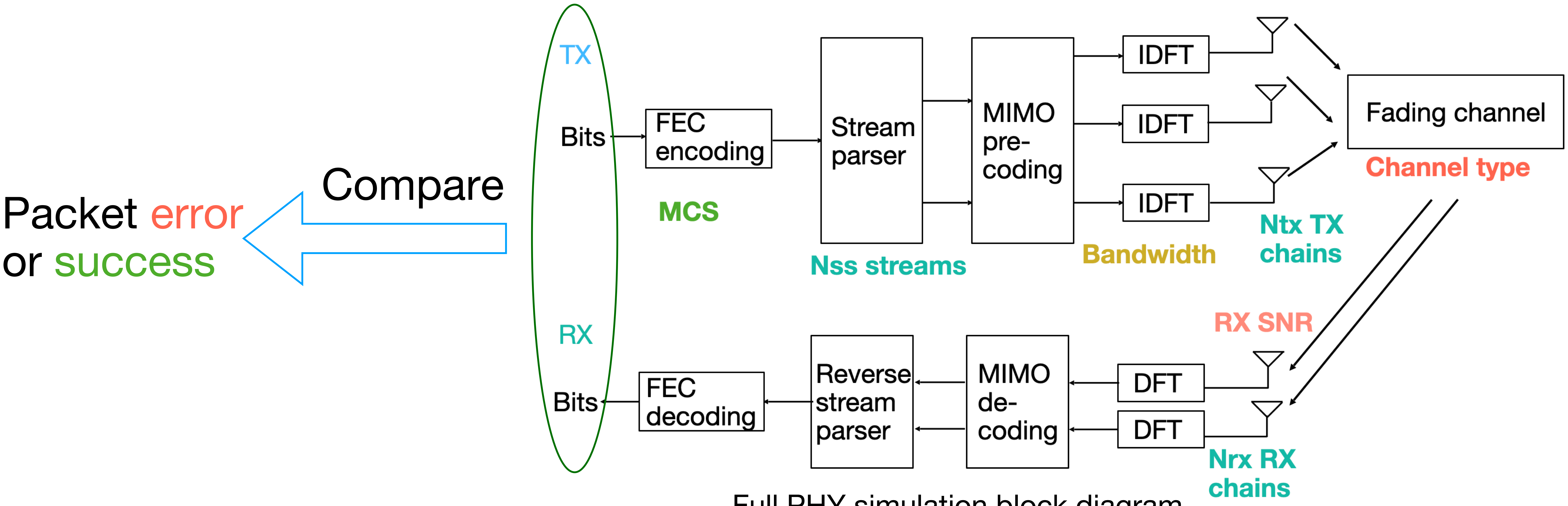

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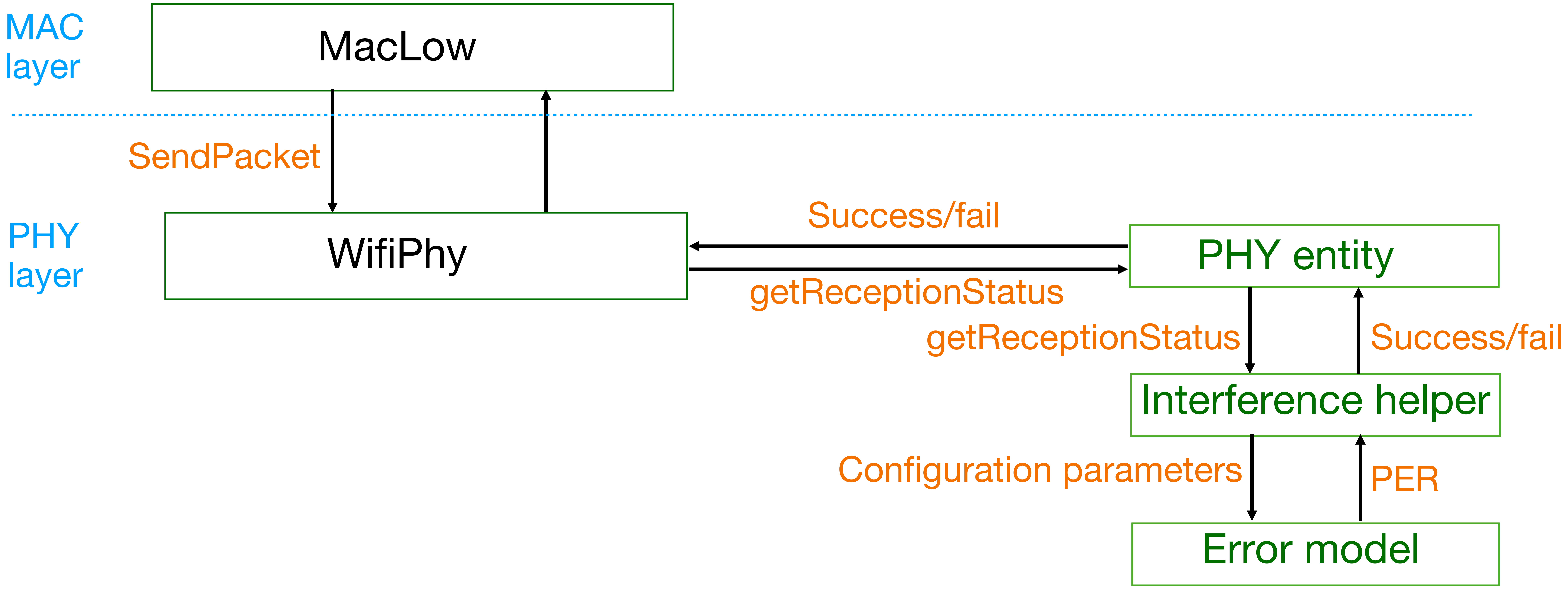
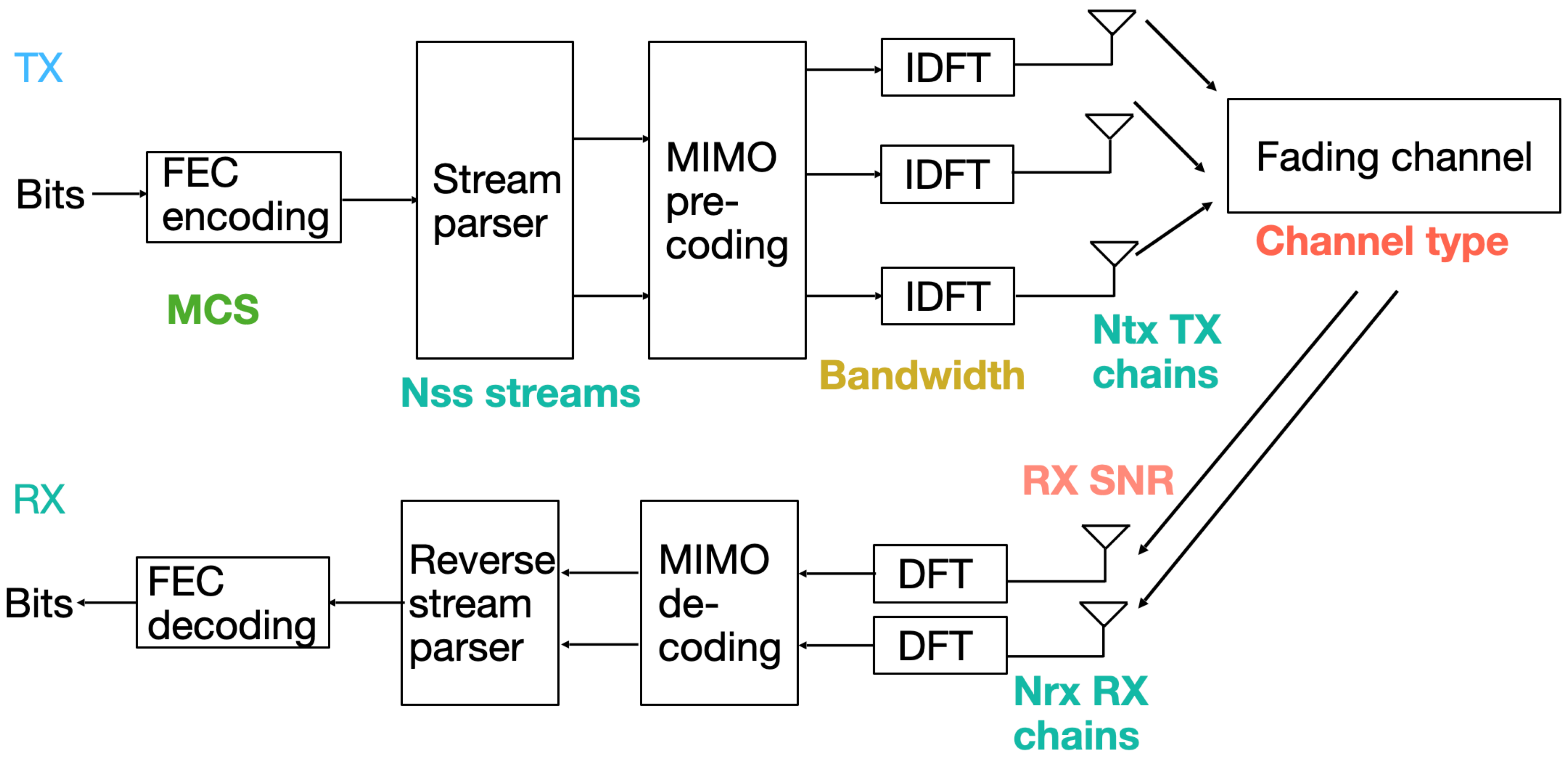


ns-3 WifiNetDevice example

Why Need an Efficient Error Model?

- Full PHY model is the most accurate error model



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Why Need an Efficient Error Model?

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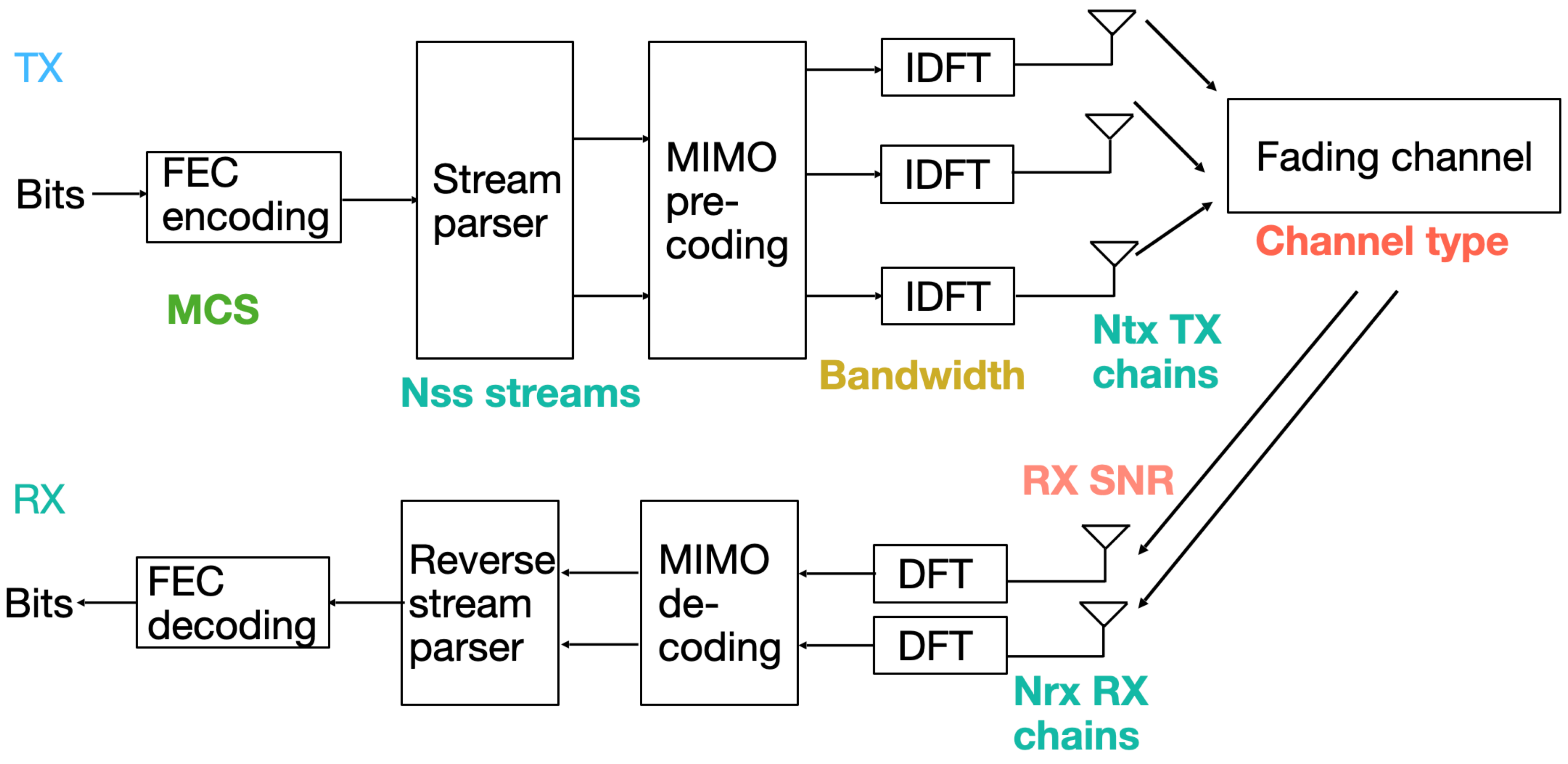
- However, full PHY simulation is prohibitively slow for a cross-layer simulator



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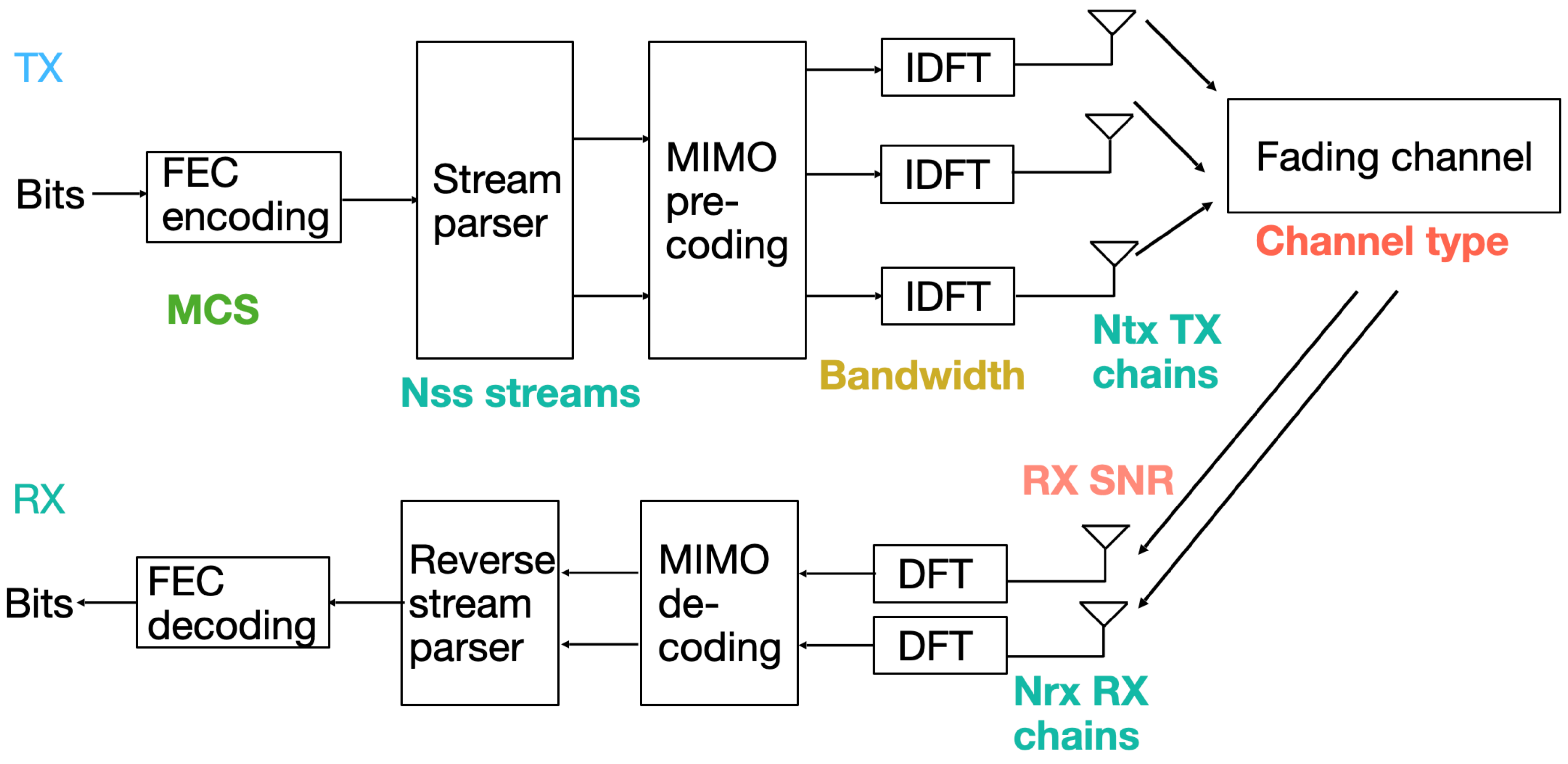

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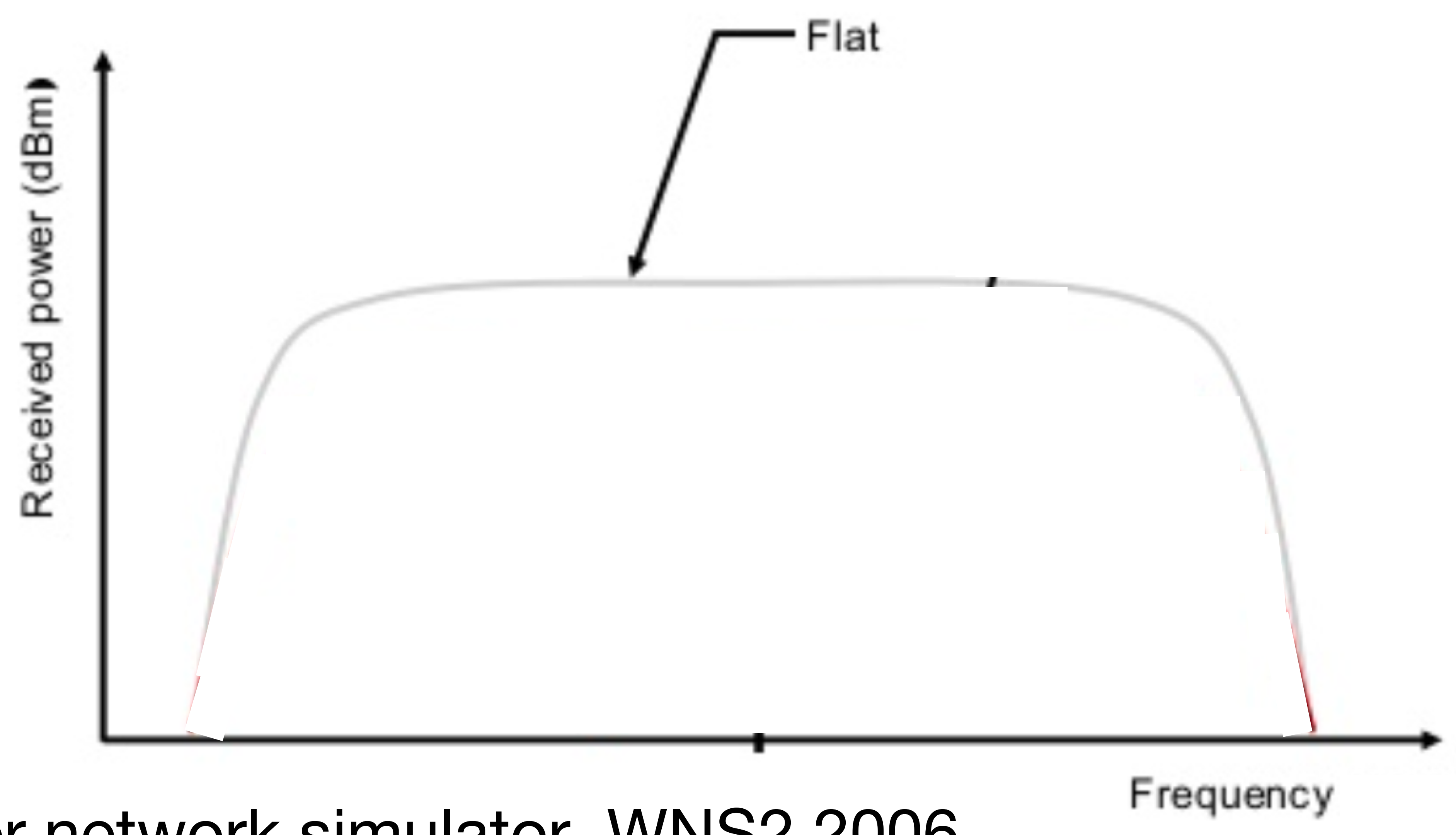
History of ns-3 Error Models

YANS model

- Original ns-3 Wi-Fi PHY is based on OFDM, SISO, frequency-flat additive white Gaussian noise (AWGN) channel, and can be easily computed



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YANS model

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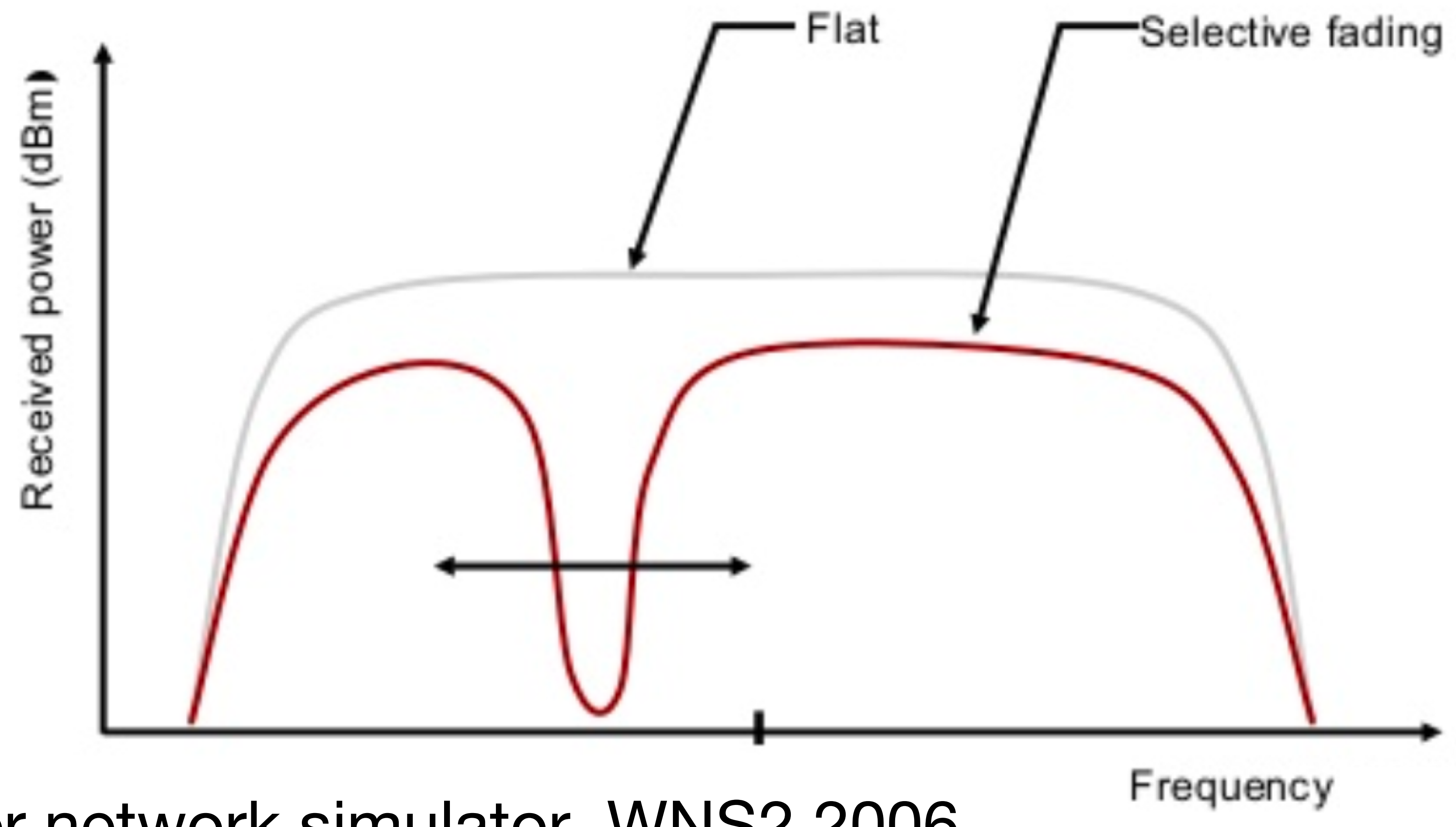
- However, frequently-selective fading channels commonly occur in OFDM system, and this greatly impacts system performance



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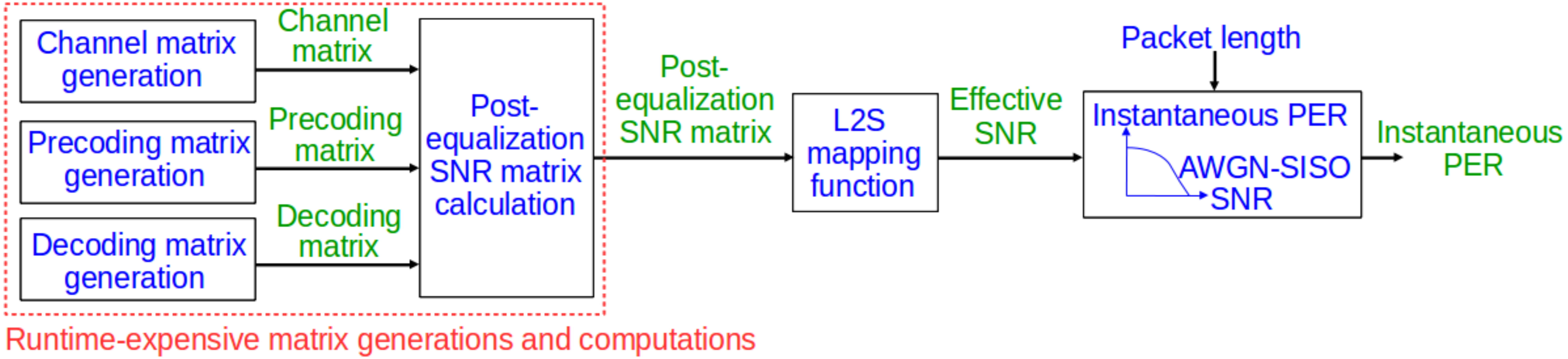

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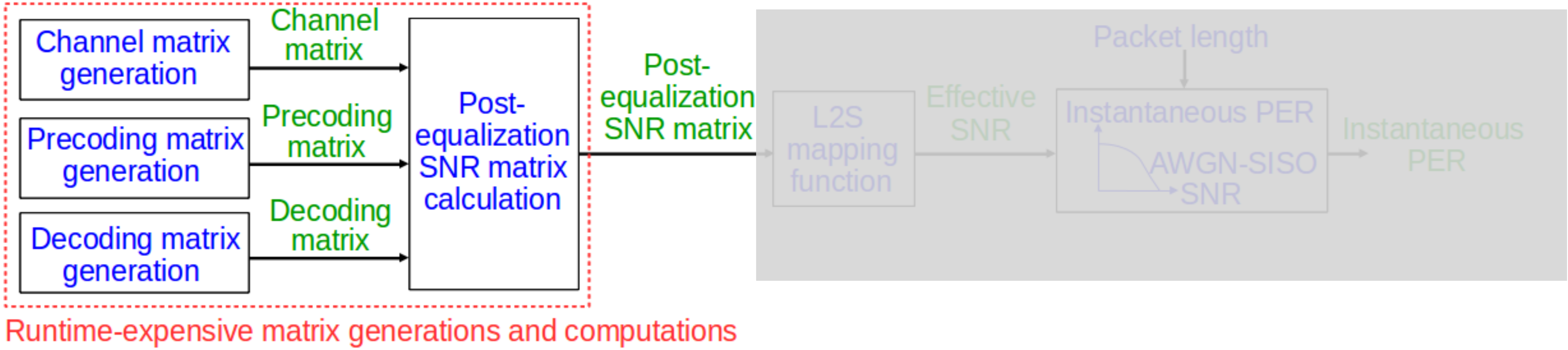

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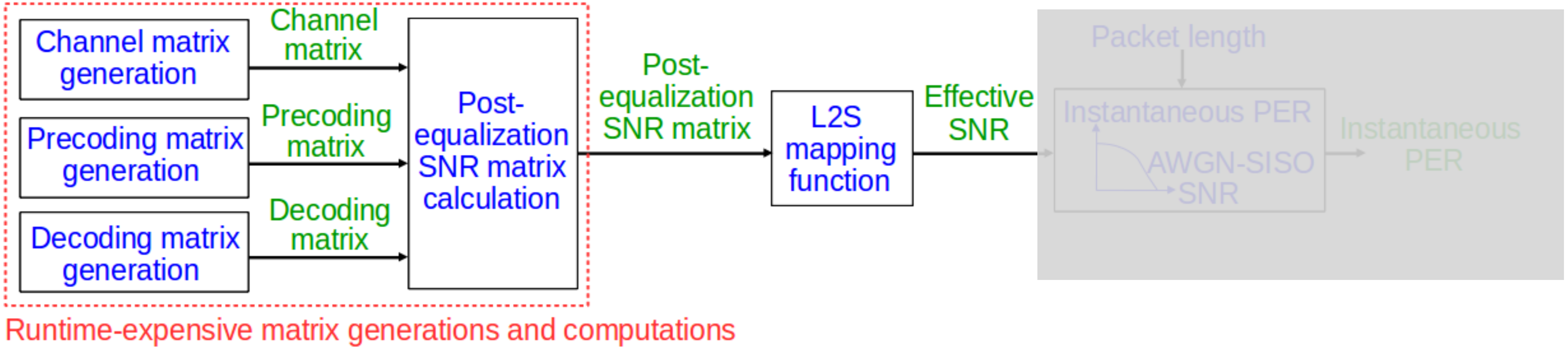

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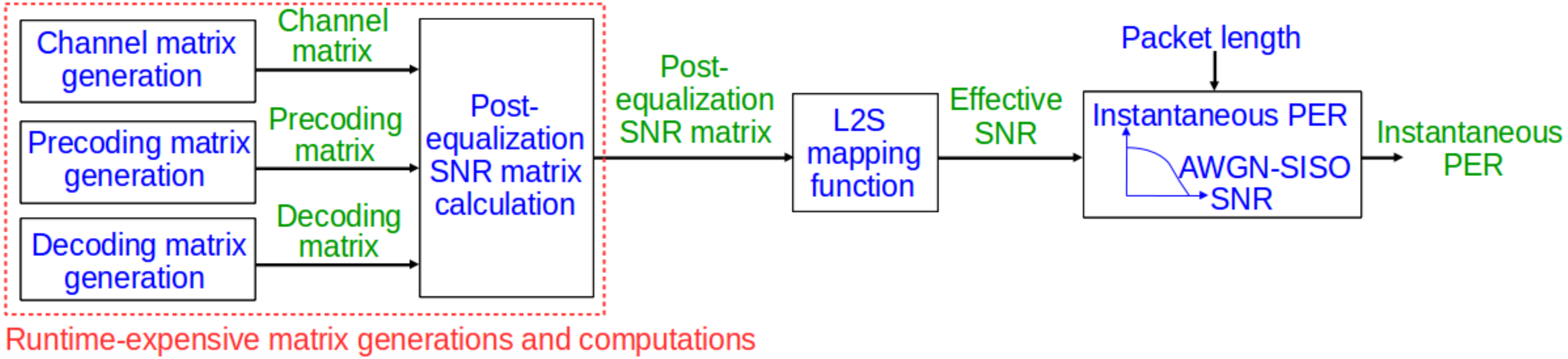

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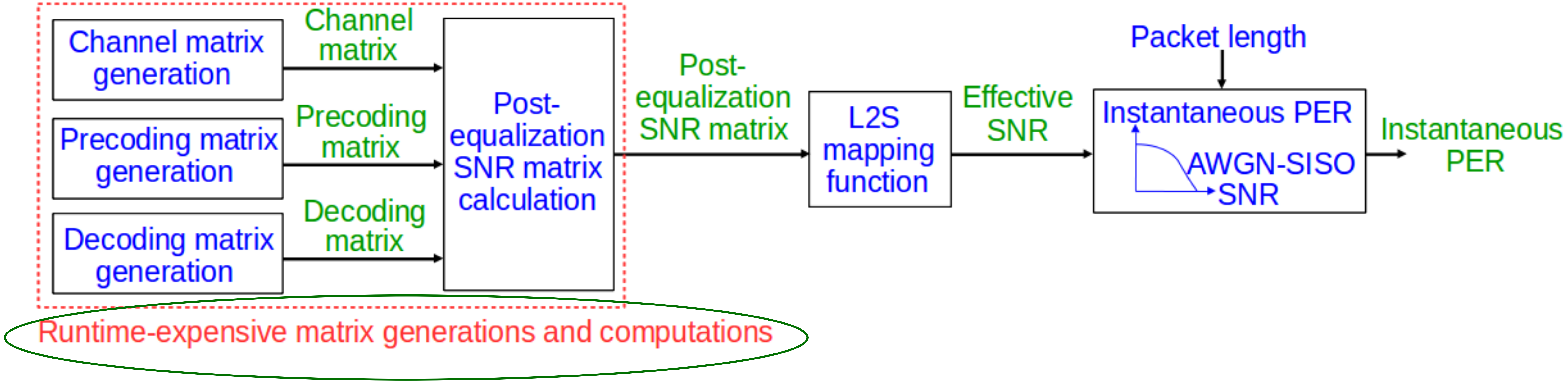

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Runtime Scaling Issue

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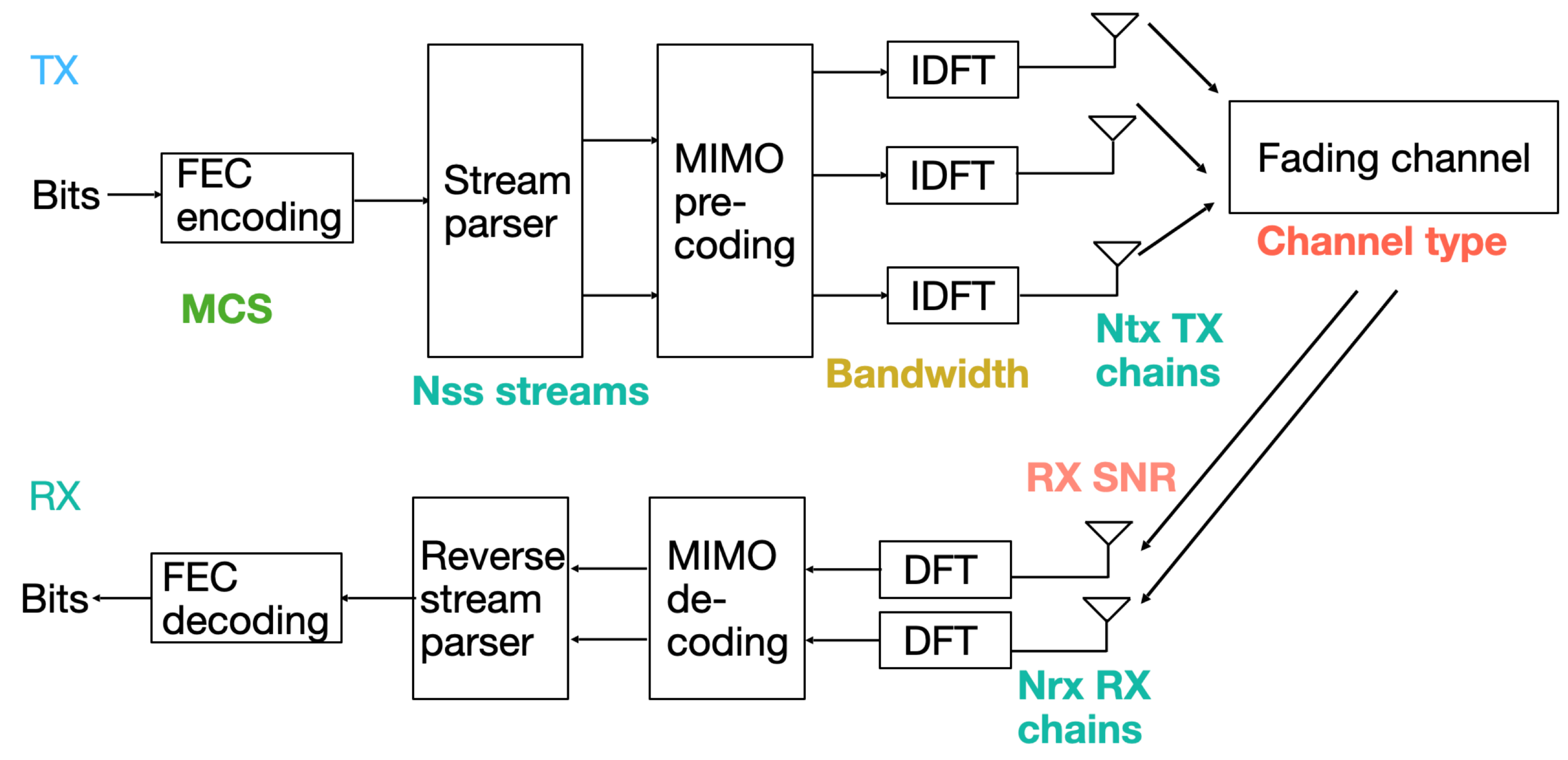

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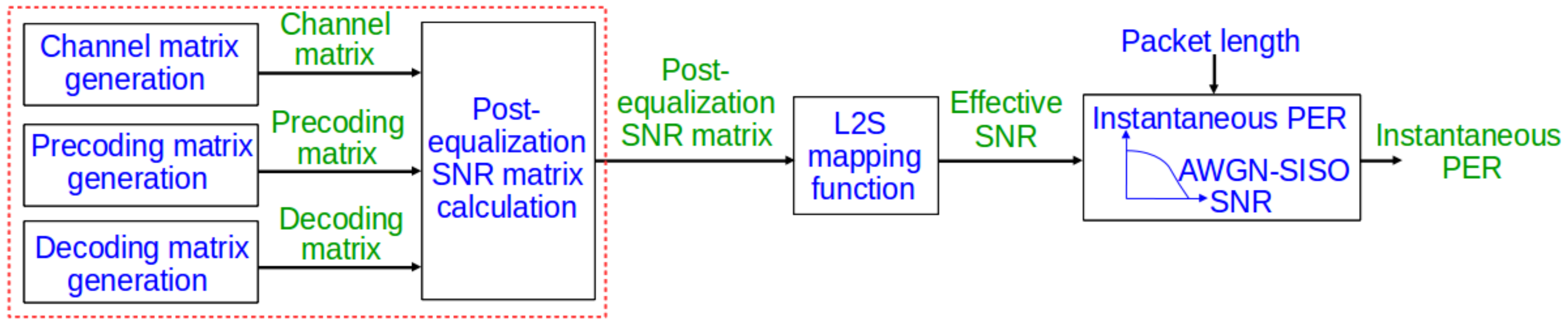

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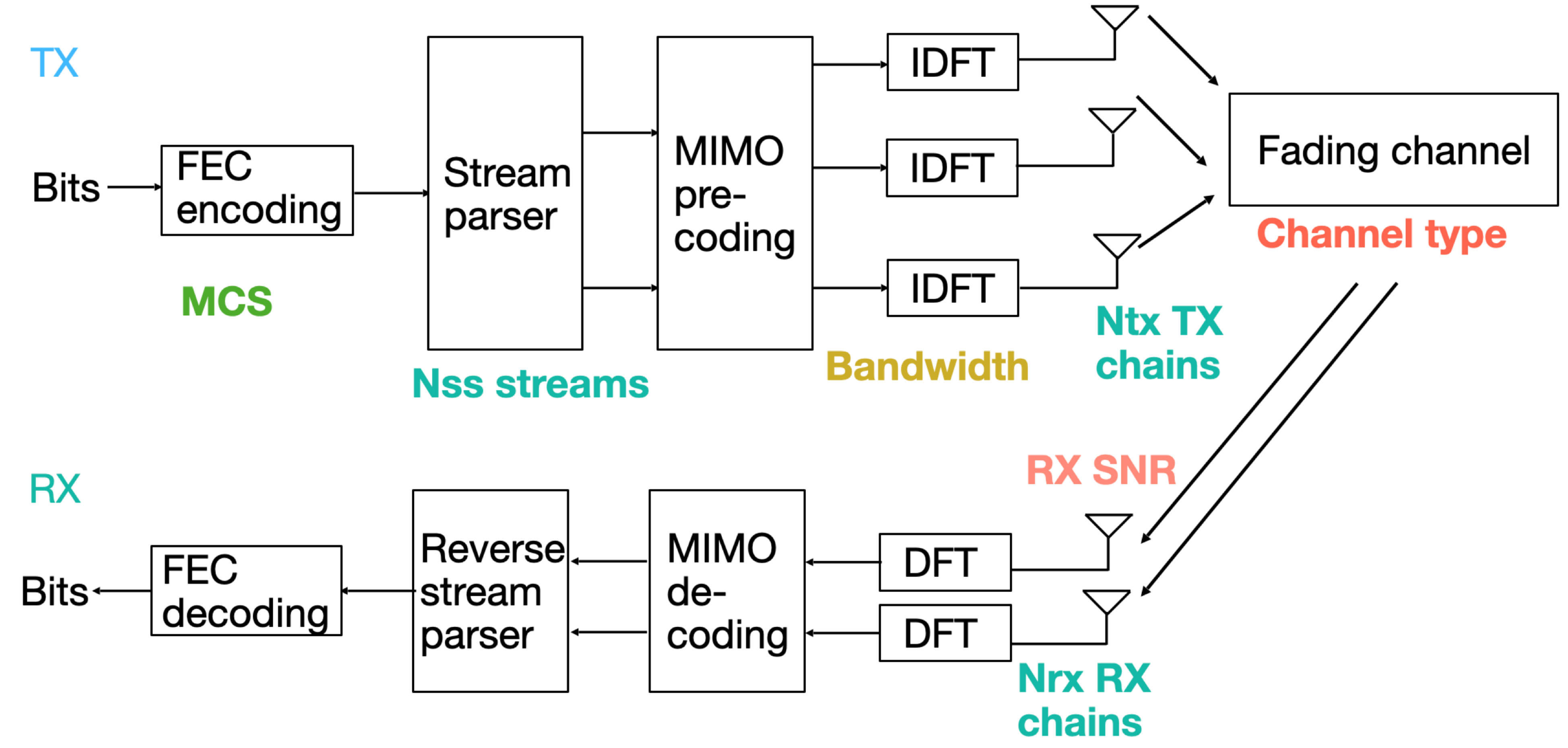

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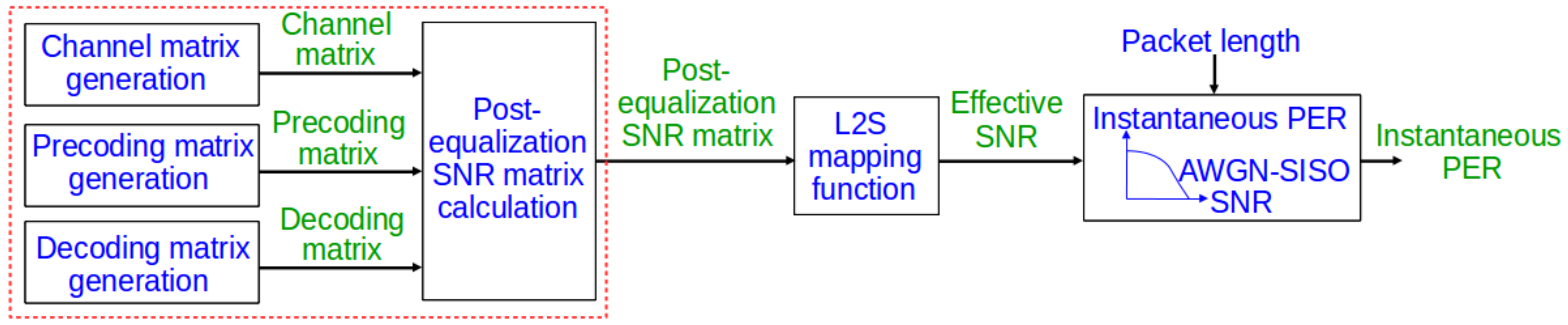
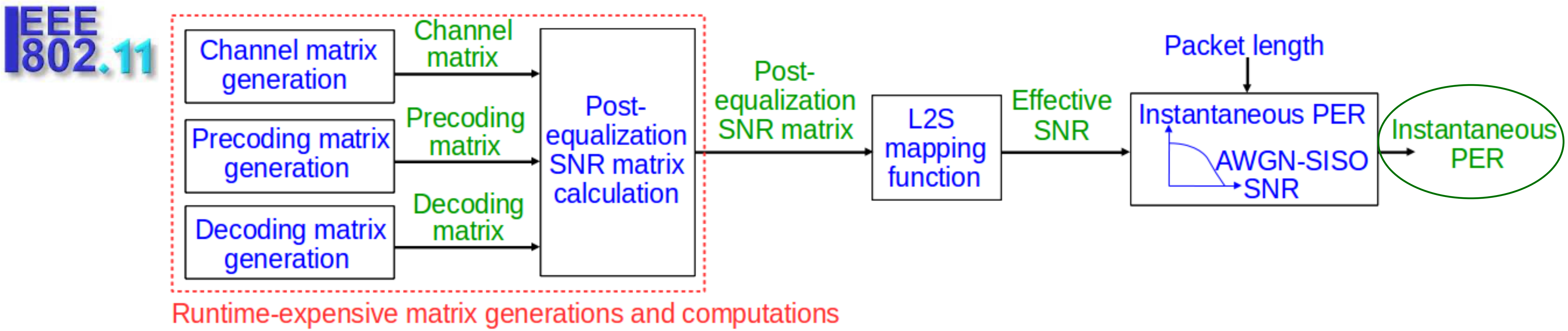


How to reduce runtime when simulating complex PHY?

Key Observation

L2S mapping suggested by IEEE TGax group:



Observation: upper layer only needs instantaneous PER (random process)

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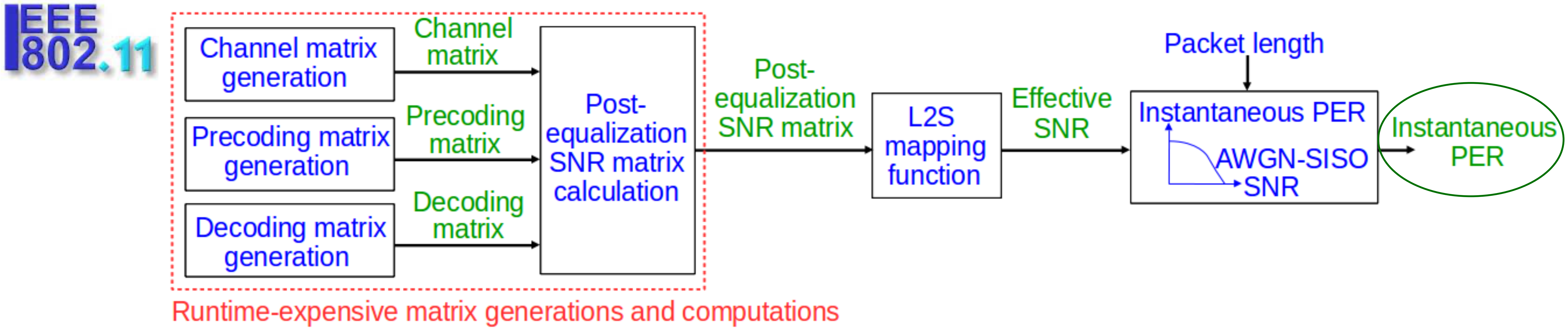

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Q1: Can we bypass runtime-expensive matrix calculation and directly store average PER (mean of instantaneous PER)?

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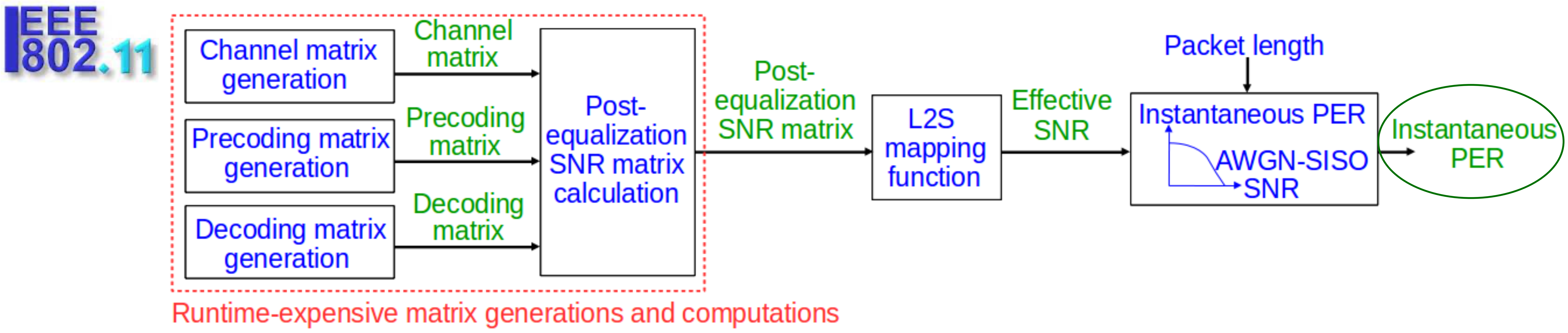

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No variance, skewness, kurtosis, time correlation information

Key Observation

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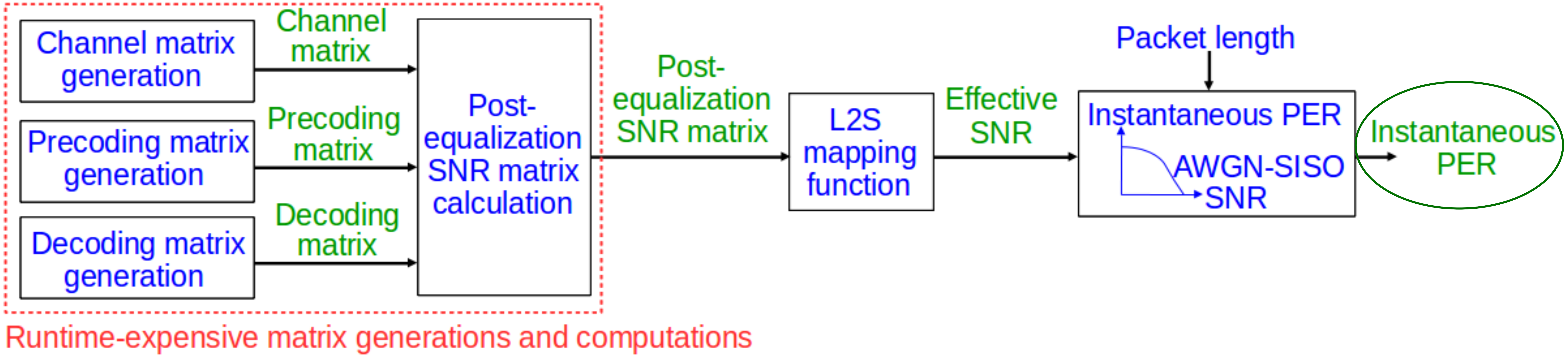
IEEE 802.11



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Q2: Can we bypass runtime-expensive matrix calculation and directly model instantaneous PER?

Key Observation

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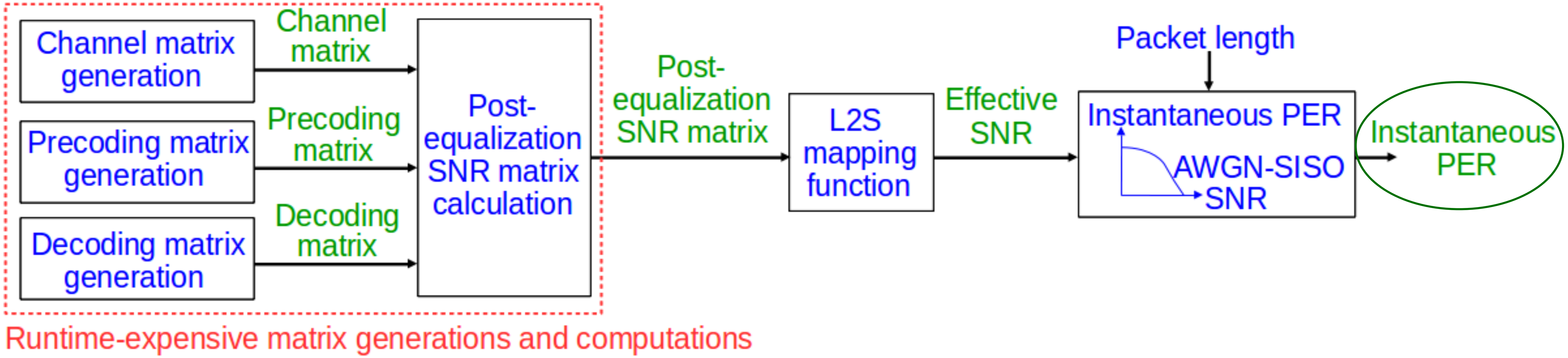

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Cannot provide models of instantaneous PERs for different packet lengths

Key Observation

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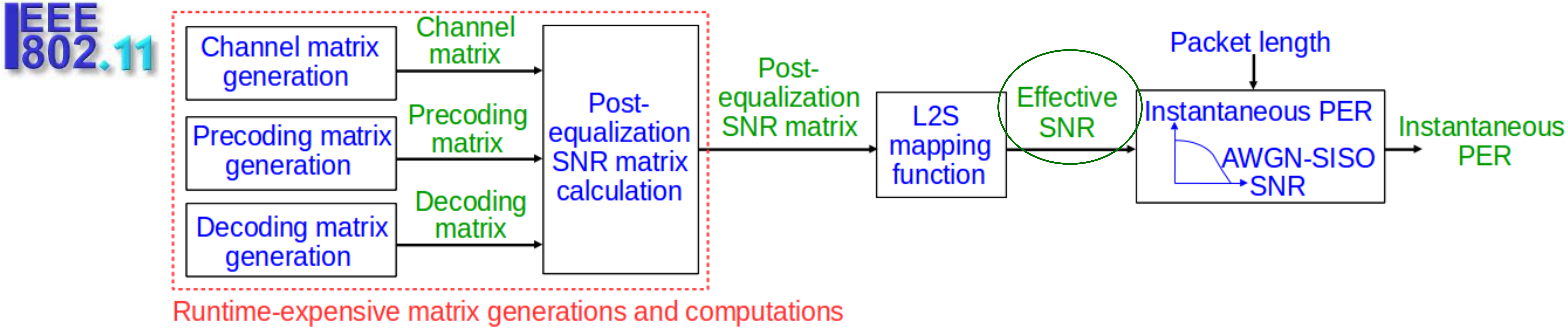

Observation: upper layer only needs instantaneous PER (random process)

Q3: Can we bypass runtime-expensive matrix calculation and directly model effective SNR?

Key Observation

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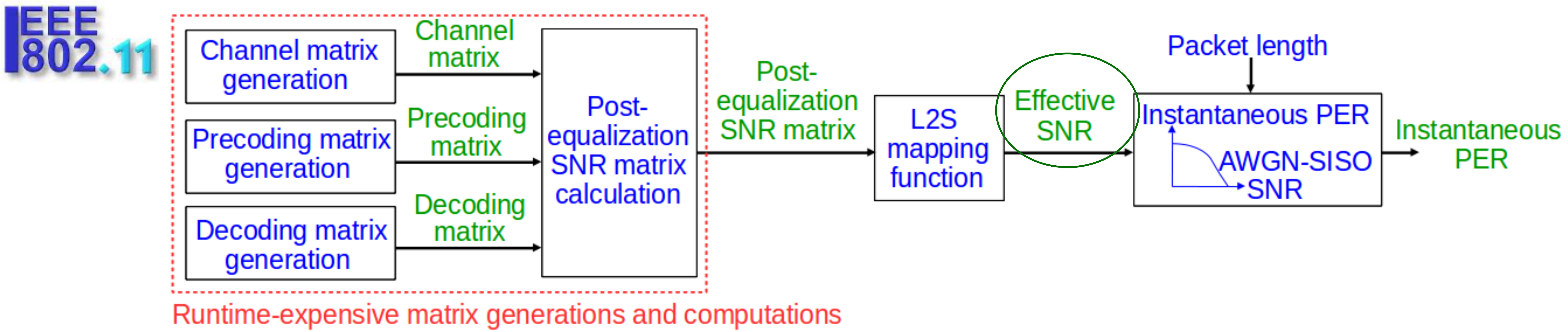


Observation: upper layer only needs instantaneous PER (random process)

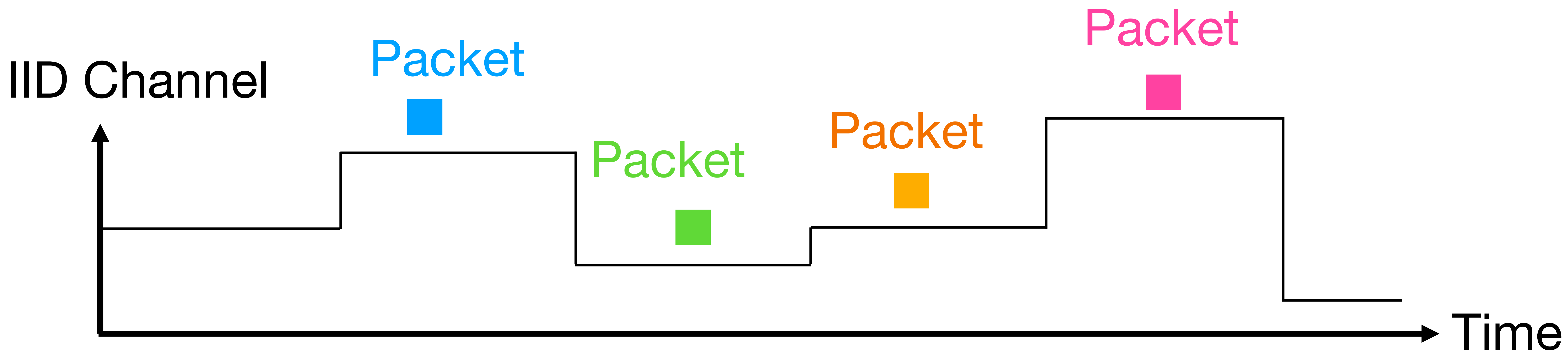
Q3: Can we bypass runtime-expensive matrix calculation and directly model effective SNR?

😃 Effective SNR is insensitive to packet length and is easy to be mapped into instantaneous PER

New Method: EESM-log-SGN

Previous State-of-the-art

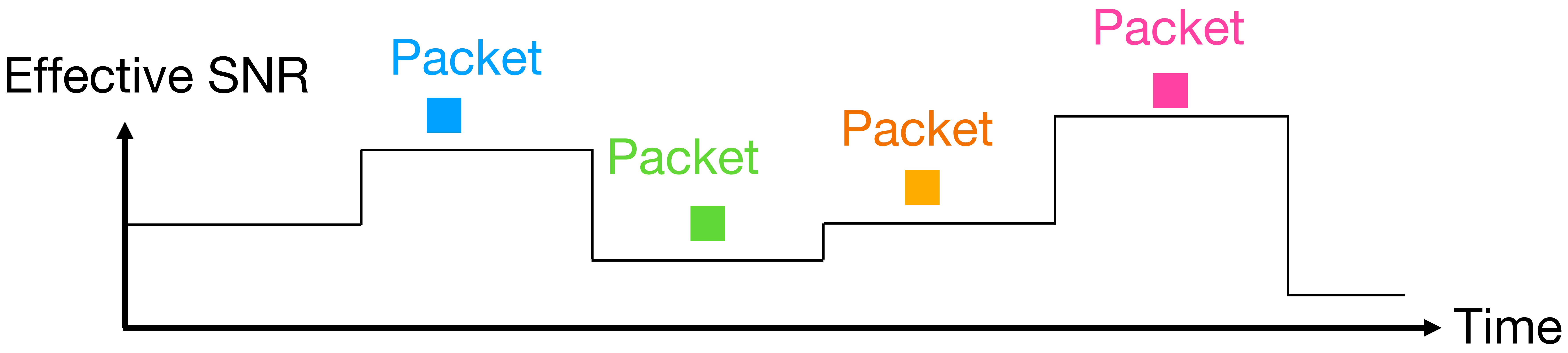
Assume IID channel for different packets



New Method: EESM-log-SGN

Previous State-of-the-art

Assume IID channel for different packets, then effective SNR for different packets are also IID



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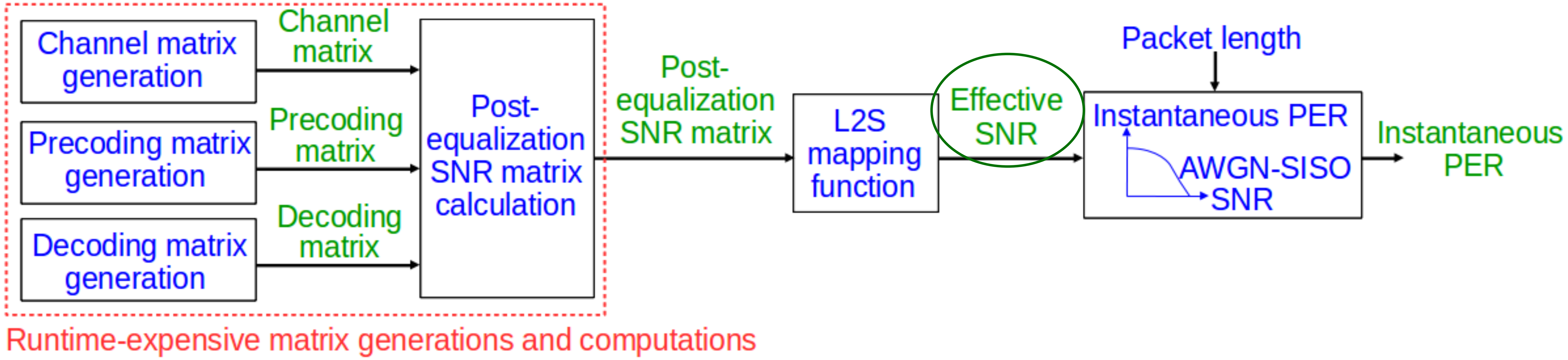
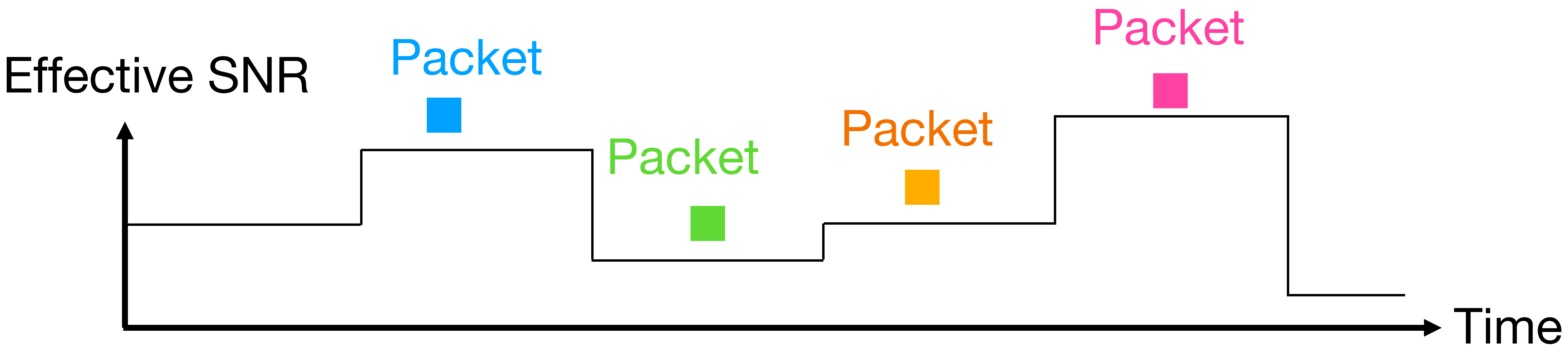


Assume IID channel, model effective SNR distribution, and directly outputs IID effective SNRs



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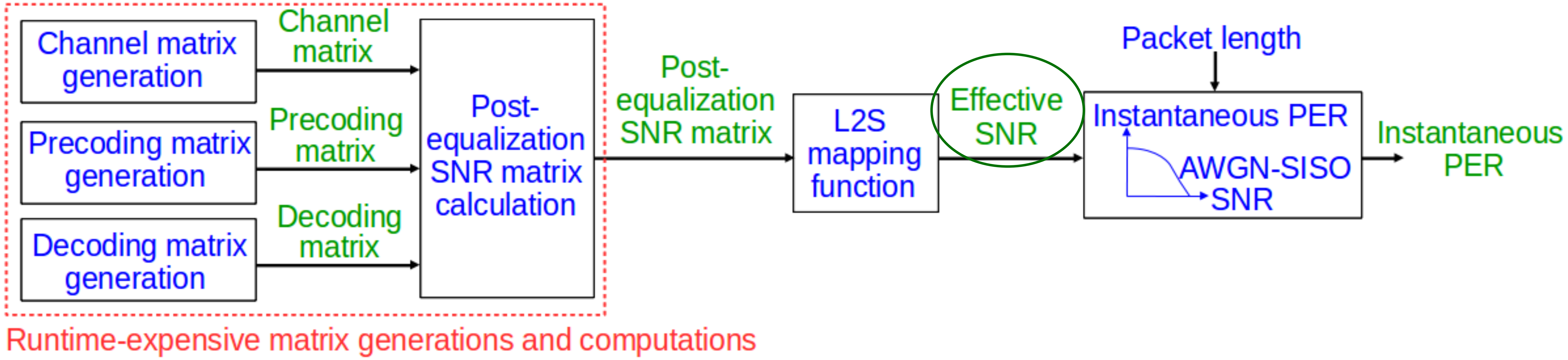

Under IID channel & EESM L2S mapping function, effective SNR distribution follows:

Log-skew generalized normal (log-SGN) distribution

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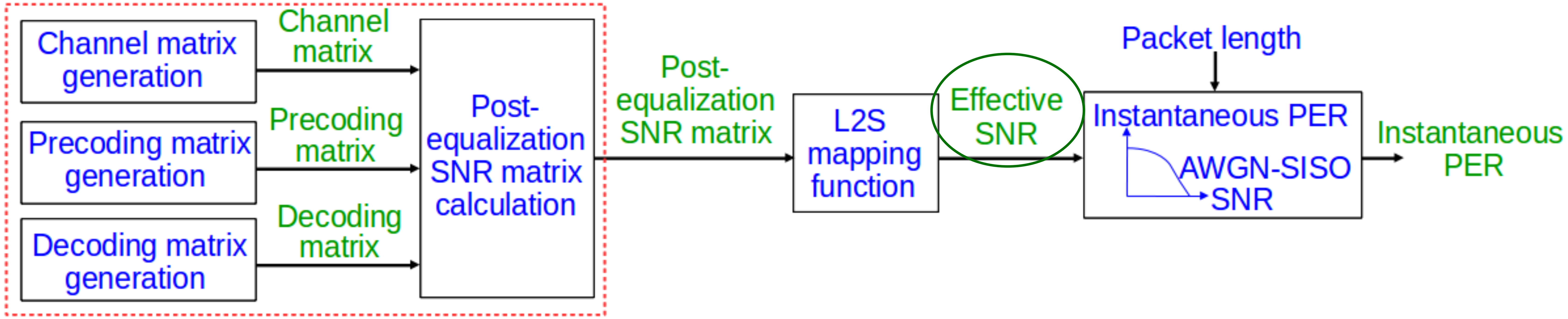

Runtime-expensive matrix generations and computations

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$f_X(x; \hat{\mu}, \hat{\sigma}, \hat{\lambda}_1, \hat{\lambda}_2)$ PDF of X

$$= \frac{2}{\hat{\sigma}} \psi\left(\frac{x-\hat{\mu}}{\hat{\sigma}}\right) \Psi\left(\frac{\hat{\lambda}_1 (x-\hat{\mu})}{\sqrt{\hat{\sigma}^2 + \hat{\lambda}_2 (x-\hat{\mu})^2}}\right), \quad x \in \mathbf{R},$$

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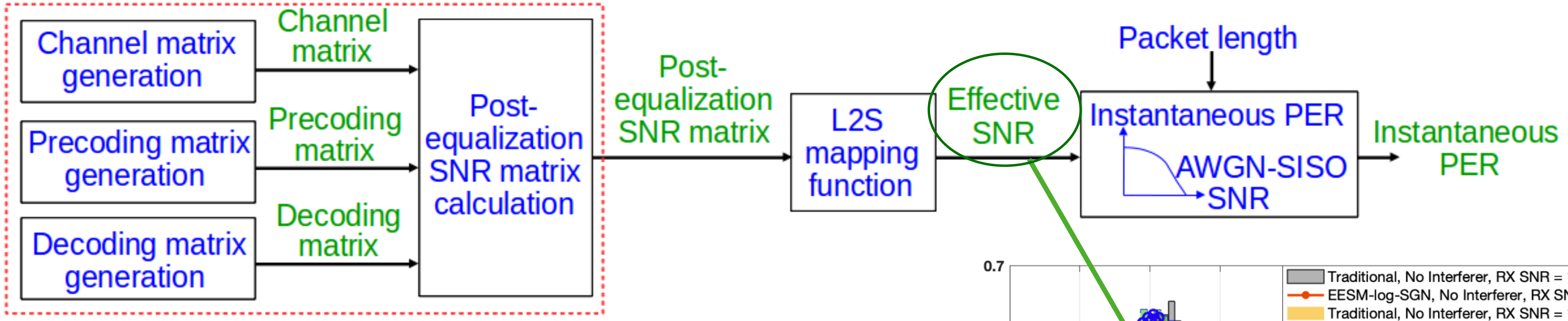

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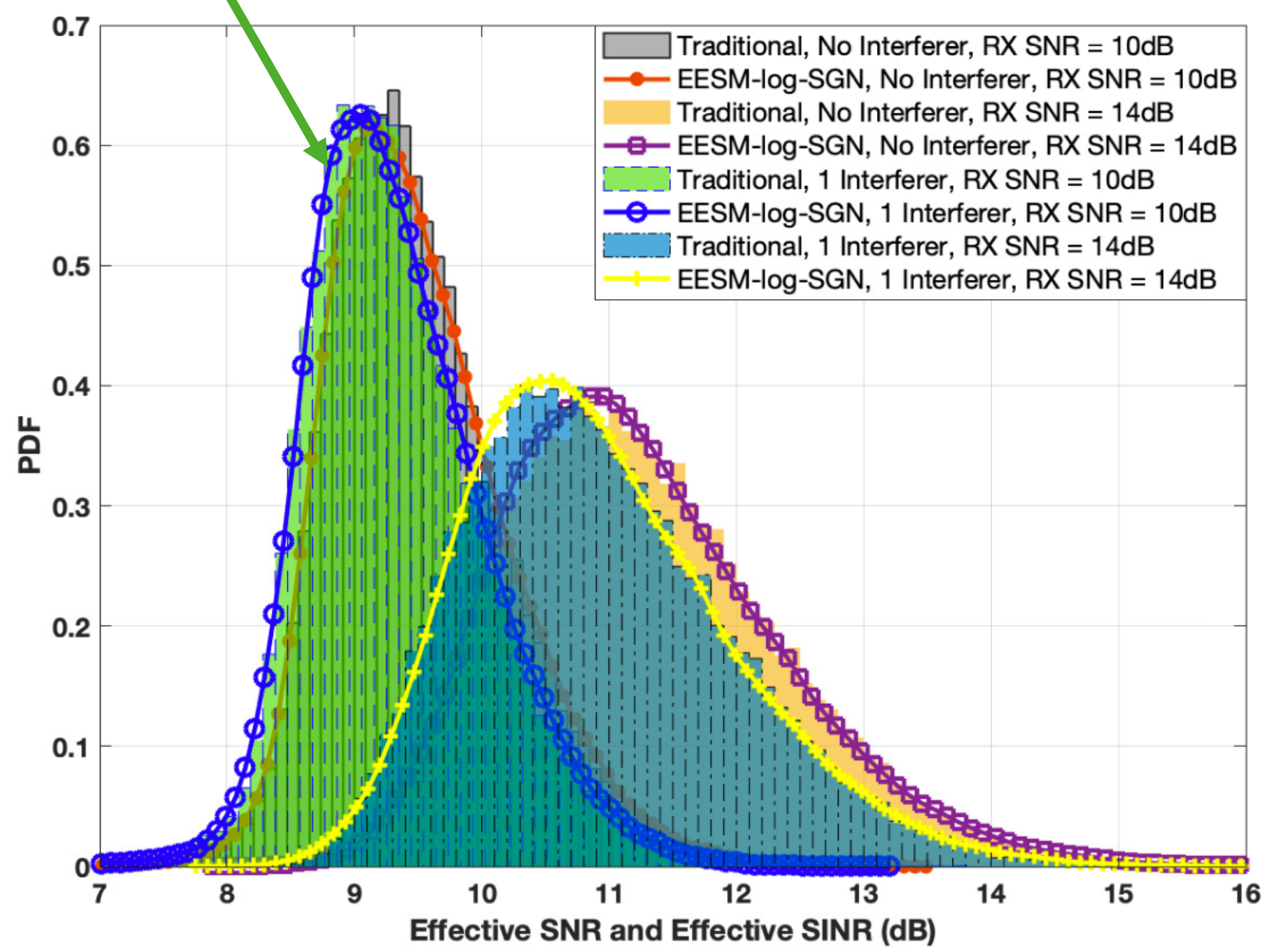

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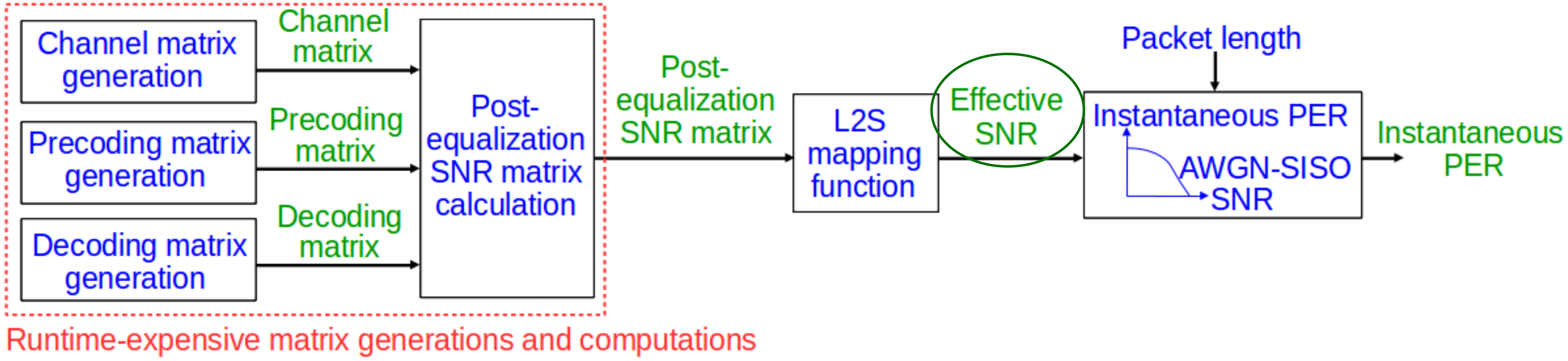

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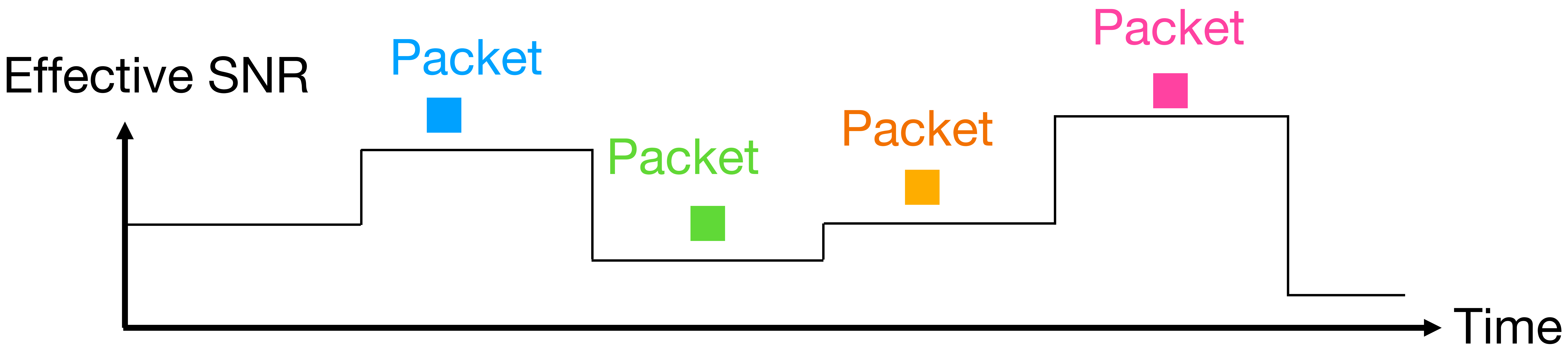
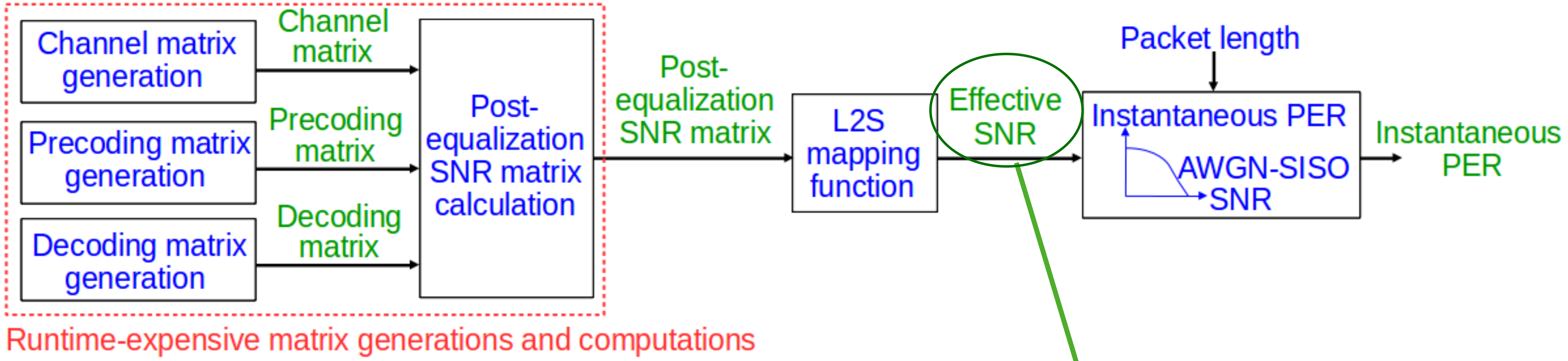


Sub-6GHz Wi-Fi Time-varying Channel

L2S mapping:

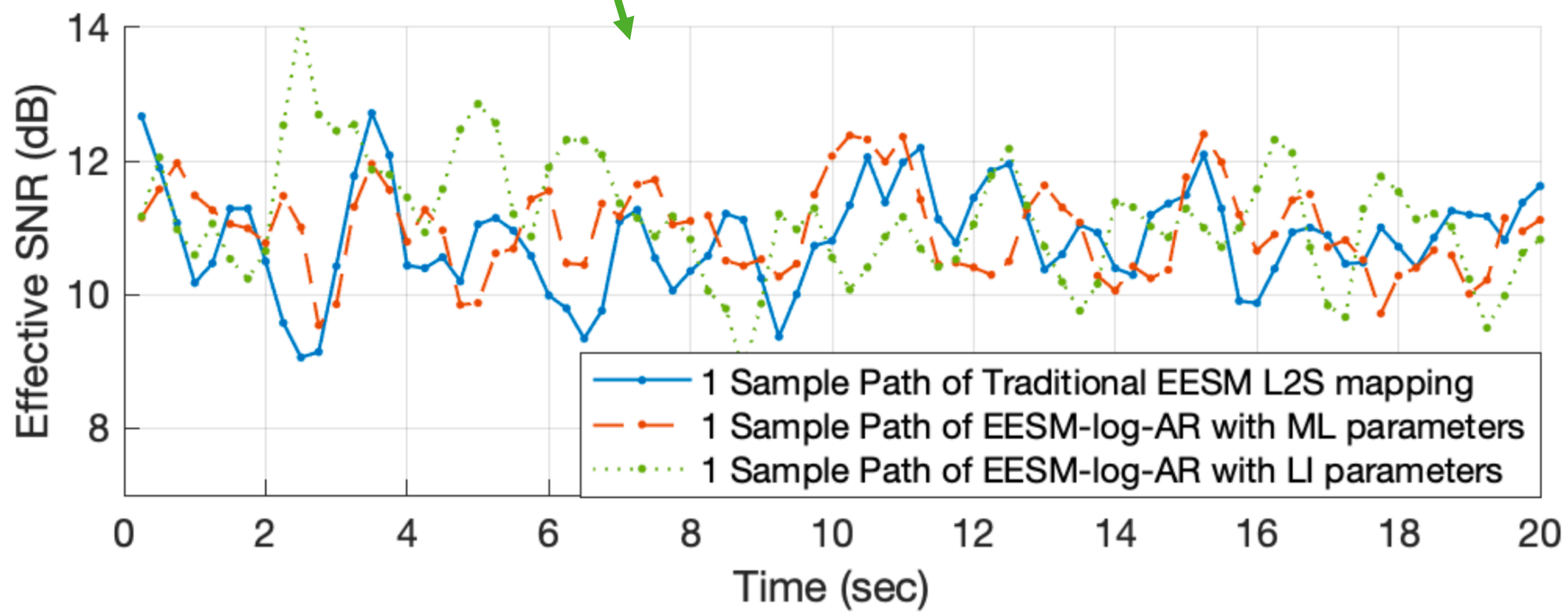


Sub-6GHz Wi-Fi channel is time-varying

Have correlations

Vary slowly overtime

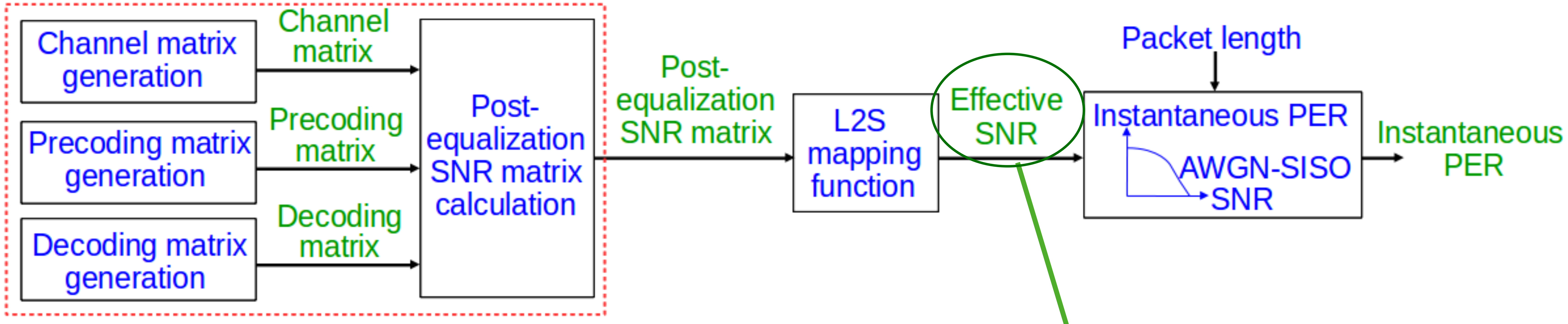
Burst error



Real Wi-Fi Time-varying Channel

L2S mapping:

IEEE 802.11

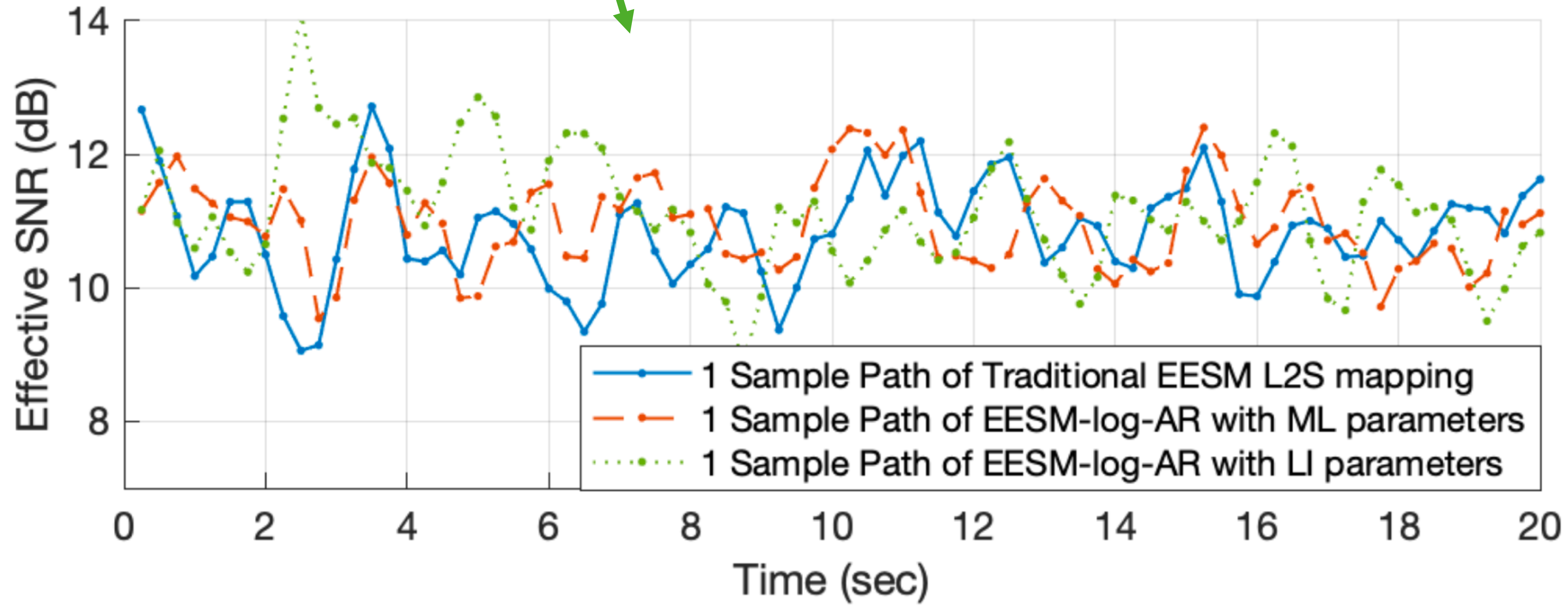


Real Wi-Fi channel: time-varying channel

Have correlations

Vary slowly overtime

Burst error



Extend EESM-log-SGN method to time-varying channel

EESM-log-AR: Main Idea

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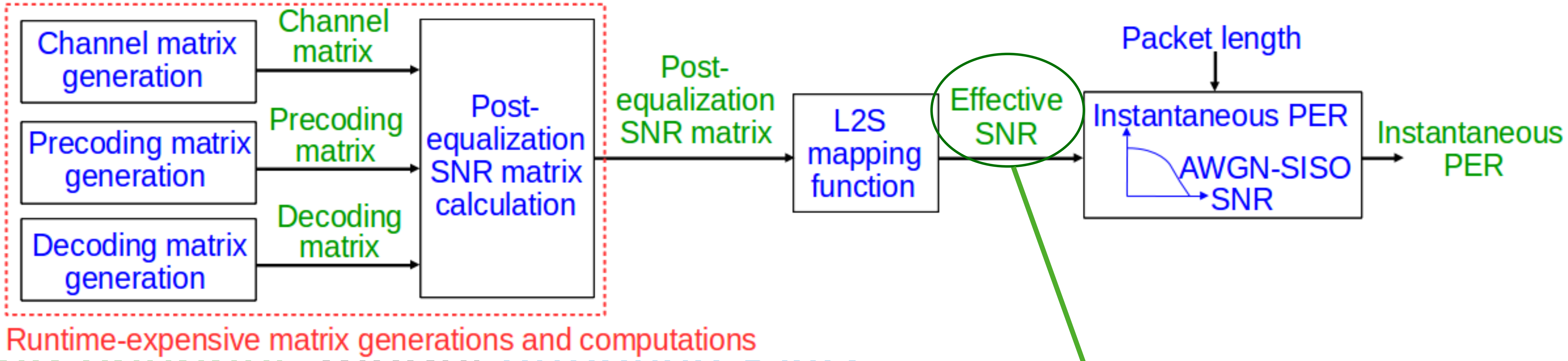
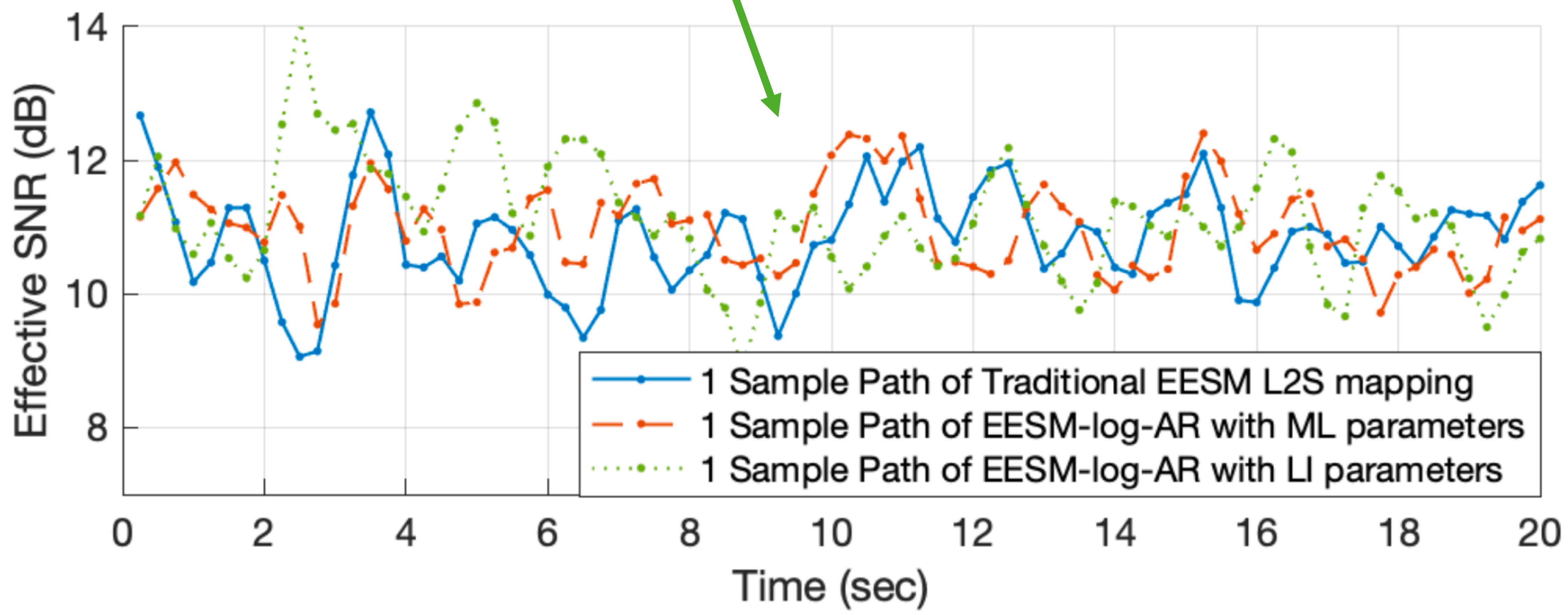
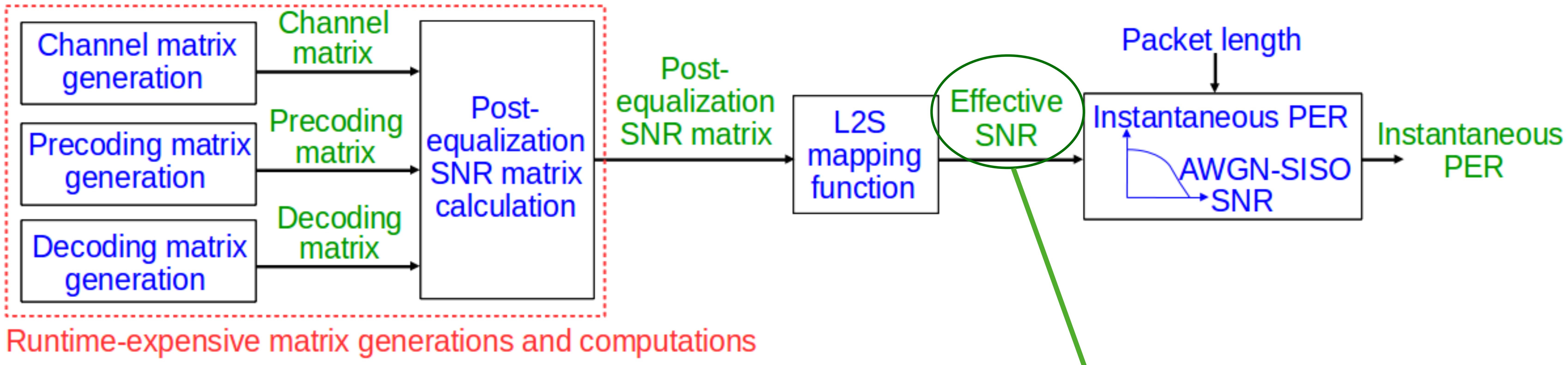


Assume time-varying channel, model effective SNR process, and directly outputs effective SNR process



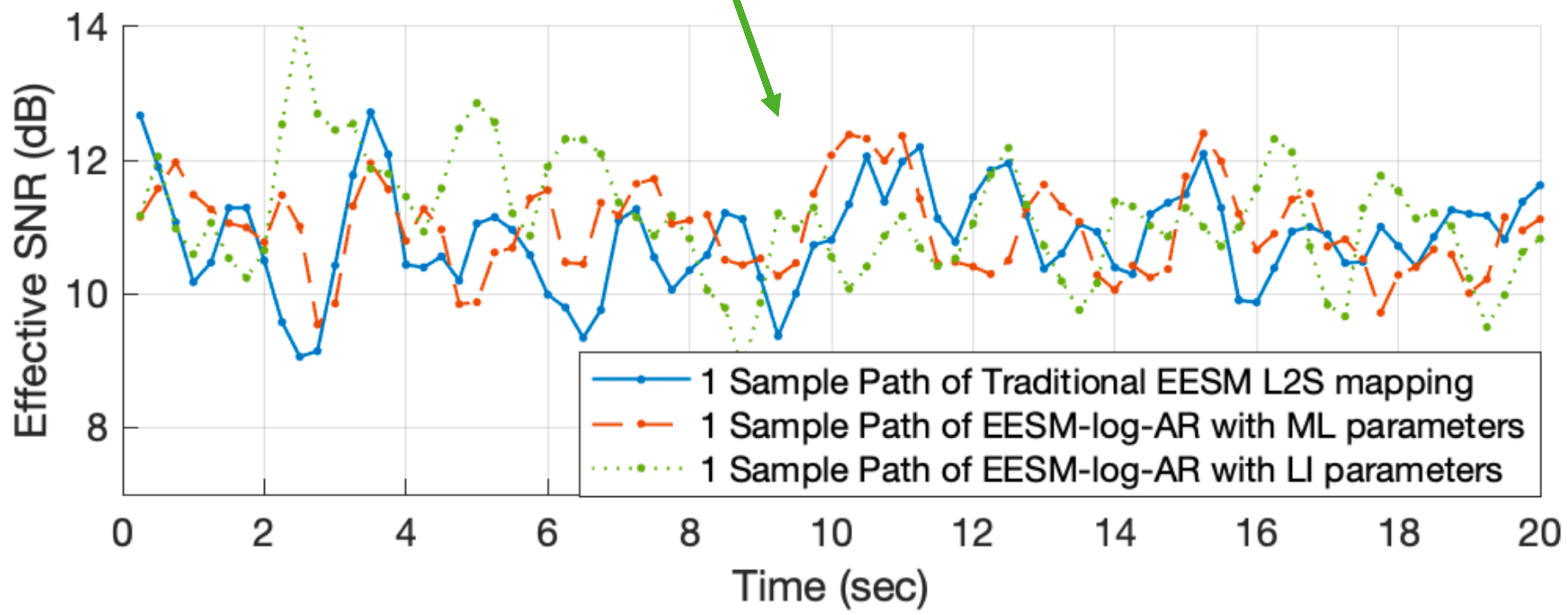
EEESM-log-AR: Main Idea

L2S mapping:



Under time-varying channel & EESM L2S mapping function, effective SNR process follows:

Log-AutoRegressive (log-AR) process



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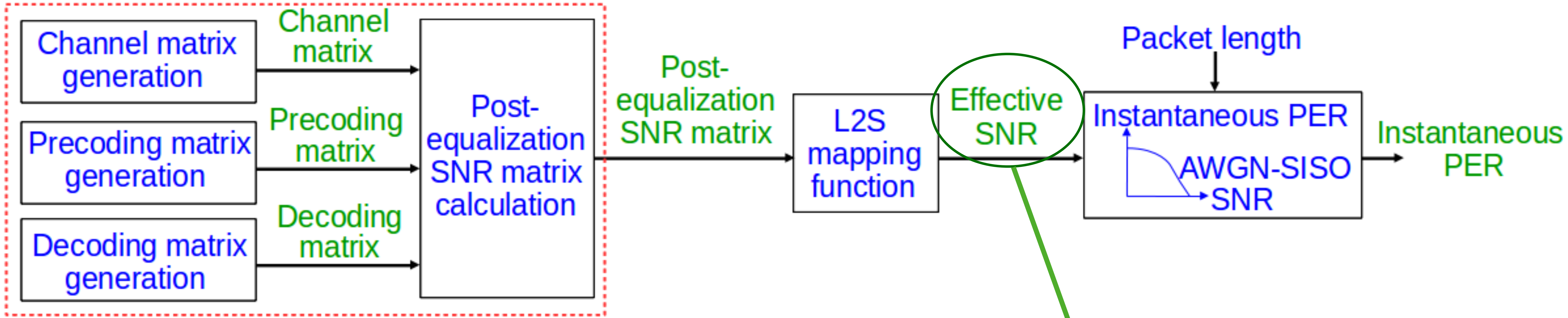


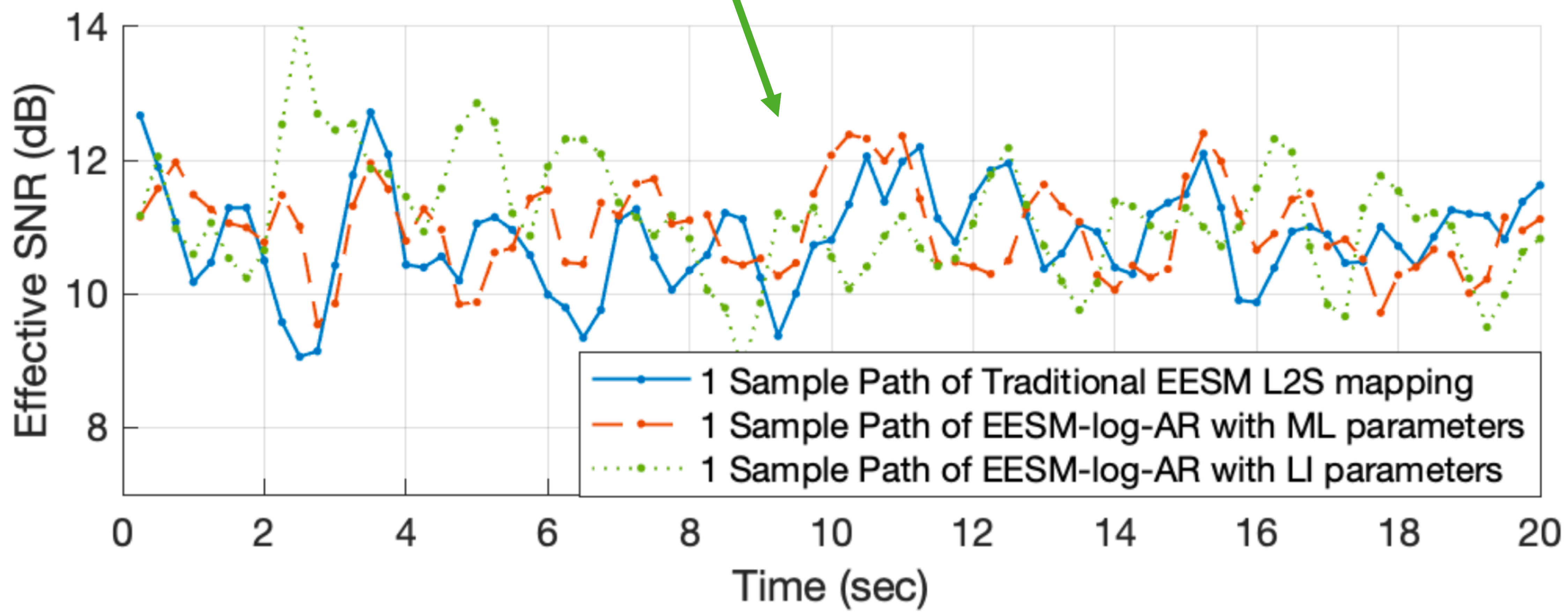
Under time-varying channel & EESM L2S mapping function, effective SNR process follows:

Log-AutoRegressive (log-AR) process

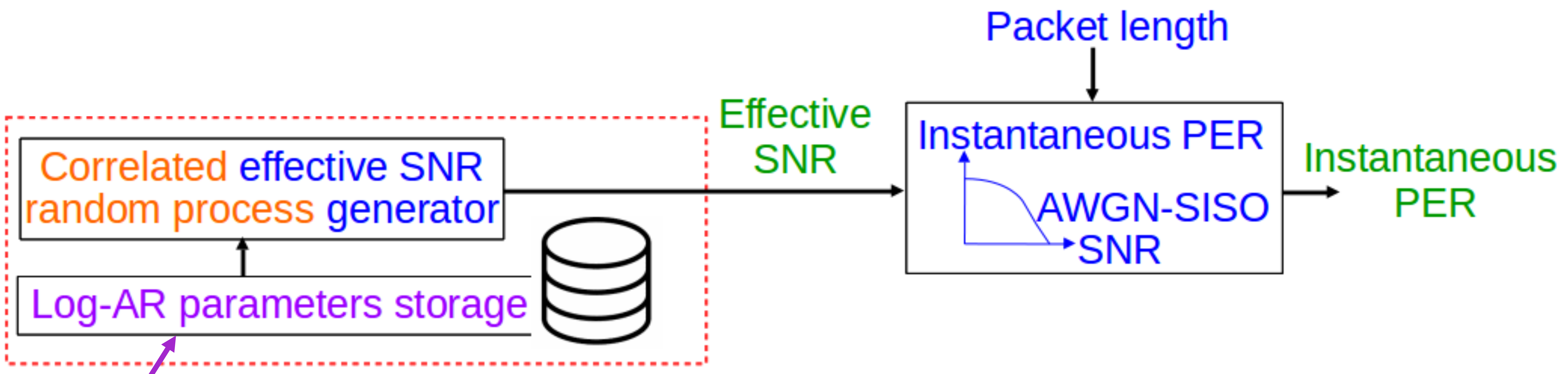
$X[l] \triangleq \ln(\Gamma_{eff}[l])$ Take log of effective SNR

$X[l] = c + \sum_{m=1}^{p} \phi_m X[l-m] + \epsilon[l]$ AR model

Normal variable



EESM-log-AR: Main Idea



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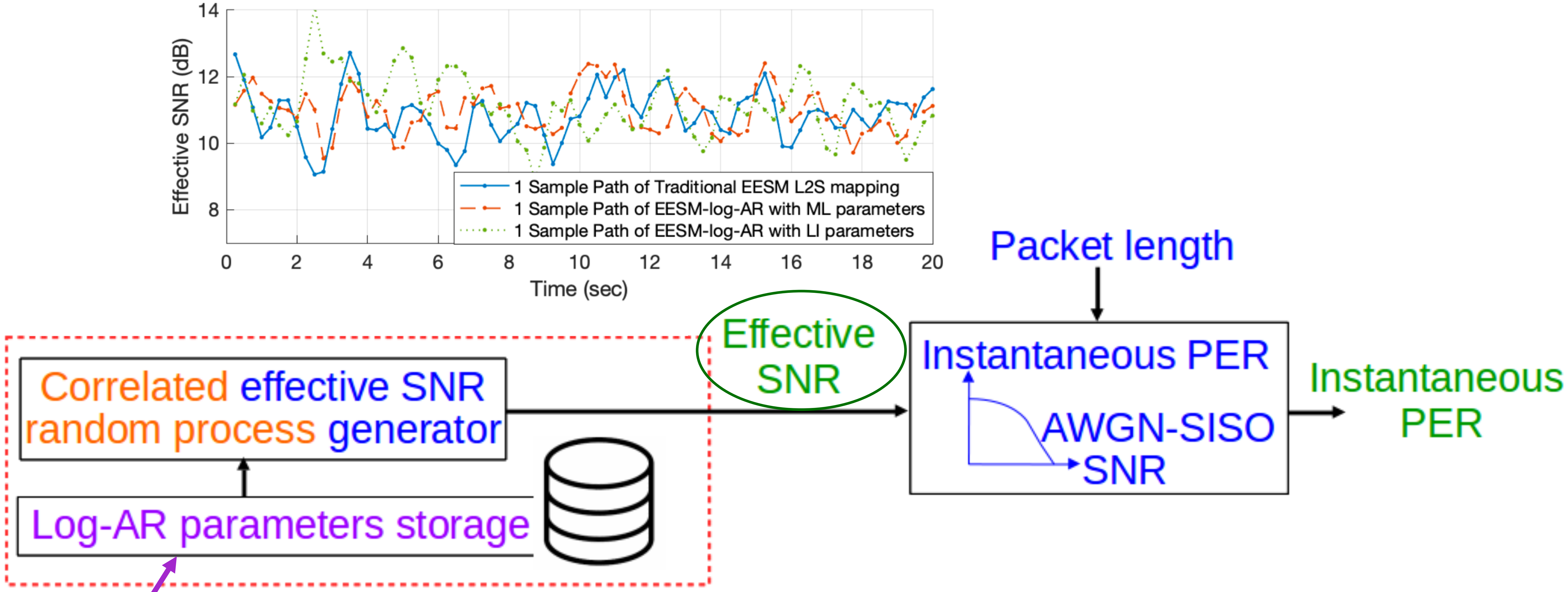

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log-AR parameters depend on:
MIMO setup, bandwidth, MCS, and channel types

EESM-log-AR: Runtime

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Runtime of single link 200,000-packet simulation (Table 4)

$N_t \times N_r$	Bandwidth	L2S Mapping	EESM-log-AR
1×1	20MHz	97 min	0.4 sec
1×1	40MHz	126 min	0.4 sec
4×2	20MHz	234 min	0.4 sec
4×2	40MHz	320 min	0.4 sec
8×2	20MHz	428 min	0.4 sec
8×2	40MHz	573 min	0.4 sec

Runtime of the proposed method is significantly smaller and insensitive to system dimension change

EESM-log-AR: Accuracy

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1st order performance: Average PER VS. RX SNR

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1st order performance: Average PER VS. RX SNR

2nd order performance: AutoCorrelation Function (ACF) and Partial ACF (PACF)

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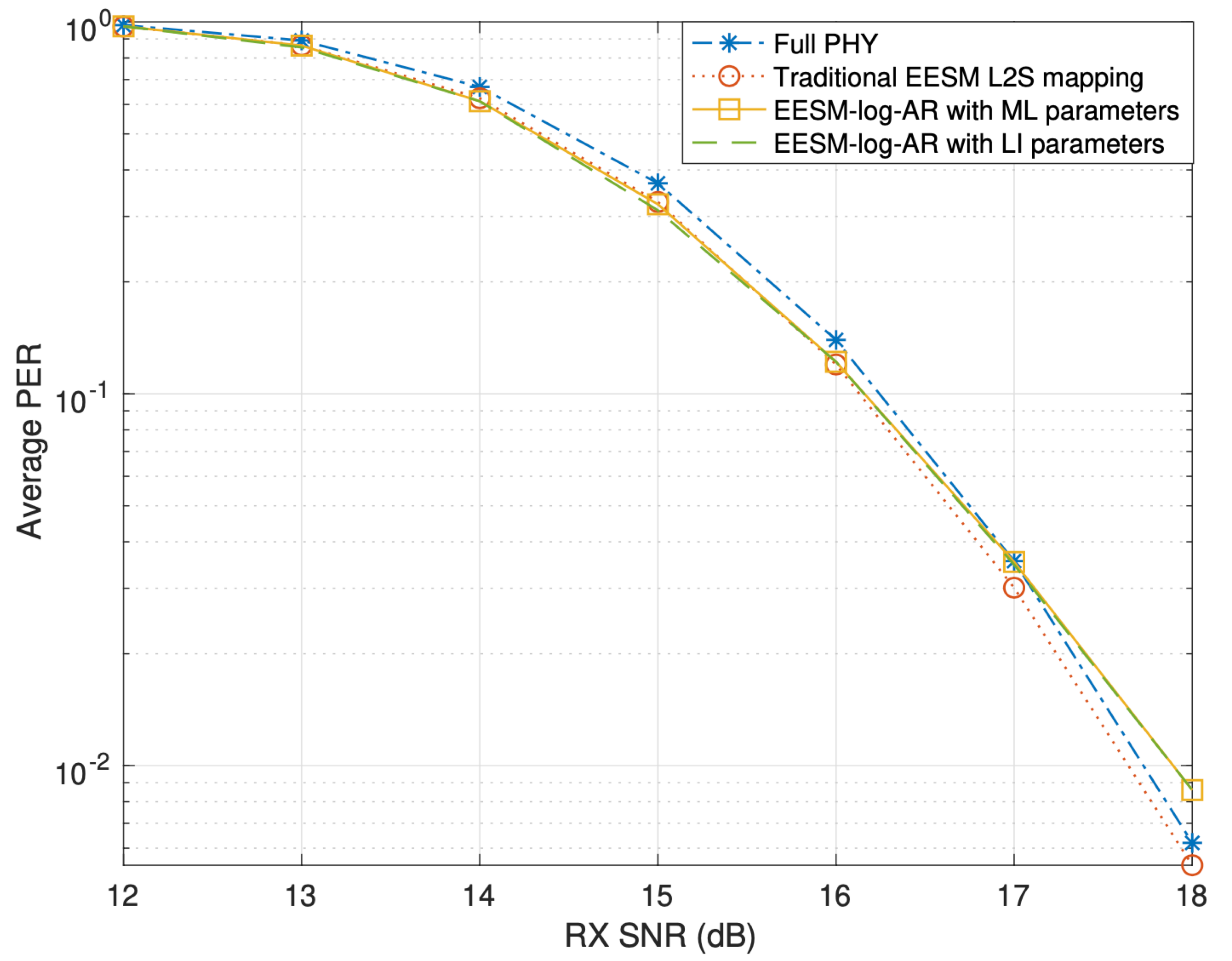
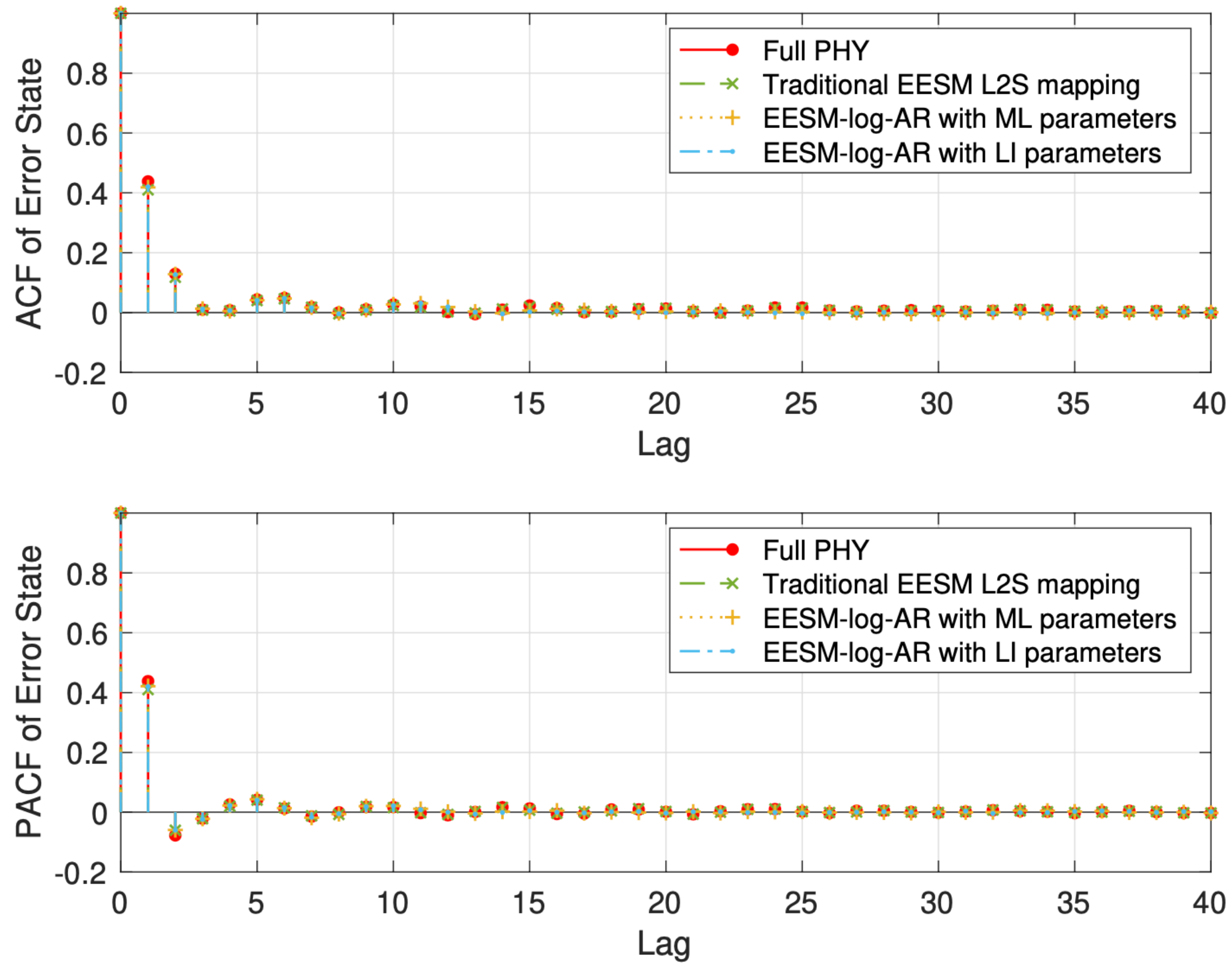
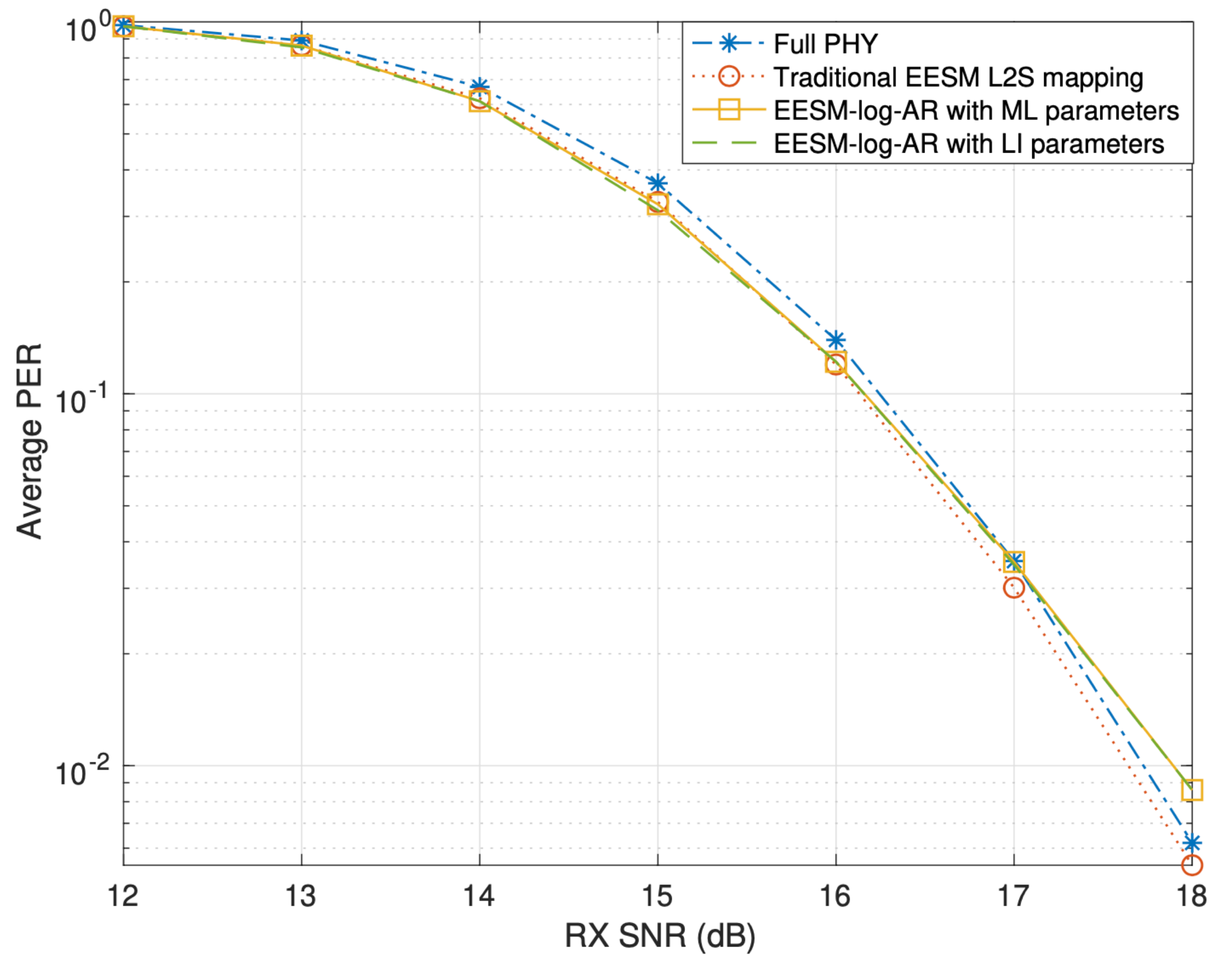


1st order performance: Average PER VS. RX SNR

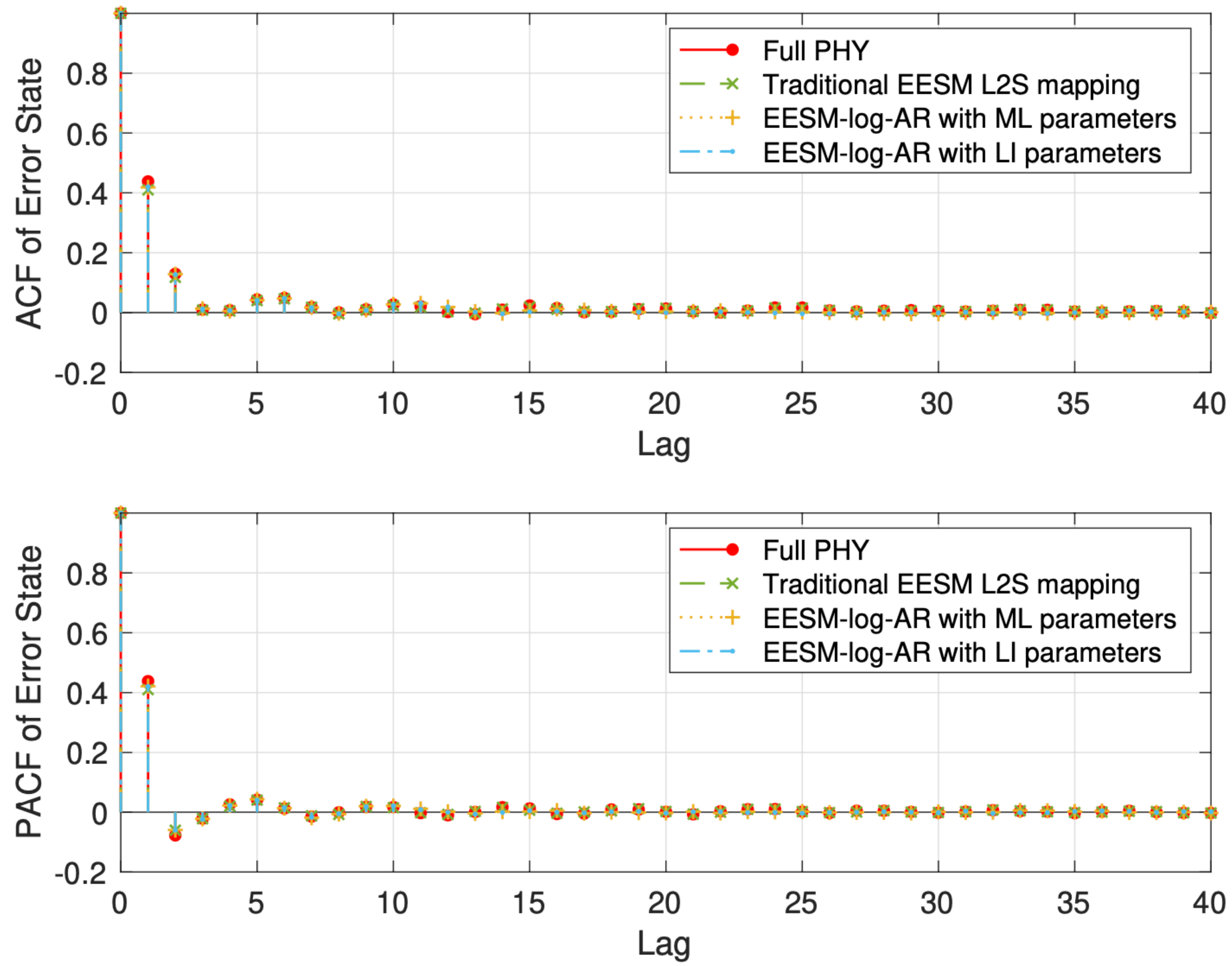


2nd order performance: AutoCorrelation Function (ACF) and Partial ACF (PACF)

EESM-log-AR: Accuracy



1st order performance: Average PER VS. RX SNR



2nd order performance: AutoCorrelation Function (ACF) and Partial ACF (PACF)

We also validated EESM-log-AR using modified LMC test & residual diagnoses

Contributions

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- Under time-varying channel, EESM-log-AR directly outputs effective SNR process rather than generating channels and calculating effective SNR on a per-packet basis

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- Payoff: good accuracy with substantial run-time improvements
- Cost: require store log-AR parameters at different PHY configurations

Contributions and Future Work

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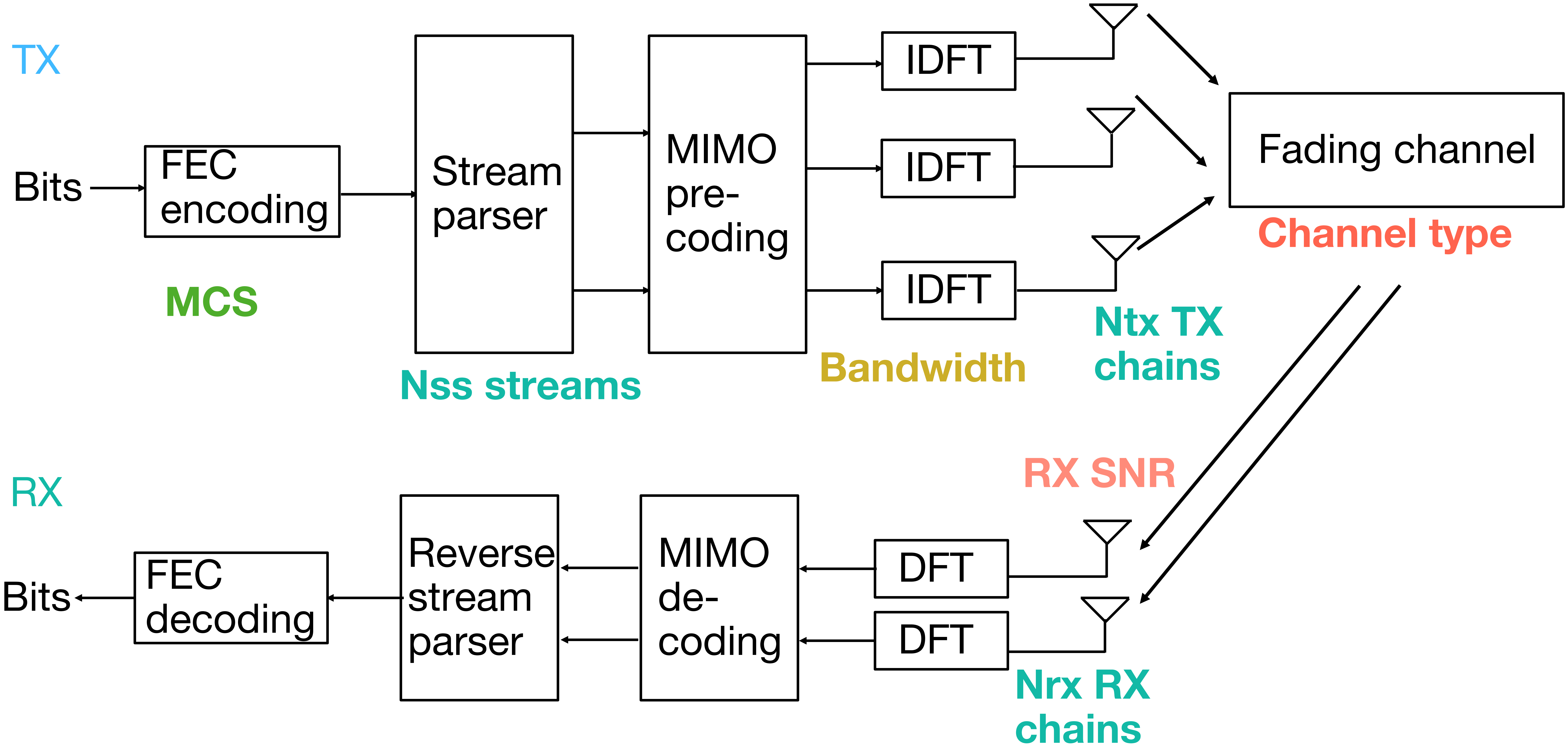
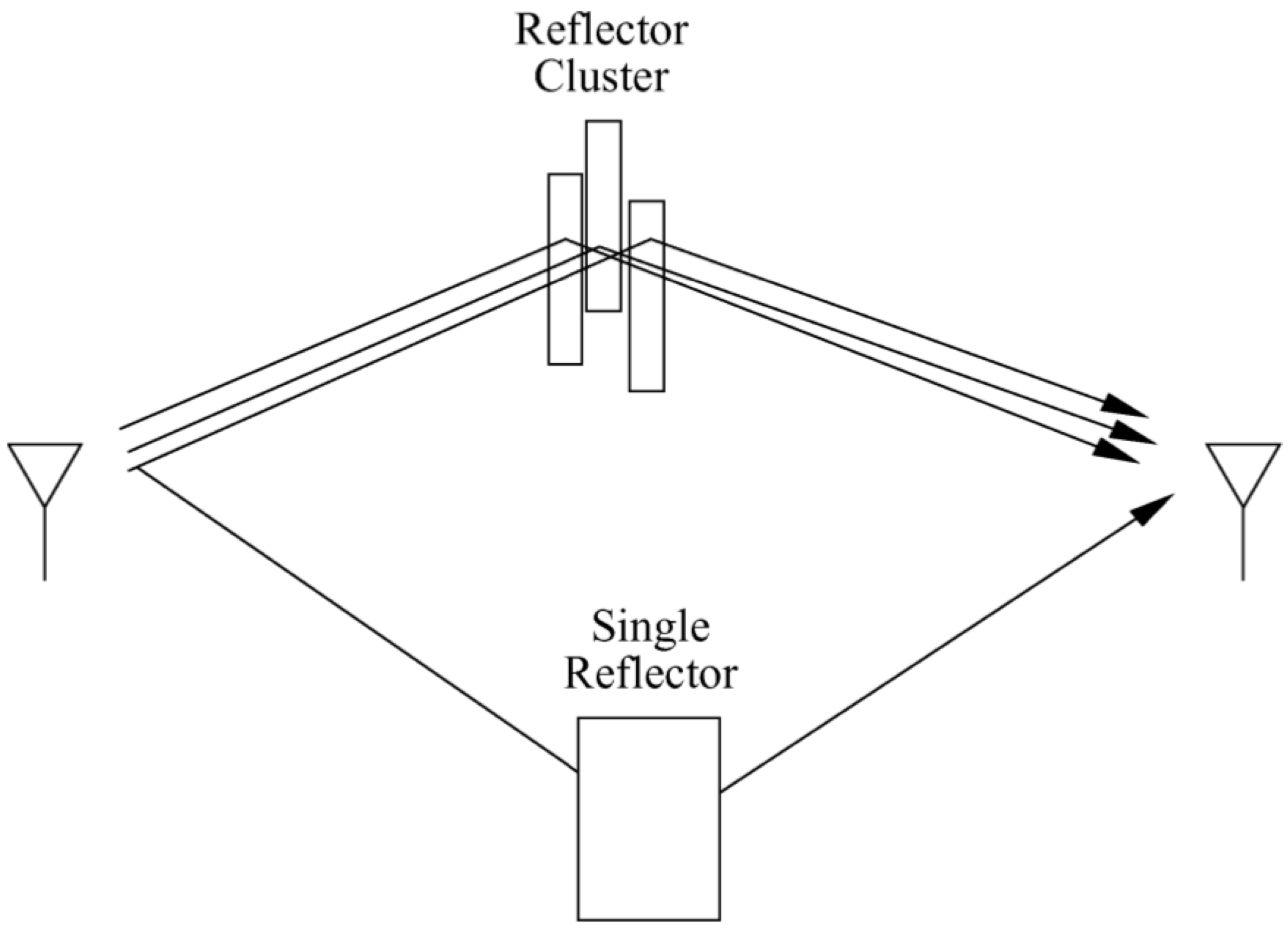
- Under time-varying channel, EESM-log-AR directly outputs effective SNR process rather than generating channels and calculating effective SNR on a per-packet basis
- Payoff: good accuracy with substantial run-time improvements
- Cost: require to store log-AR parameters at different PHY configurations
- Future work:
  - Model the impact of interference
  - Extension to OFDMA and MU-MIMO cases

Backup Slides

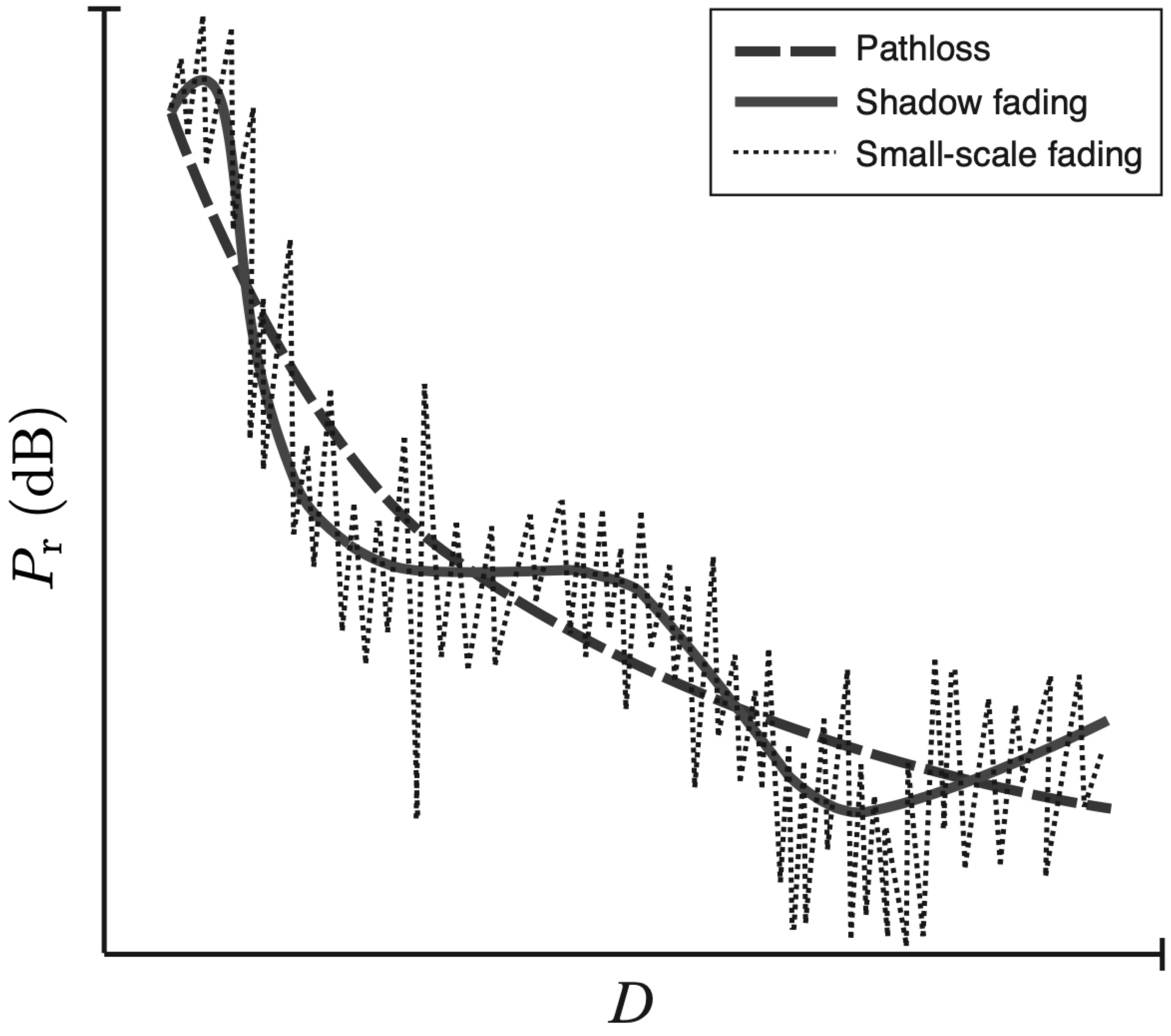
Full-PHY Block Diagram



Multi-path Propagation



Fading



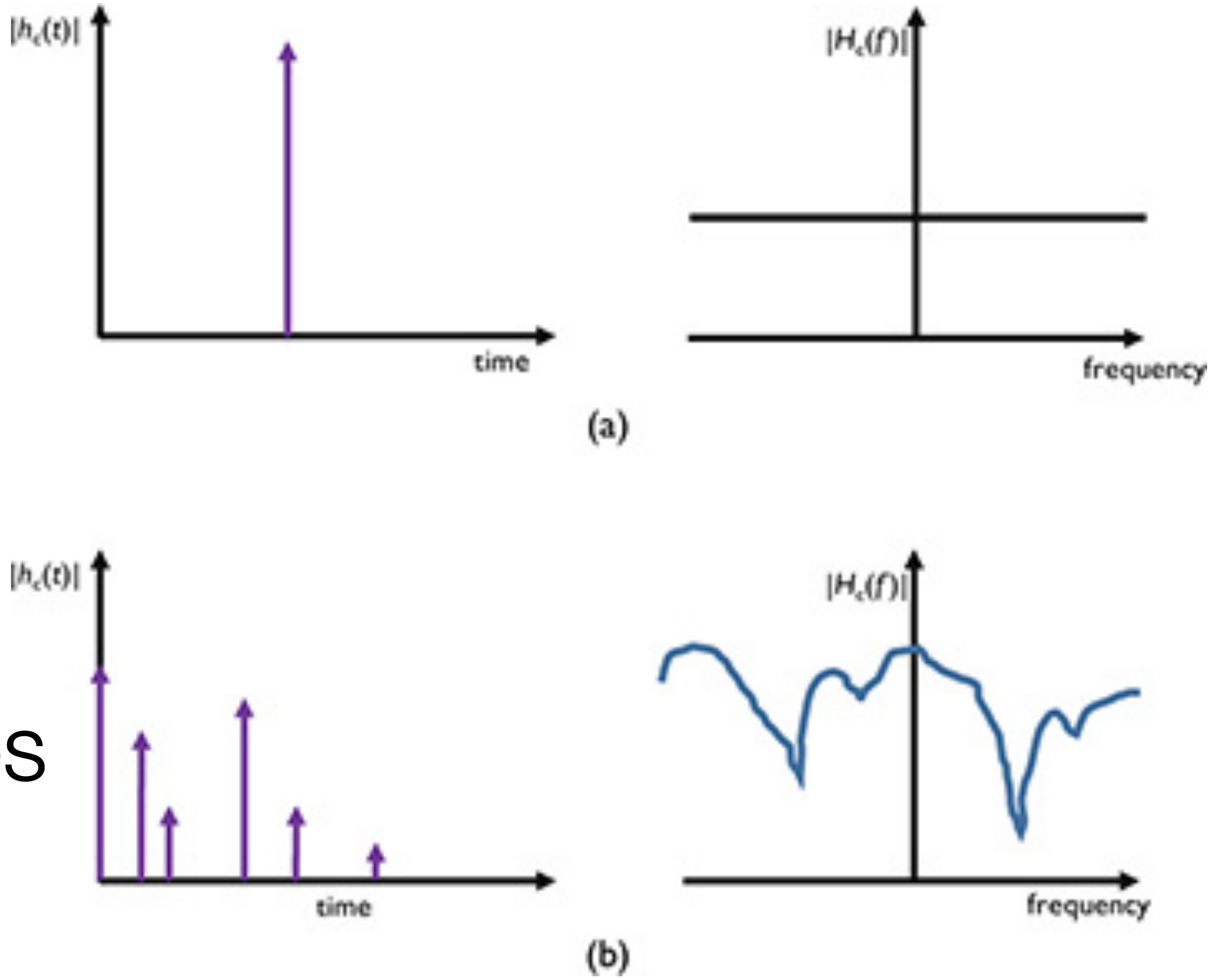
Received signal power VS. distance

Frequency-selective Channel

LOS

LOS +

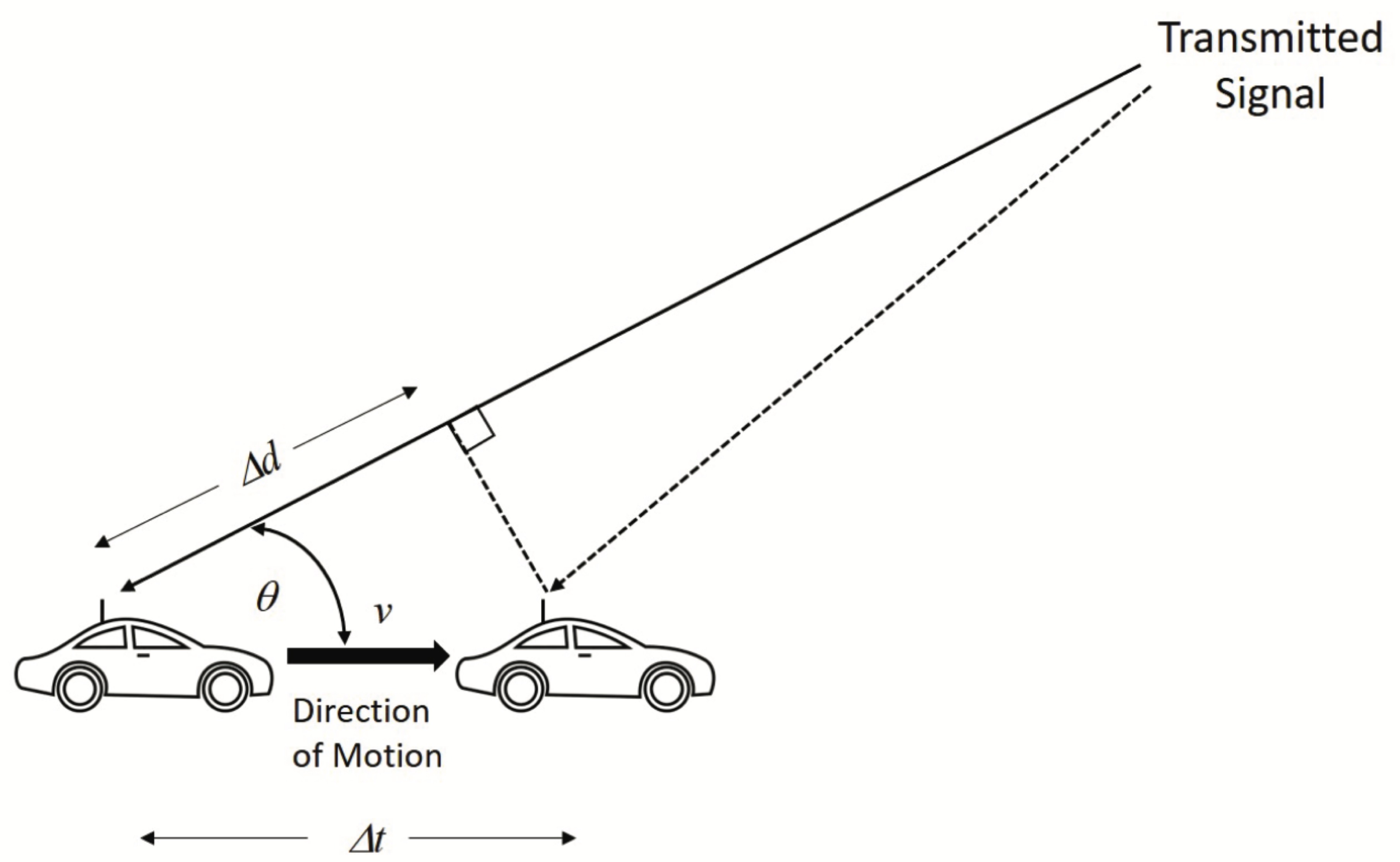
multi-path NLOS

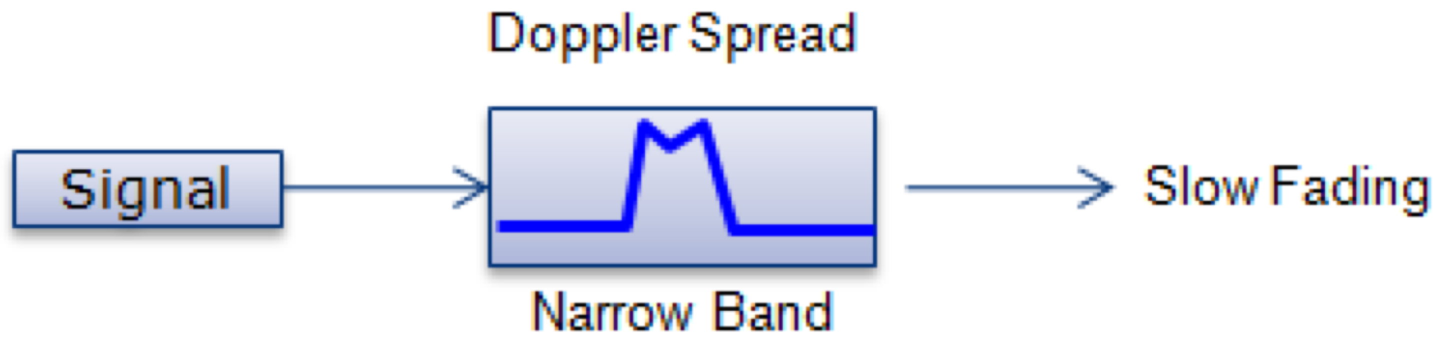


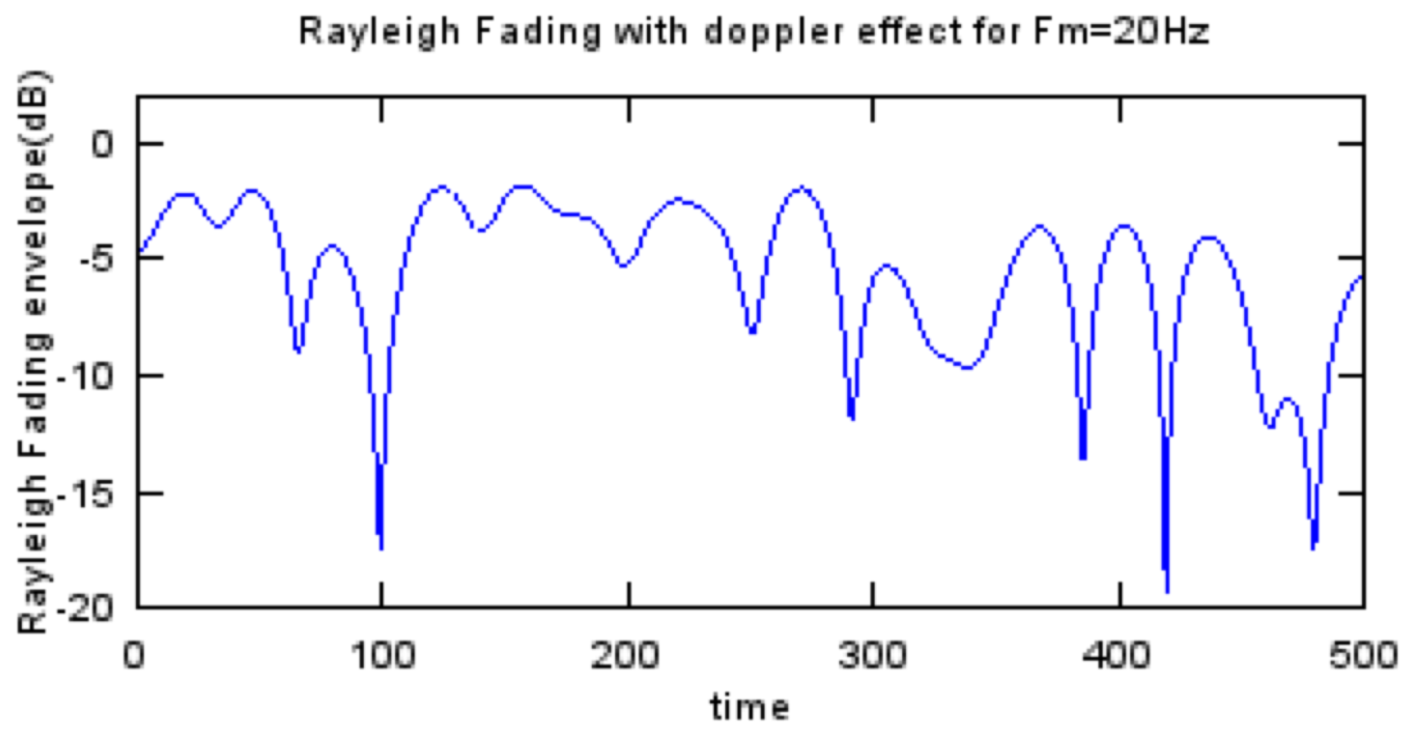
Frequency flat

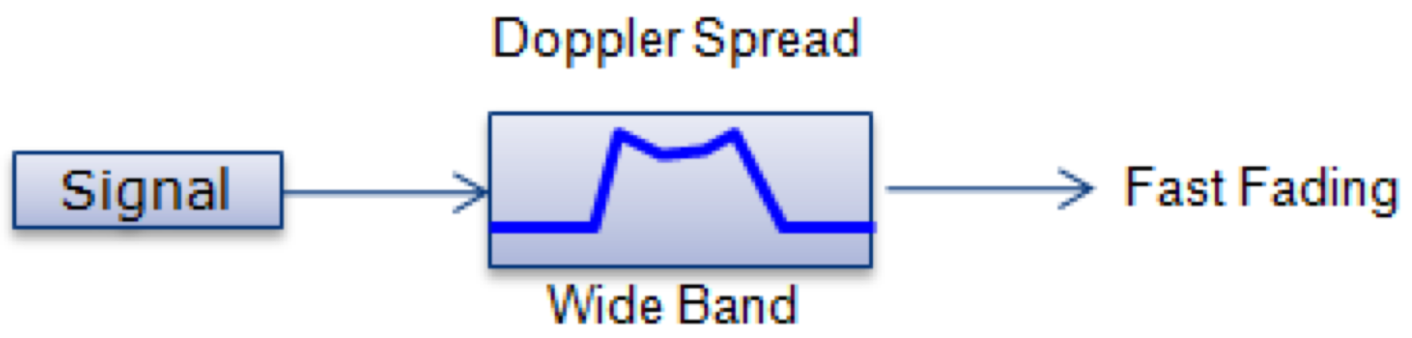
Frequency selective

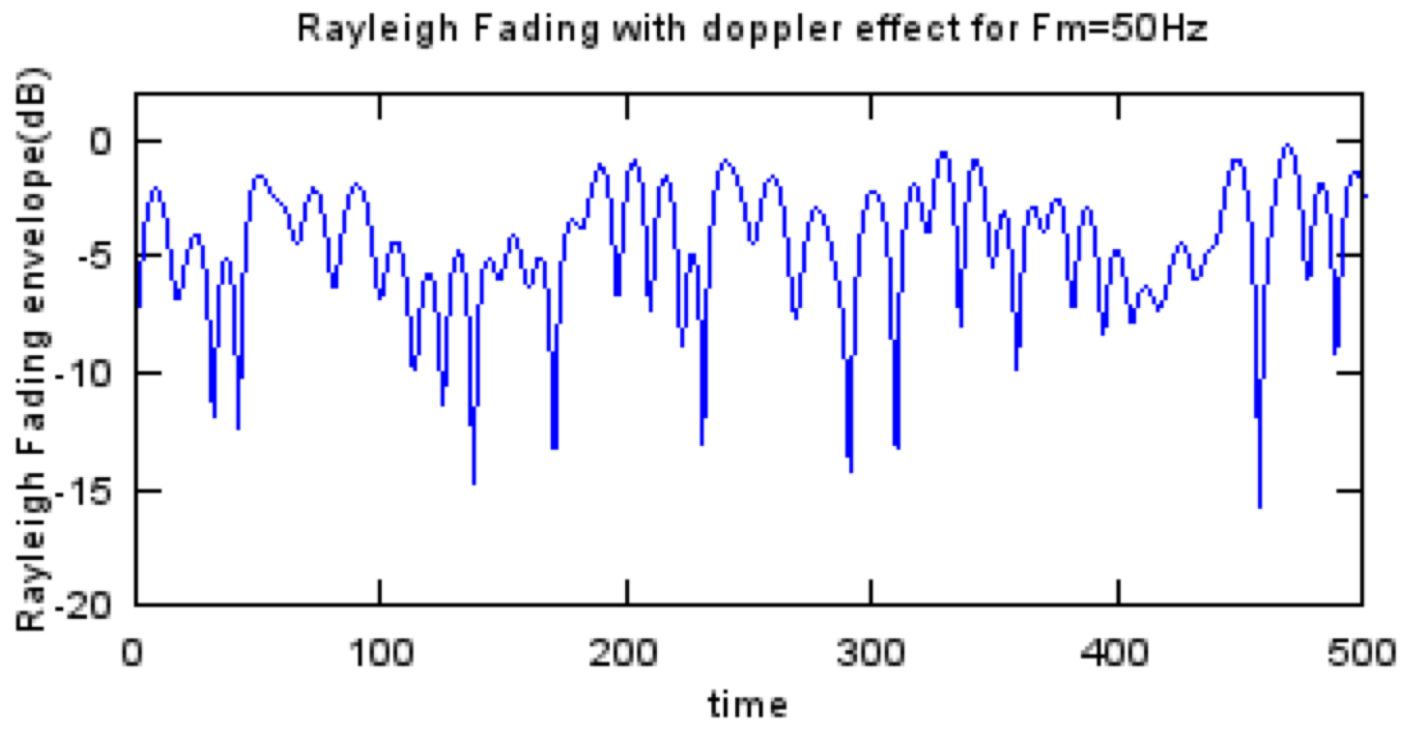
Time-varying Channel





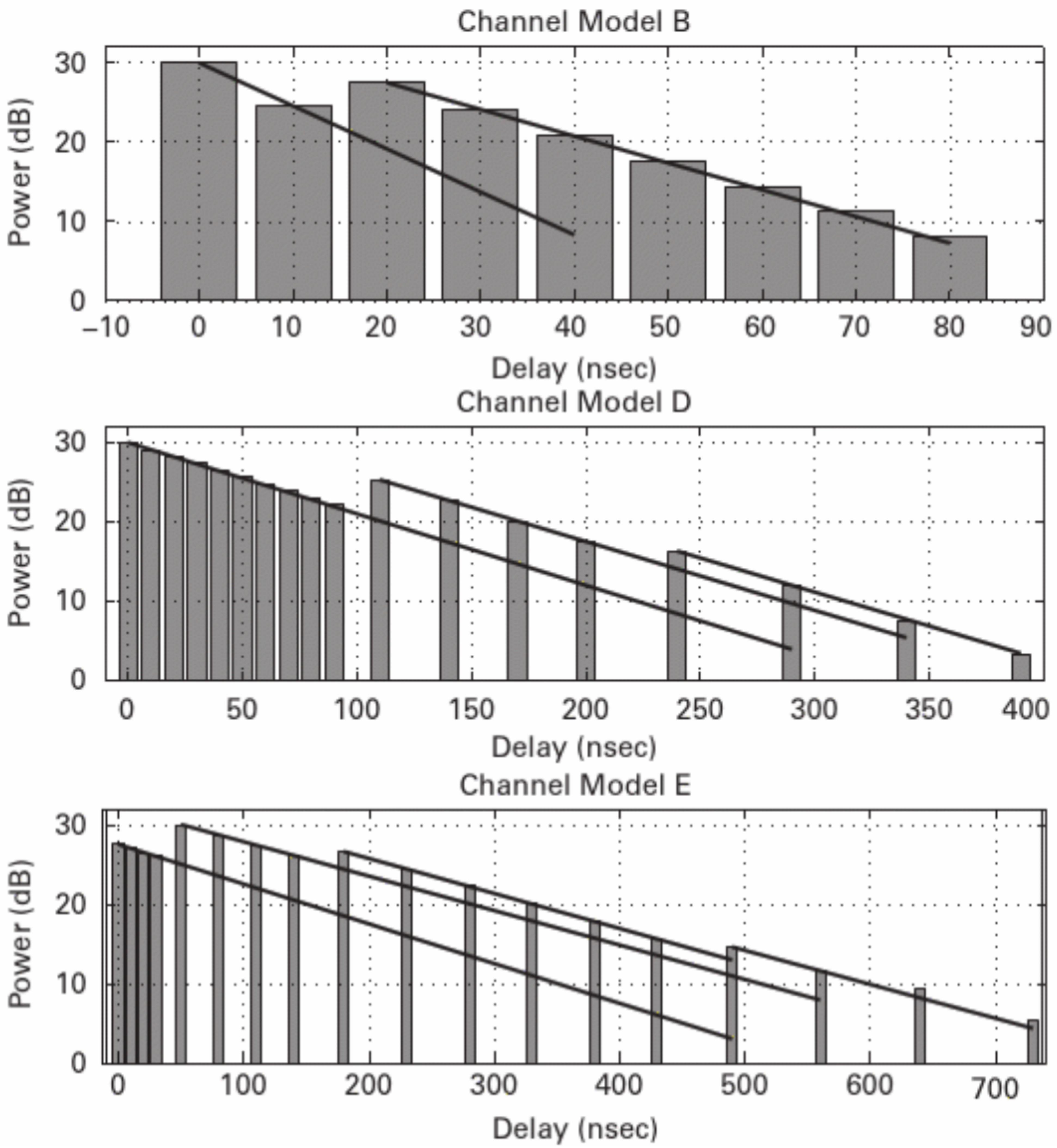






TGax Channel Models

TGax channel Models: A~F



Power Vs received multi-path signal delay

Jakes' Model

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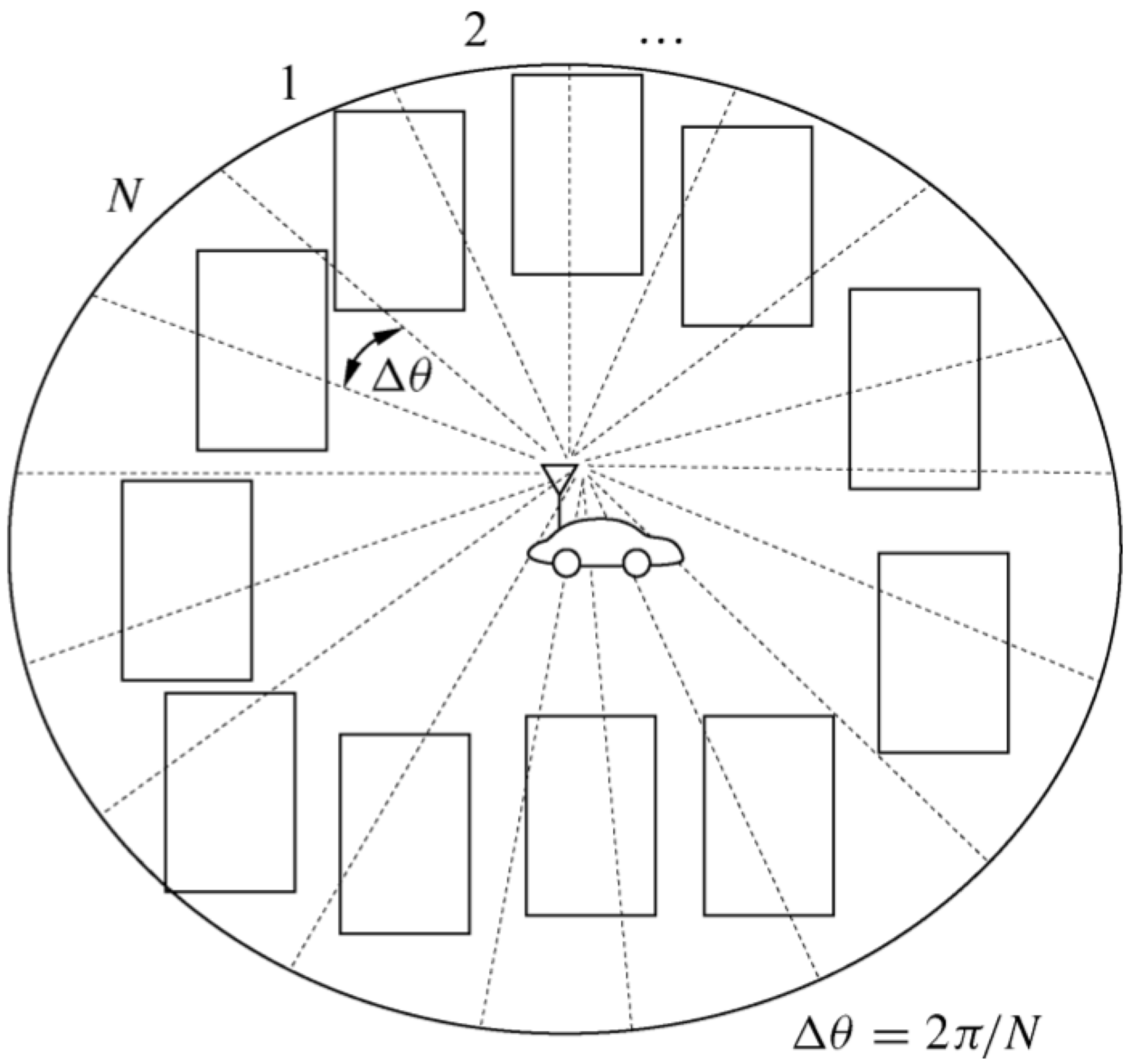
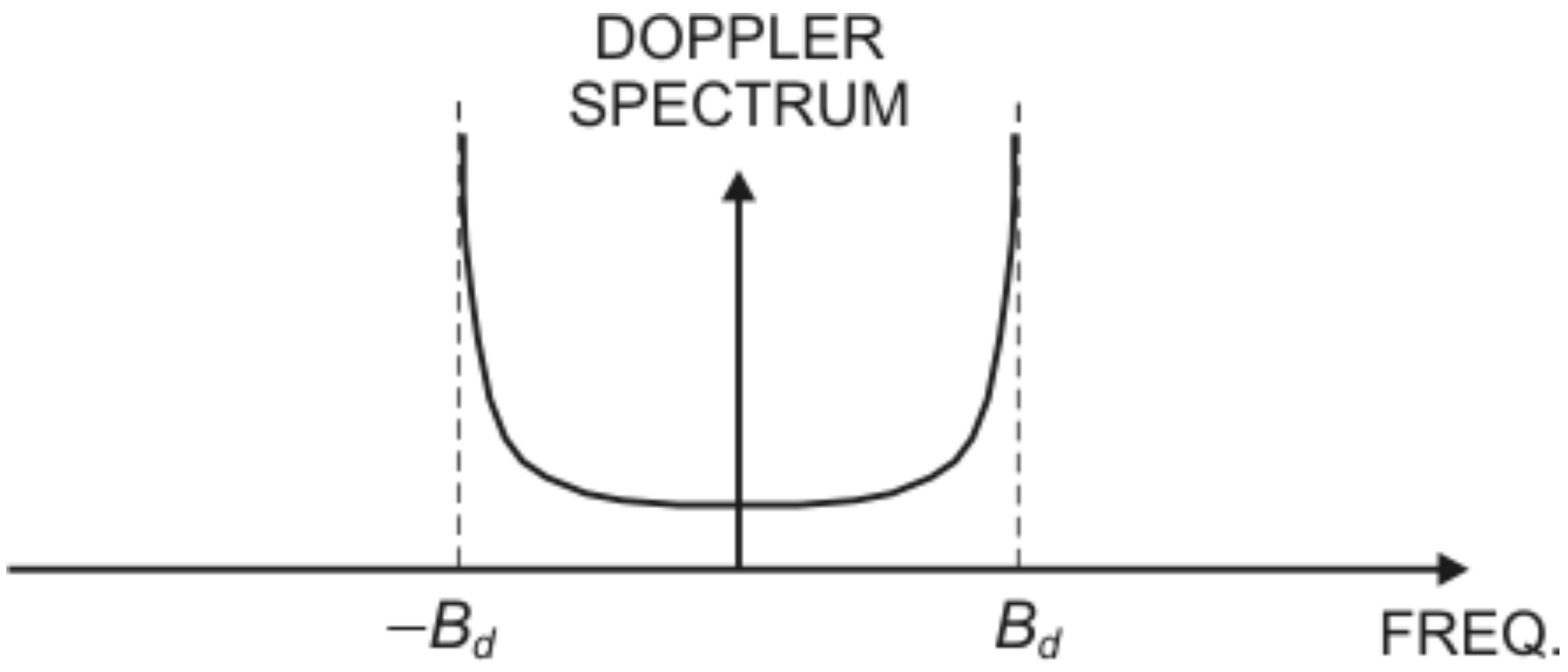


Uniform scattering environment



Doppler spectrum

PHY Layer Simulation Setup

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Communication system	IEEE 802.11ax
Link simulator	MATLAB WLAN & Communication Toolboxes R2020b
# of packets per simulation	200000
Channel type	TGax channel model-D [22]
Doppler spectrum	Jakes' model [1]
Maximum moving speed	0.089km/h [29]
Coherence time	$T_c = 0.978$s [32]
Sample period	$T_s = 0.250$s
Channel coding	LDPC
Payload length	1000
MCS	4
RX SNR	15dB
Bandwidth	20 MHz
Channel estimation	Noise-free
Phase tracking & Synchronization	Perfect
MIMO precoding/decoding	SVD/MMSE
MIMO dimension	$n_t \times n_r = 4 \times 2$
MIMO streams	$n_{ss} = 2$
CPU	Intel Core i5 CPU at 2.0GHz

Properties of log-AR process

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Properties of log-AR process:

1) fully characterized by p+2 parameters;

2) easy to generate;

3) but cannot capture skewness and kurtosis of marginal distribution well.

$$X[l] \triangleq \ln(\Gamma_{eff}[l])$$

$$X[l] = c + \sum_{m=1}^{p} \phi_m X[l-m] + \epsilon[l]$$

Traditional L2S Mapping

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- Over an OFDM/OFDMA MIMO/MU-MIMO system, abstracting the post-MIMO processing SINRs over all subcarriers and spatial streams into a a *single* scalar metric - effective SNR

L2S mapping function

$$\Gamma_{eff,k}^{sinr} = \alpha\Phi^{-1}\left(\frac{1}{n_{sc,k}}\frac{1}{n_{ss,k}}\sum_{i\in\mathcal{N}_{sc,k}}\sum_{j=1}^{n_{ss,k}}\Phi\left(\frac{\Gamma_{k,i,j}}{\beta}\right)\right)$$

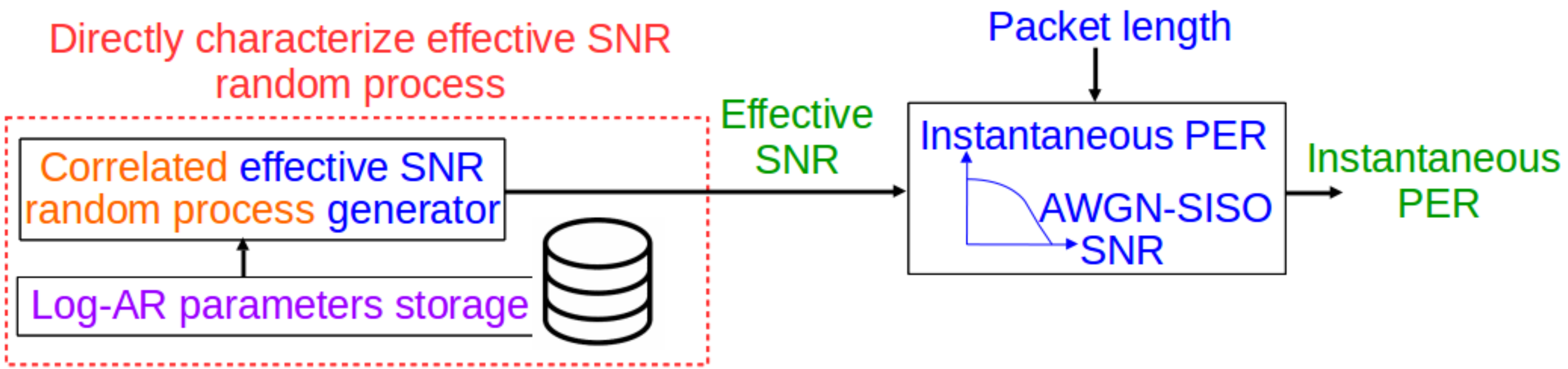
- The single effective SINR is a convenient metric to describe the packet-level performance for a network simulator

- 2 popular L2S mapping functions: EESM and RBIR

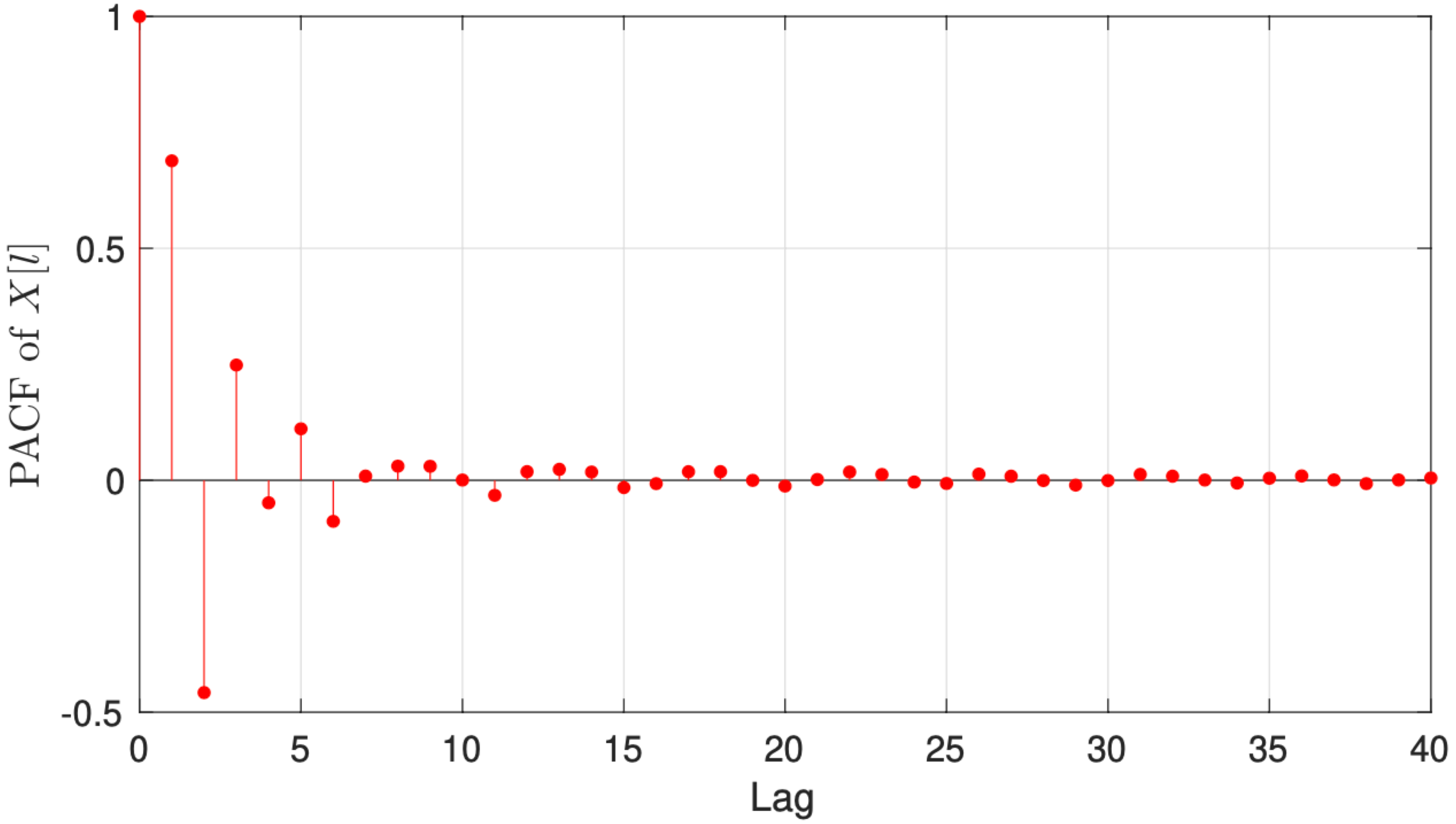
- For EESM, $\Phi(x) = \exp(-x)$ and $\alpha = \beta$

$$\Gamma_{eff,k}^{sinr} = -\beta\ln\left(\frac{1}{n_{sc,k}}\frac{1}{n_{ss,k}}\sum_{i\in\mathcal{N}_{sc,k}}\sum_{j=1}^{n_{ss,k}}\exp\left(-\frac{\Gamma_{k,i,j}}{\beta}\right)\right)$$

EESM-log-SGN


Directly characterize effective SNR random process
Correlated effective SNR random process generator
Log-AR parameters storage
Effective SNR
Packet length
Instantaneous PER
AWGN-SISO
SNR
Instantaneous PER

PACF of Effective SNR Processes



ML Estimation of Log-AR Parameters

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RX SNR γ	$\hat{c}(\gamma)$	$\hat{\phi}_1(\gamma)$	$\hat{\phi}_5(\gamma)$	$\hat{\phi}_9(\gamma)$	$\hat{\sigma}^2_{10}(\gamma)$
12dB	0.5764	1.3454	0.3685	0.0607	0.0076
13dB	0.6525	1.2702	0.3068	0.0474	0.0085
14dB	0.7297	1.2047	0.2561	0.0370	0.0096
15dB	0.8093	1.1443	0.2128	0.0294	0.0112

Storage-complexity aspect

Handling wide range of RX SNRs: challenge & principle

- Fact: effective SNR depends on RX SNR
- Challenge: cannot store effective SNR process under any RX SNR
- Solution: estimate effective SNR process for any RX SNR using a small # of stored effective SNR processes - Linear Interpolated (LI) log-AR parameter estimation

$$\hat{c}(\gamma) = (1-\epsilon)\hat{c}(\gamma_1) + \epsilon\hat{c}(\gamma_2),$$
$$\hat{\phi}_m(\gamma) = (1-\epsilon)\hat{\phi}_m(\gamma_1) + \epsilon\hat{\phi}_m(\gamma_2), \quad m = 1, 2, \ldots, p,$$
$$\hat{\sigma}_p^2(\gamma) = (1-\epsilon)\hat{\sigma}_p^2(\gamma_1) + \epsilon\hat{\sigma}_p^2(\gamma_2)$$

$$\epsilon = \frac{\gamma-\gamma_1}{\gamma_2-\gamma_1}$$

Estimated parameters

Stored parameters

Sample Paths of Effective SNR Processes

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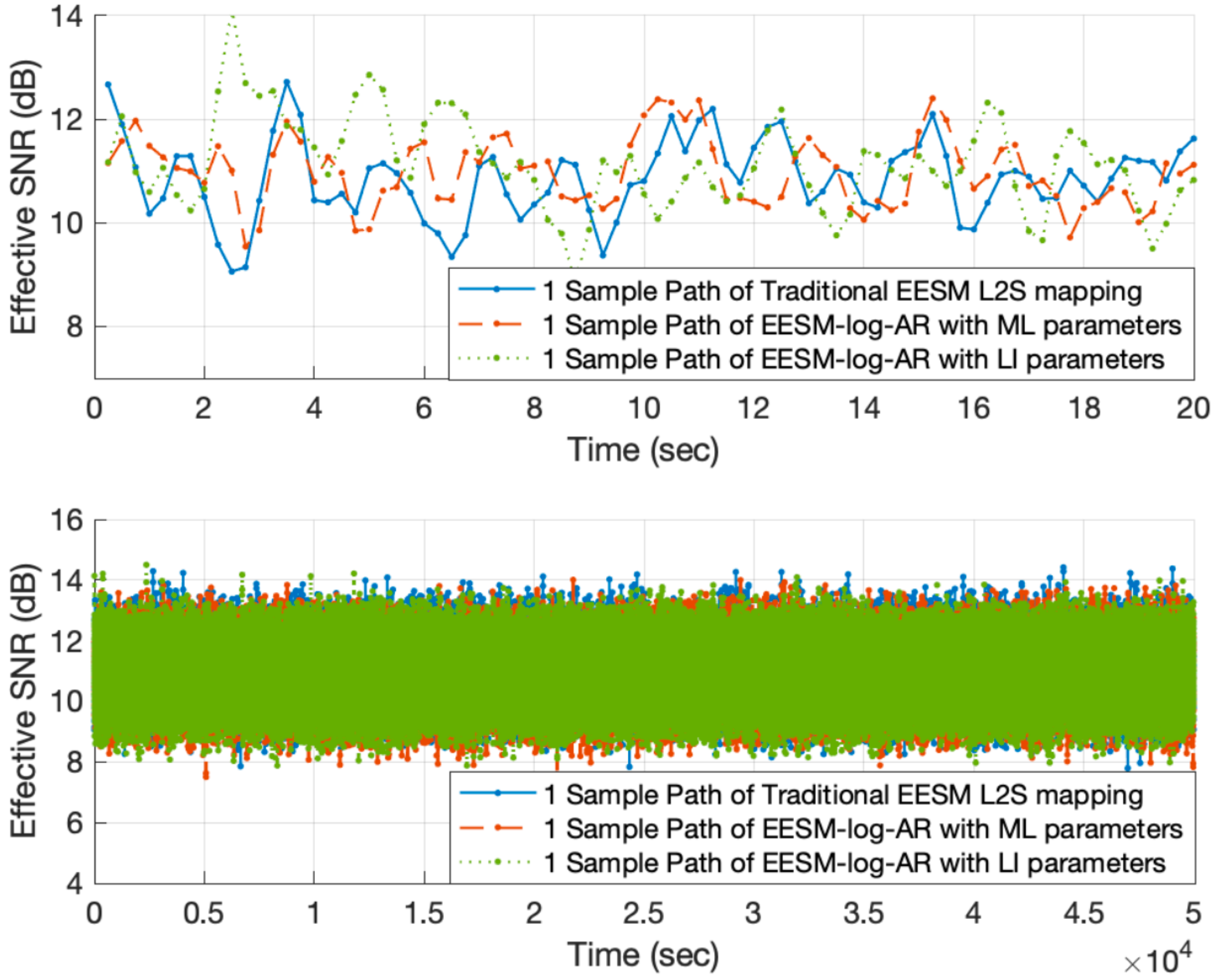


Residual Definition

- AR model

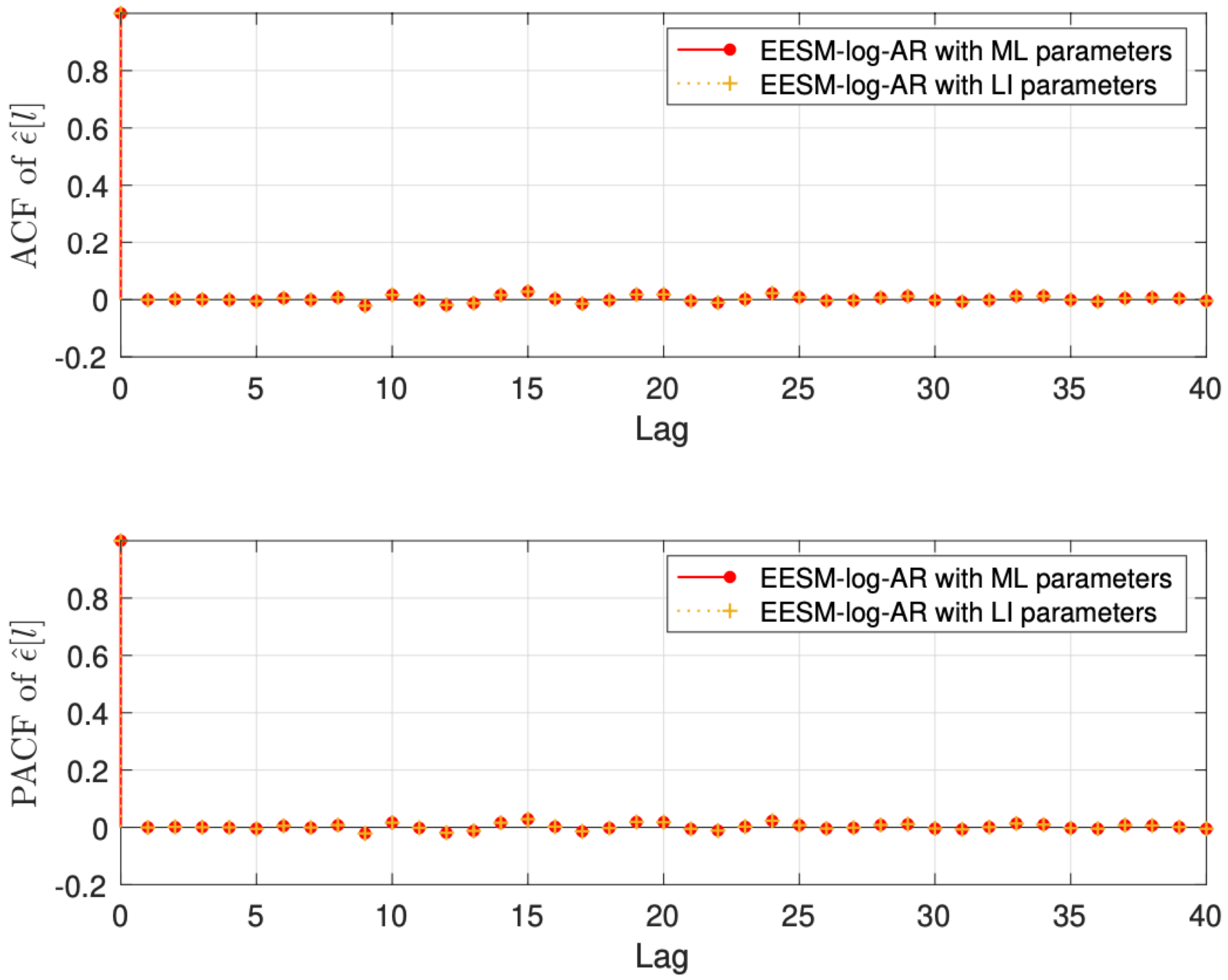
$$X[l] = c + \sum_{m=1}^{p} \phi_m X[l-m] + \underline{\epsilon[l]}$$

zero-mean white Gaussian process with a constant variance

- Residual

$$\hat{\epsilon}[l] \triangleq X[l] - \hat{c}(\gamma) - \sum_{m=1}^{p} \hat{\phi}_m(\gamma) X[l-m]$$

Residual Whiteness Test

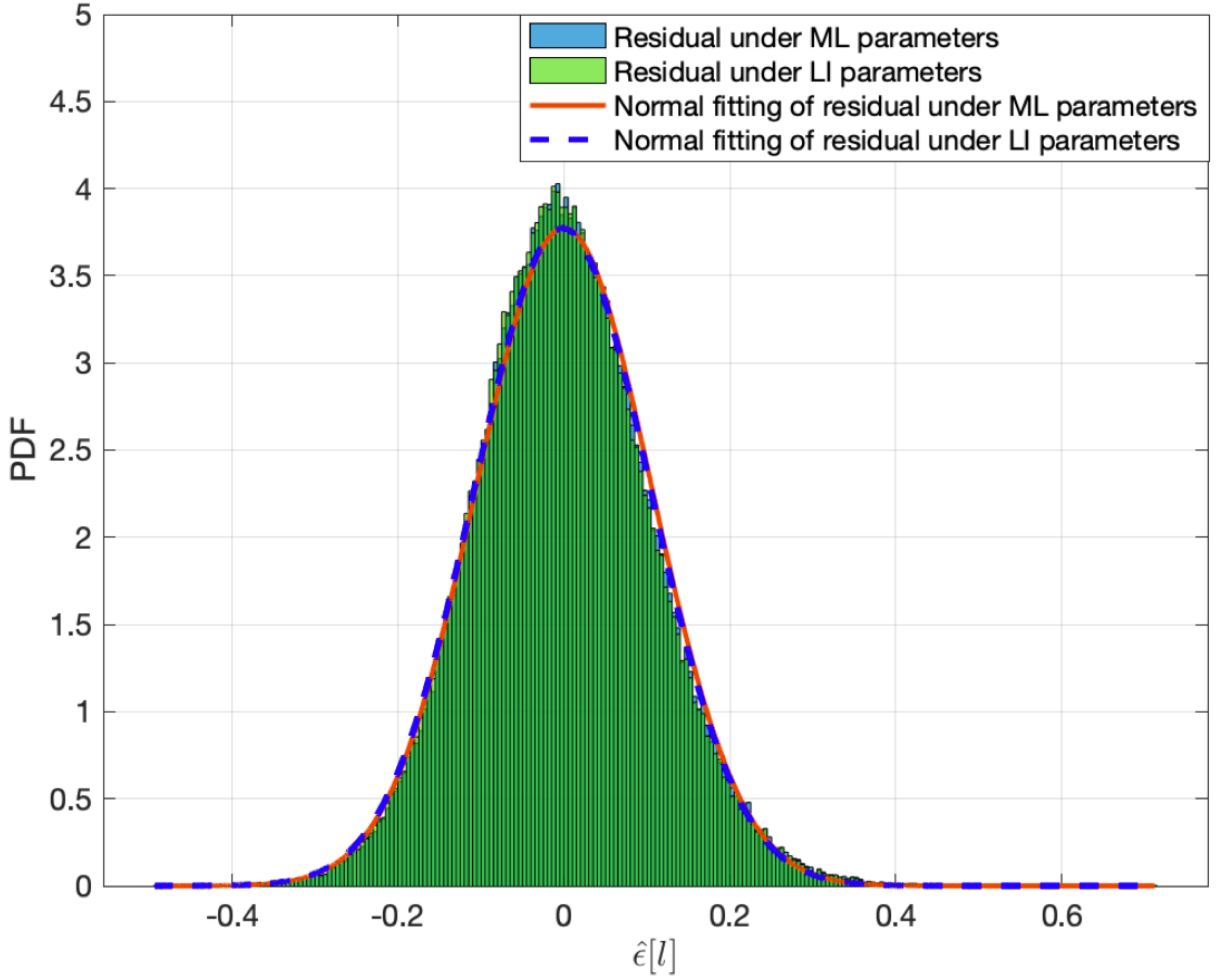


Check whether residual is white

Modified Leybourne- McCabe (LMC) Test

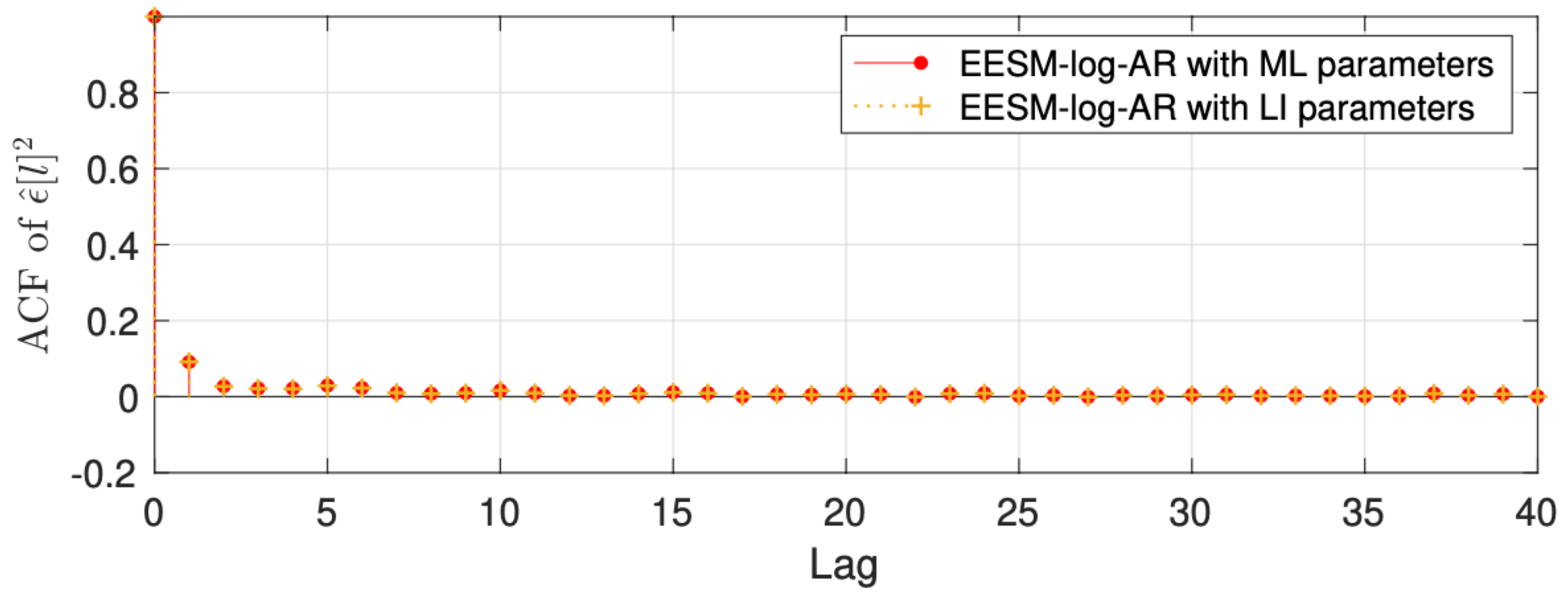
- Null hypothesis: $X\ [l]$ is a stationary AR(p) process
- Our simulation: the modified LMC test fails to reject the null hypothesis with a large p-Value (> 0.05)
- Thus, $X\ [l\ ]$ is stationary and can be modeled as an AR(p) process

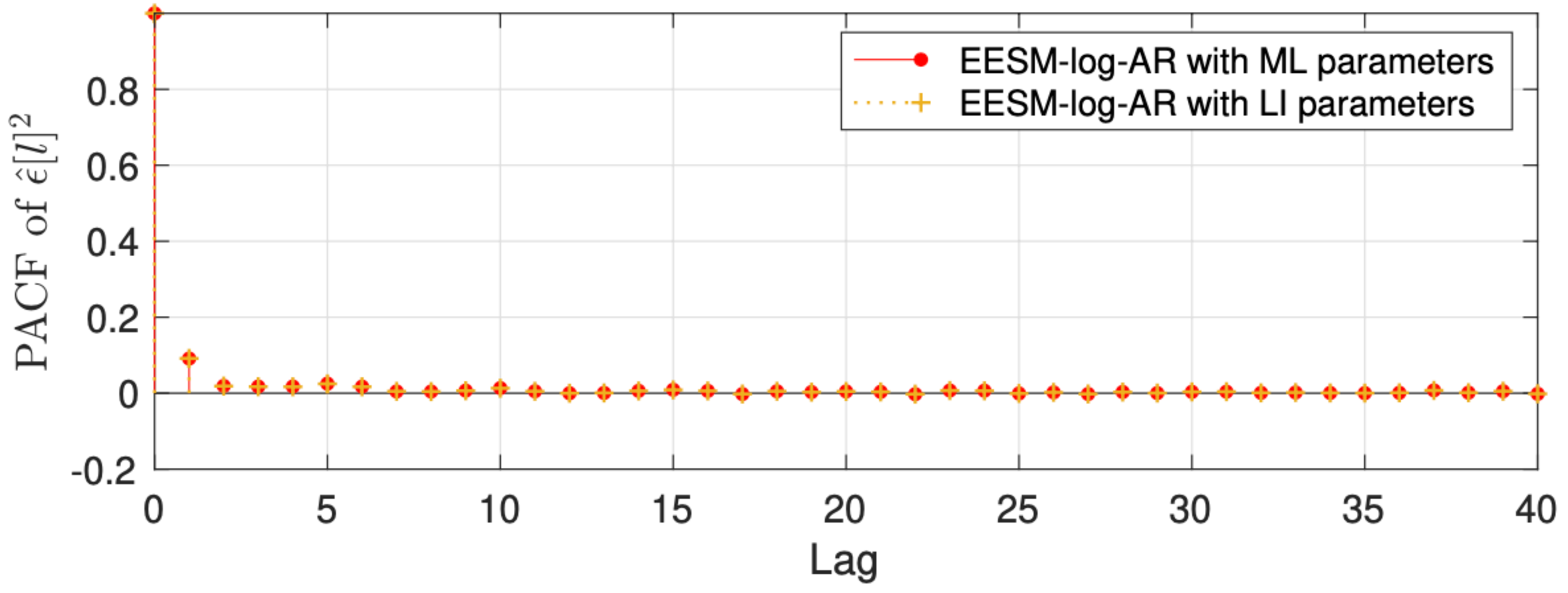
Residual Distribution



Check whether residual~Gaussian distribution

ACF and PACF of Squared Residual





Check whether residual has constant variance

Comparison

- EESM-log-SGN VS EESM-log-AR:
  - EESM-log-SGN model is more accurate for IID channel
  - EESM-log-AR has wider applicability as it is modeled for the general time-varying channel

Extension to 5G

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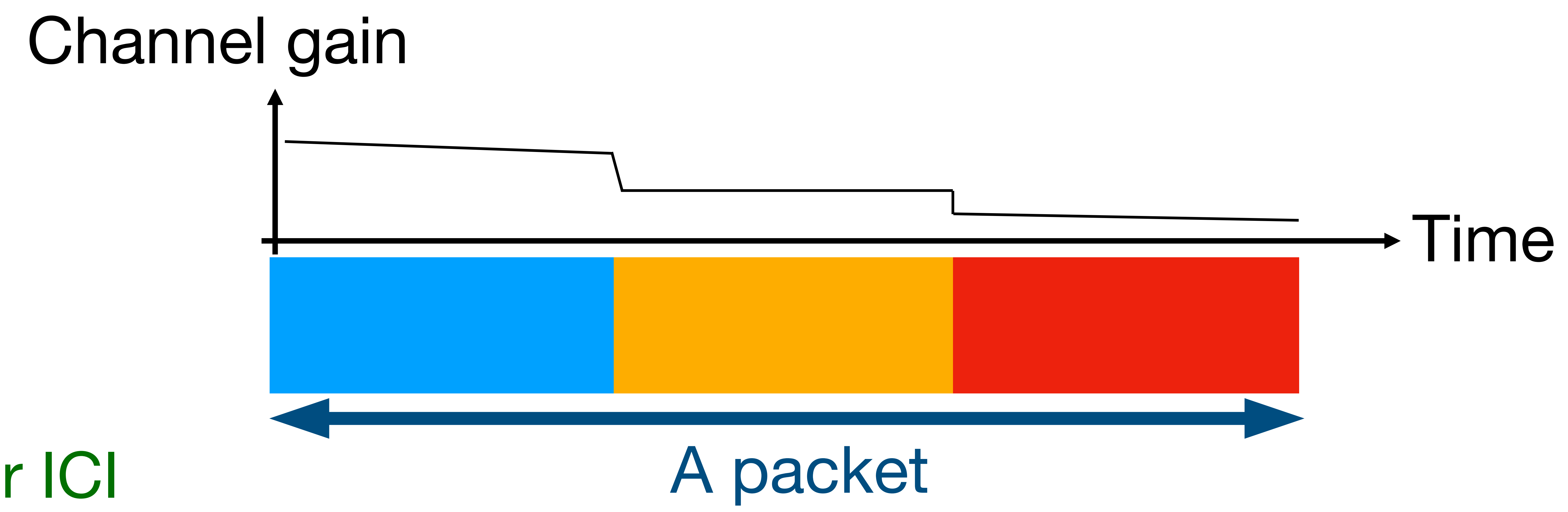
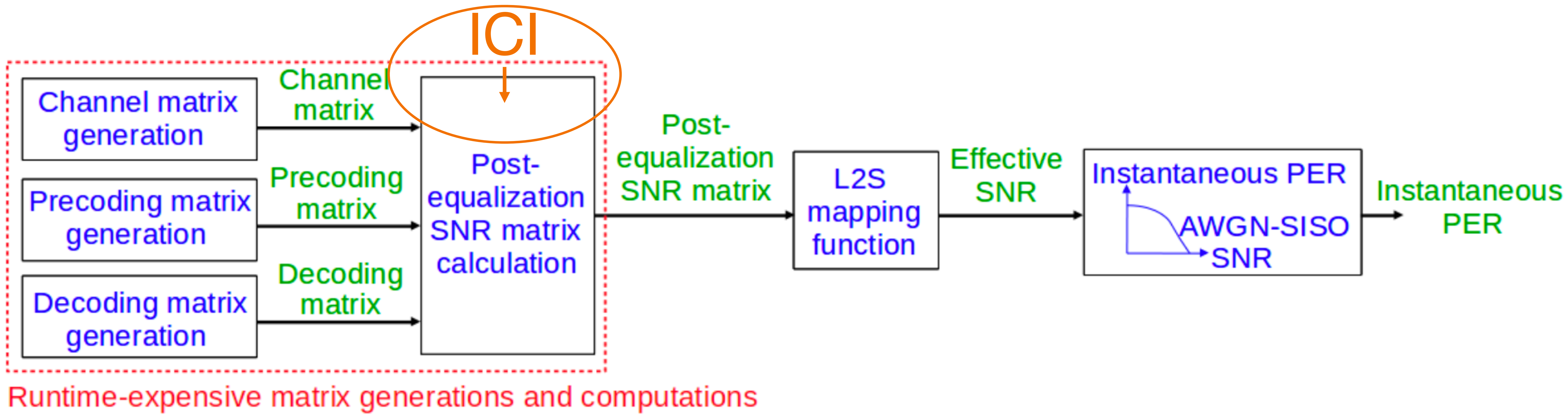
- Inherent assumption for WiFi:
  - Slow fading (channel gain does not change in a packet duration)
  - No inter-carrier interference or ICI (extreme low Doppler)
- Extension to 5G
  - Fast fading
  - ICI introduced by Doppler

Extension to 5G

- Fast fading



- Consider ICI



Interference Scenario