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Chaos-based anytime reliable coded communications over fading channels with and without information aging

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Outline

1. Introduction and motivation
2. AS-CCM
3. AB-CCM
4. Ax-CCM on fading channels
5. Simulation results
6. Conclusions

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Introduction and motivation

- Control systems where observer and controller are not co-located (e.g., wireless sensor/actuator networks) are of increasing interest
  - As a consequence, the measurements received at the controller are often impaired by noise, fading, etc.
- Error-correction coding can enhance the reliability of received measurements
  - To obtain stability in the controlled system, anytime reliability (AR) must be achieved!

Introduction and motivation

- Define the error probability at time *t* for a symbol transmitted at time *t-d* as $P_e(t, d)$
  - *d* is the delay, which is an important variable in remote control

- The codec scheme is said to be anytime reliable if

$$P_e(t,d) < K\mathrm{e}^{-\beta d}, \;\; \forall t,\, d > d_0$$

  - β is the anytime exponent of the codec scheme

Introduction and motivation

- In [1], on AWGN channel, we introduced two codec schemes, based on chaos-coded modulation (CCM):
  - Adaptive-size CCM (AS-CCM), which has fixed spectral efficiency and adaptive instantaneous power
  - Adaptive-bandwidth CCM (AB-CCM), with adaptive spectral efficiency and instantaneous power

- In this paper, we analyze their performance on fading channels.

[1] A. Tarable and F. J. Escribano, "Chaos-Based Anytime-Reliable Coded Communications," *IEEE Systems Journal*, vol. 14, no. 2, pp. 2214-2224, June 2020

AS-CCM

- It is based on a given chaotic map f from [0,1] to [0,1] with invariant pdf F_f
- We define a mapper M_f, specific for map f, which is able to map a semiinfinite binary sequence $\mathbf{b} = (b_0, b_1, \ldots)$ into a real value in [0,1]
- In the next slide, the steps of AS-CCM encoding are given

AS-CCM

- Ideally, given **b**, we first form a sequence of chaotic samples z_1, z_2, … as

$$z_n = \begin{cases} \mathscr{M}_f(\mathbf{b}), & n = 1 \\ f^{(\delta_n)}(z_{n-1}), & n > 1 \end{cases}$$

- δ_n is a nonnegative integer and $f^{(\delta_n)}$ means that the chaotic map f is applied δ_n times

AS-CCM

- Then the quantized chaotic samples are obtained as

$$z_n^Q = F_f\left(\mathscr{Q}_U^{(q_n)}\left(F_f^{-1}(z_n)\right)\right)$$

  – $Q^{(q_n)}{}_U$ is a uniform quantizer on [0,1] with 2^{q_n} levels

- In practice, by a suitable choice of the mapper, the *n*-th quantized sample can be written as

$$z_n^Q = \mathscr{M}_f\left([\mathbf{b}_{\varepsilon_n}^n, 0, 0, \ldots]\right)$$

  – where $q_n = n - \varepsilon_n + 1$ and $\delta_n = \varepsilon_n - \varepsilon_{n-1}$

AB-CCM

- In AB-CCM, given a map *f*, we first choose a pair of initial conditions *z*(0), *z*(1) in [0,1]
- Symbol transmitted at time *n* is

$$\mathbf{s}_n = \left(s_n^1, \cdots, s_n^{q_n}\right)$$

through $q_n = n - \varepsilon_n + 1$ orthogonal channels, where

$$s_n^i = \begin{cases} f\left(s_{n-1}^{i-1}\right), & i > 1 \\ f\left(z^{(b_n)}\right), & i = 1 \end{cases}$$

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AB-CCM

- For both schemes, the receiver decodes ML and feeds back to the TX the value of ε_n, the index of the oldest information bit which is not yet reliably decoded

- Both techniques are anytime reliable on the AWGN provided that some conditions are met on the scheme and on the channel

Ax-CCM on fading channels

- Signal received when AS-CCM is used

$$r_n = \alpha_n s_n + w_n,$$

where α_n is the fading coefficient

- Signal received when AB-CCM is used

$$r_n^{(i)} = \alpha_n^{(i)} s_n^{(i)} + w_n^{(i)}, \; i = 1, \ldots, q_n.$$

  - For AB-CCM, we will consider flat fading, i.e.,

$$\alpha_n^{(i)} = \alpha_n, \qquad i = 1, \ldots, q_n$$

Simulation results

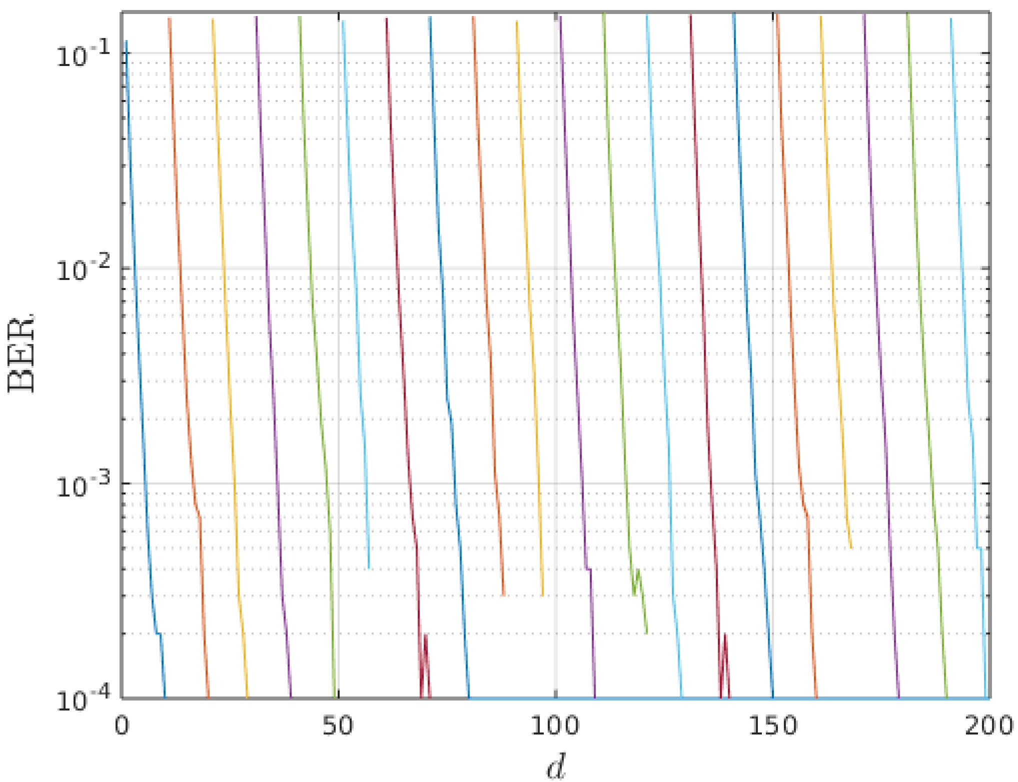
- 3 different scenarios for the flat Rician fading channel:
  - Perfect CSI at RX.
  - Perfect CSI at TX, with a threshold on the channel coefficients prior to channel gain inversion.
  - Perfect CSI at TX, with thresholding + information aging effect (channel gain information is fed back only every *B* blocks).
- We will present the results in terms of BER evolution as a function of the different system parameters:
  - Noise power, channel *K*-factor, maximum Doppler shift, threshold, updating frequency.

Simulation results

AS-CCM

- Perfect CSI at RX
- $\sigma^2 = 0.5$
- $K = 7$ dB
- $f_{max,d} = 10^{-2}$ Hz

AR is preserved

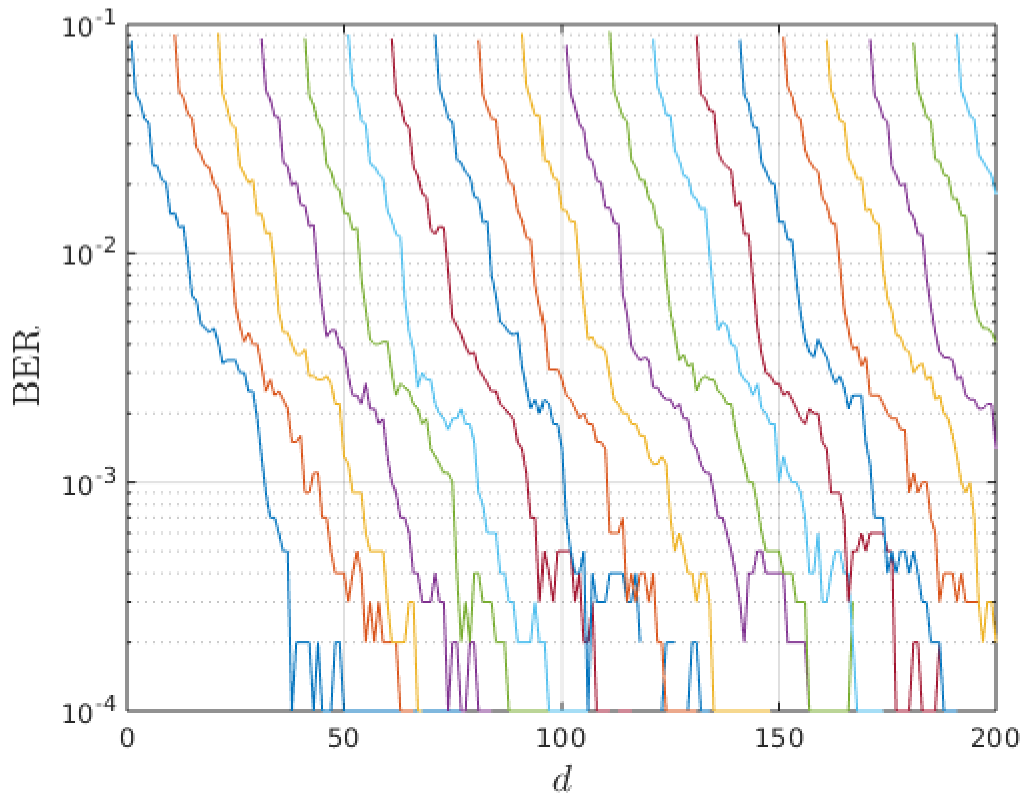


Simulation results

AB-CCM

- Perfect CSI at RX
- $\sigma^2 = 0.25$
- $K = 7$ dB
- $f_{max,d} = 10^{-2}$ Hz

AR is preserved

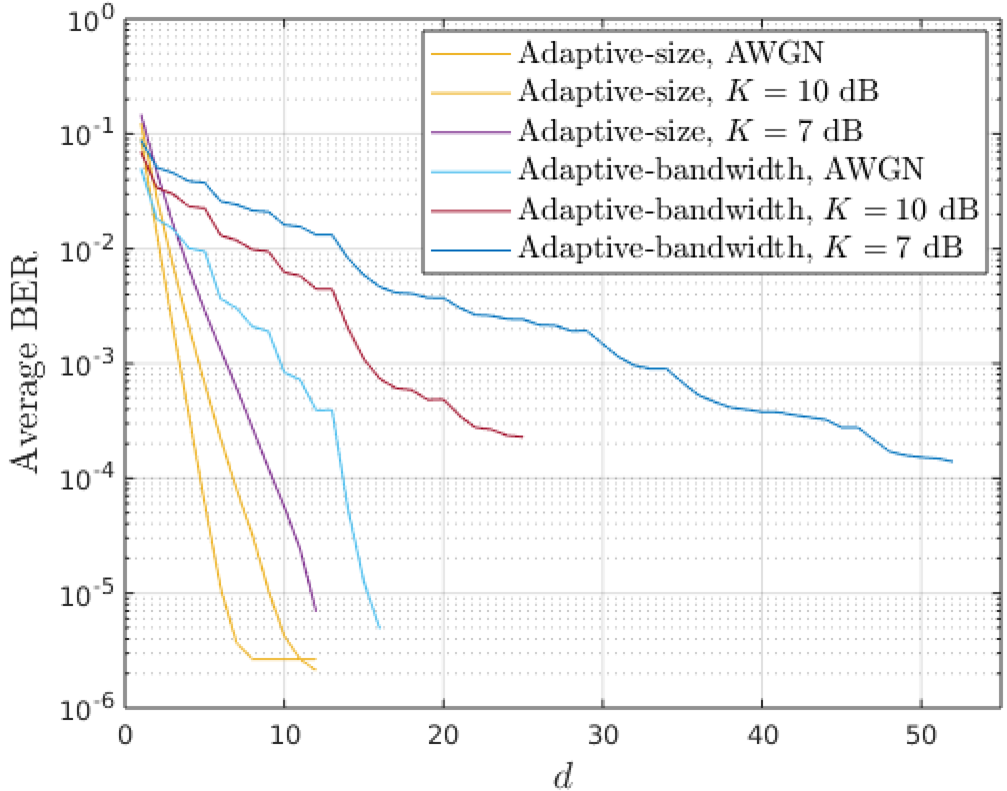


Simulation results

Average BER

- Perfect CSI at RX
- $\sigma^2 = 0.5$ (AS-CCM)
- $\sigma^2 = 0.25$ (AB-CCM)
- Different K
- $f_{max,d} = 10^{-2}$ Hz

Trends are as expected

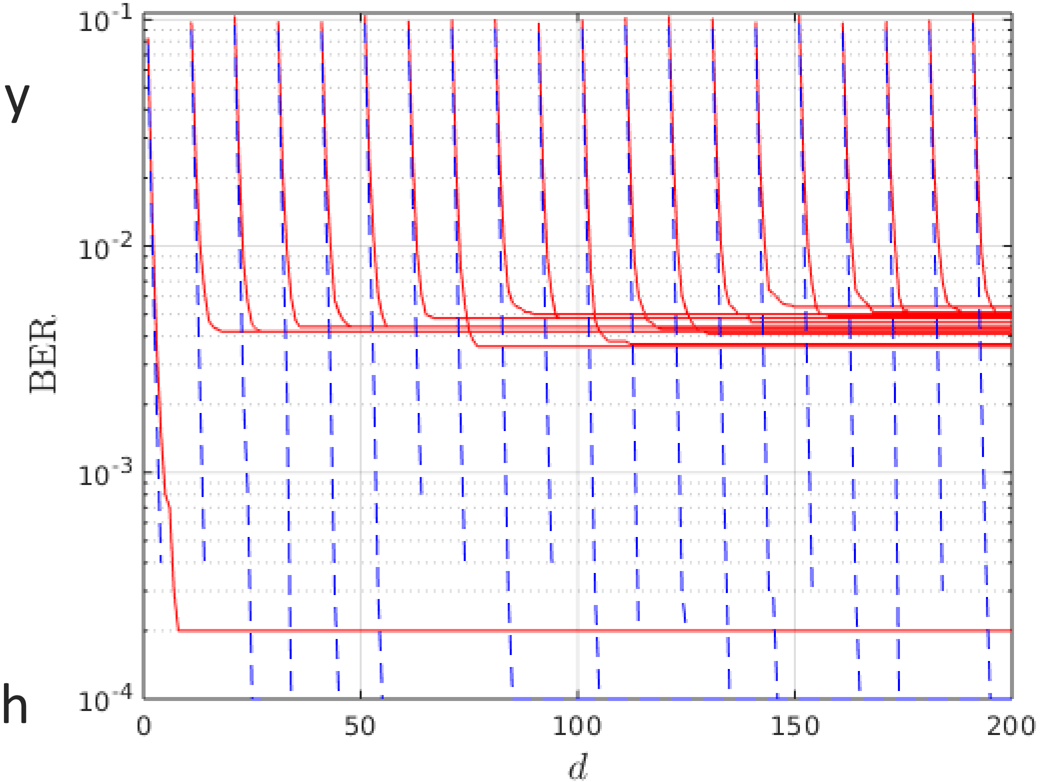


Simulation results

AS-CCM

- Perfect CSI at TX
- Channel inversion only above a threshold
- $\sigma^2 = 0.5$
- $K = 3$ dB
- $f_{max,d} = 10^{-3}$ Hz
- $\alpha_{th} = 0.1$ (red)
- $\alpha_{th} = 10^{-8}$ (blue)

AR is lost for high threshold

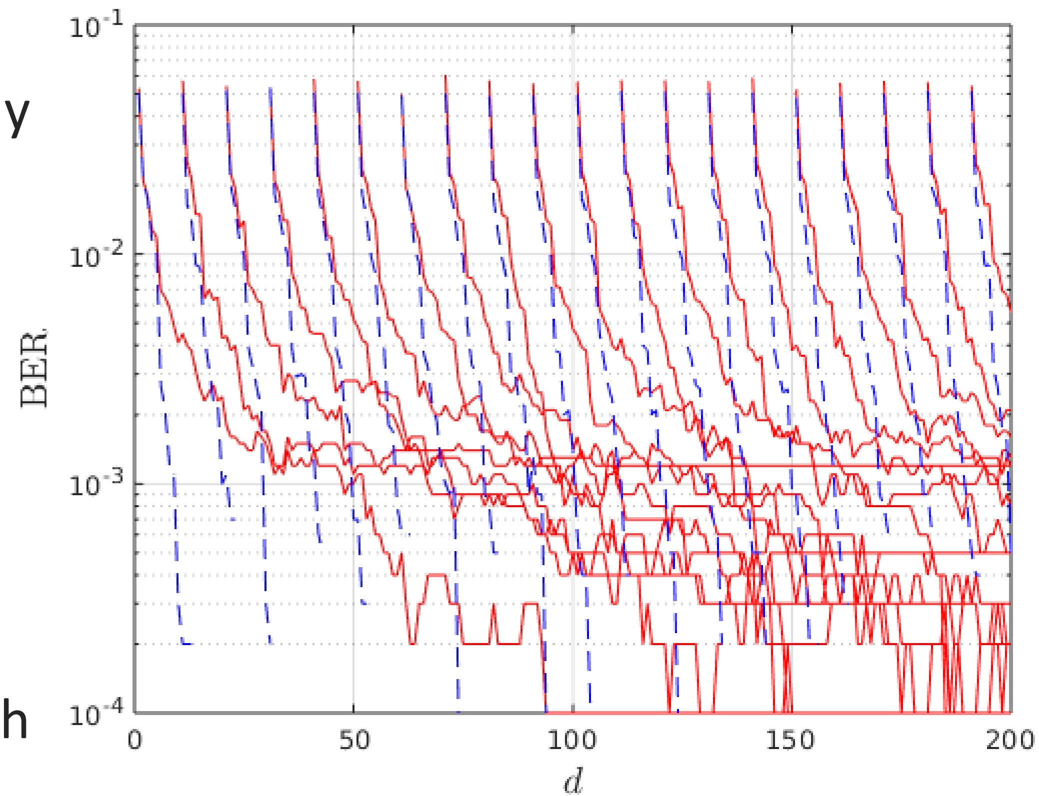


Simulation results

AB-CCM

- Perfect CSI at TX
- Channel inversion only above a threshold
- $\sigma^2 = 0.25$
- $K = 3$ dB
- $f_{max,d} = 10^{-3}$ Hz
- $\alpha_{th} = 0.1$ (red)
- $\alpha_{th} = 10^{-8}$ (blue)

AR is lost for high threshold

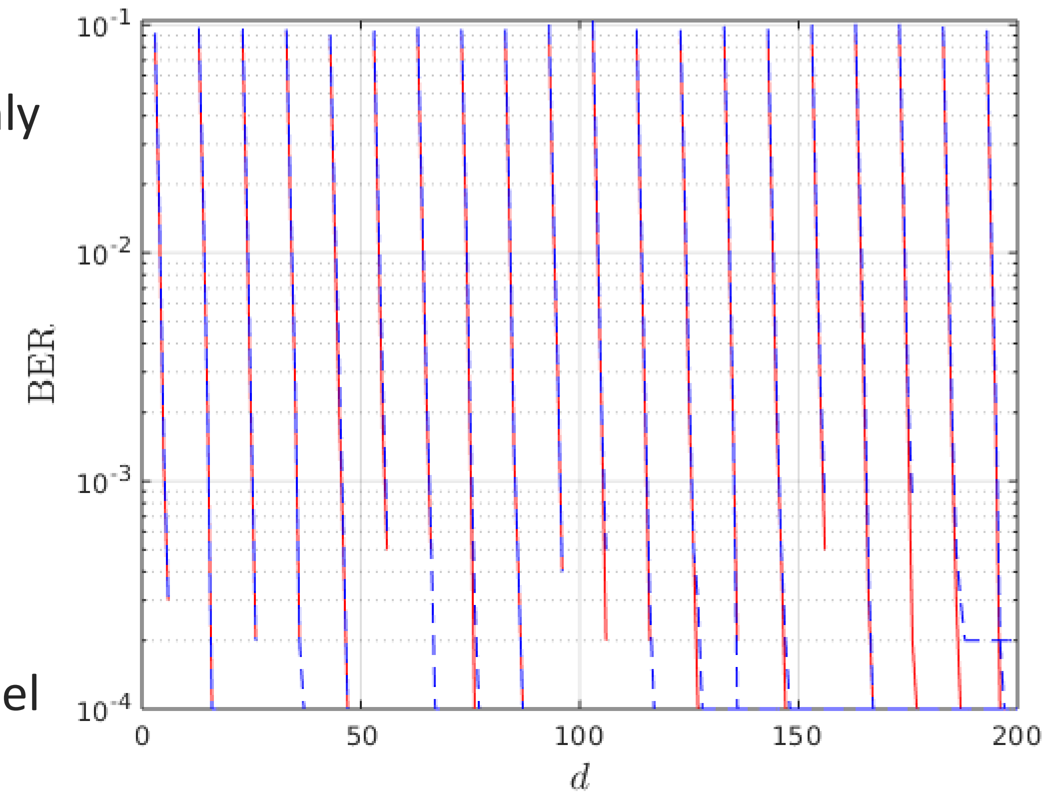


Simulation results

AS-CCM with Information Aging (IA)

- Perfect CSI at TX
- Channel inversion only above a threshold
- $\sigma^2 = 0.5$
- $K = 10$ dB
- $f_{max,d} = 10^{-2}$ Hz
- $\alpha_{th} = 0.1$
- $B = 1$ (red)
- $B = 9$ (blue)

AR is lost for low channel updating frequency

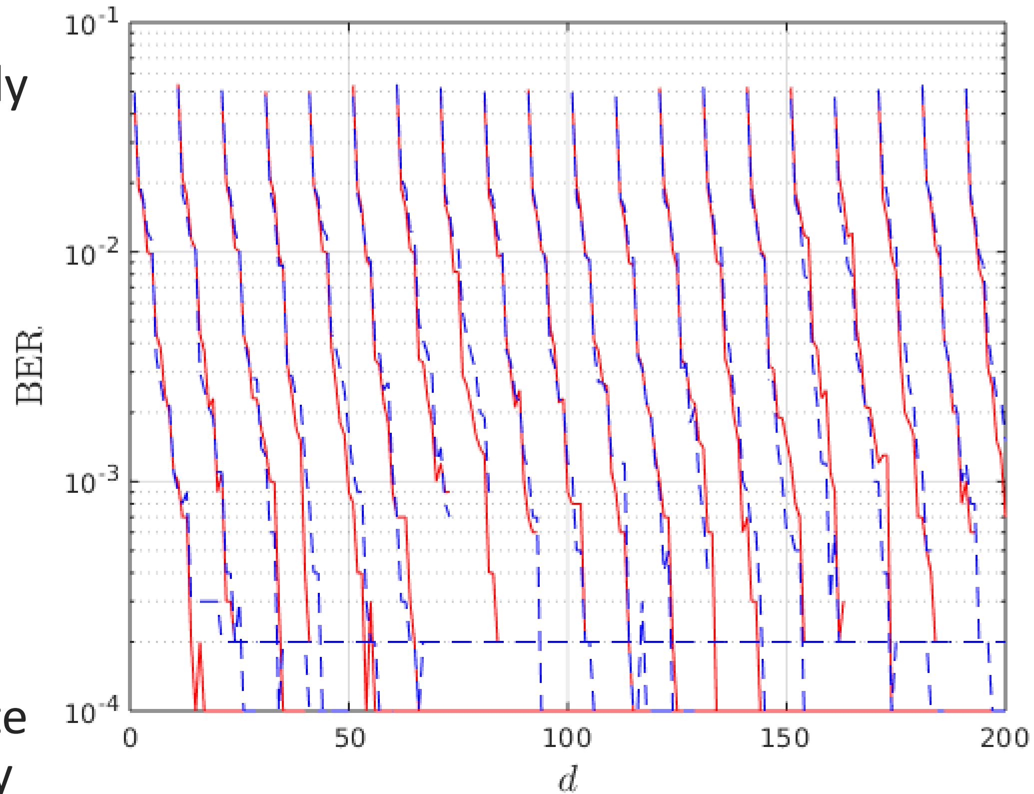


Simulation results

AB-CCM with IA

- Perfect CSI at TX
- Channel inversion only above a threshold
- $\sigma^2 = 0.25$
- $K = 7$ dB
- $f_{max,d} = 10^{-2}$ Hz
- $\alpha_{th} = 0.1$
- $B = 1$ (red)
- $B = 4$ (blue)

AR is lost for moderate channel updating frequency



Conclusions

- Two families of chaos-based AR capable systems (AS-CCM, AB-CCM) are shown to maintain AR properties in fading channels, under given conditions.
- Perfect CSI at the RX without IA leads to expected good results.
- Perfect CSI at the TX can only be reasonably applied using a threshold for channel inversion (TX power limitation).
- Thresholding affects the preservation of AR properties: high thresholds may lead to non-AR systems.
- In presence of IA (channel coefficients are fed back to the TX only every B steps), AR may not be preserved when channel update frequency is too low.

Thank you!

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