Ambient OFDM Pilot-Aided Delay-Shift Keying and Its Efficient Detection for Ultra Low-Power Communications

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Background

Internet-of-things (IoT)

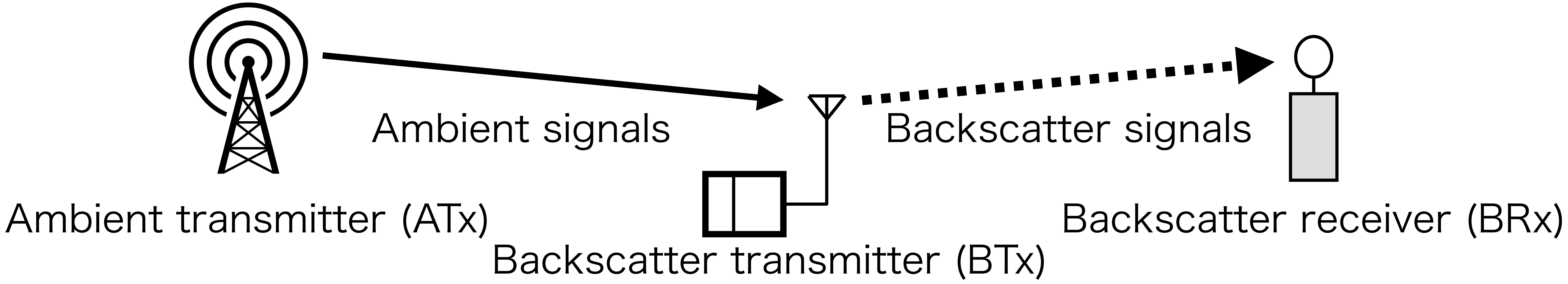
- A huge number of wireless devices will be installed.
- High cost to replace their batteries is inevitable.

- **Requires an ultra-low-power communications method.**

Conventional Studies

Ambient backscatter communication (AmBC) system [1]

- BTx has been implemented based on on-off keying.
  - Transmits information by either absorbing or reflecting **ambient** radio-frequency signals.
  - Can operate with ultra-low-power, e.g.) 0.25 μW



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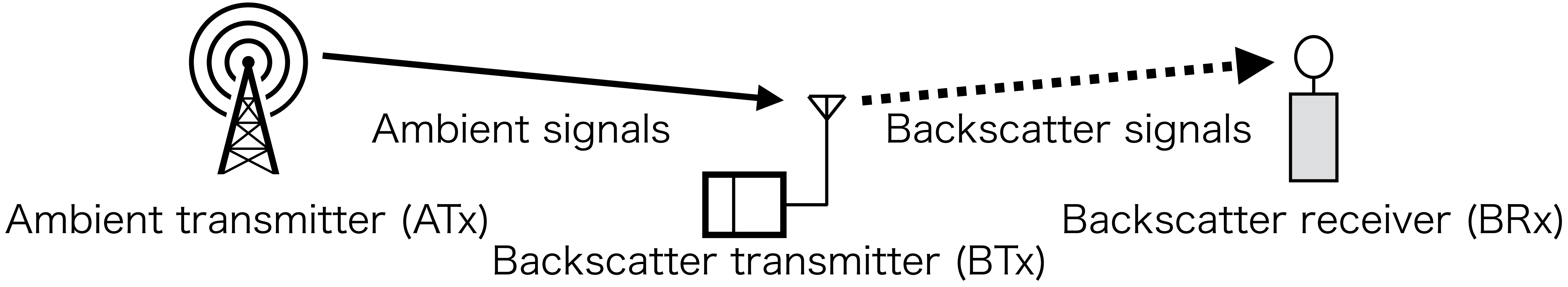
  - Can operate with ultra-low-power, e.g.) 0.25 μW
- BRx demodulated information by using LPF(1) and ED(2).
  - BTx's symbol rate must be even lower than ATx.
  - Bandwidth efficiency is limited.

LPF(1): low path filter **ED(2): energy detector**



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Conventional Studies

Cooperative AmBC system [2]

- Proposed a cooperative receiver (CRx) exploiting ambient OFDM(3) pilot symbols.
  1. Estimates the channel coefficients between ATx and CRx.
  2. Detects information from ATx and BTx via a joint maximum likelihood (ML) detector.

- The Joint ML detector allows BTx to transmit information with M-ary modulation.
  - Eliminates the bandwidth constraint.
- CRx must detect information from ATx.
  - Causes high-computational complexity.

OFDM(3): orthogonal frequency-division multiplexing

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[2] G. Yang, Q. Zhang, and Y. Liang, “Cooperative Ambient Backscatter Communications for Green Internet-of-Things,” *IEEE Internet of Things J.*, vol. 5, no. 2, pp. 1116–1130, Apr. 2018.

Our Research

Aim

- ✓ To establish an AmBC system, where BTx and BRx can operate with low-power consumption and low-computational complexity.

Contribution

- ✓ Propose a novel AmBC system exploiting that any user can perfectly know an ambient OFDM frame structure.
  - ✓ Propose **delay-shift-keying (DSK)** and its **ML detector**.
    - Different propagation delays lead to a different phase rotation of subcarriers at OFDM demodulation.
  - ✓ Achieve lower symbol error rate (SER) than system of [1].
  - ✓ Do NOT need demodulation of ATx's symbols, unlike [2].

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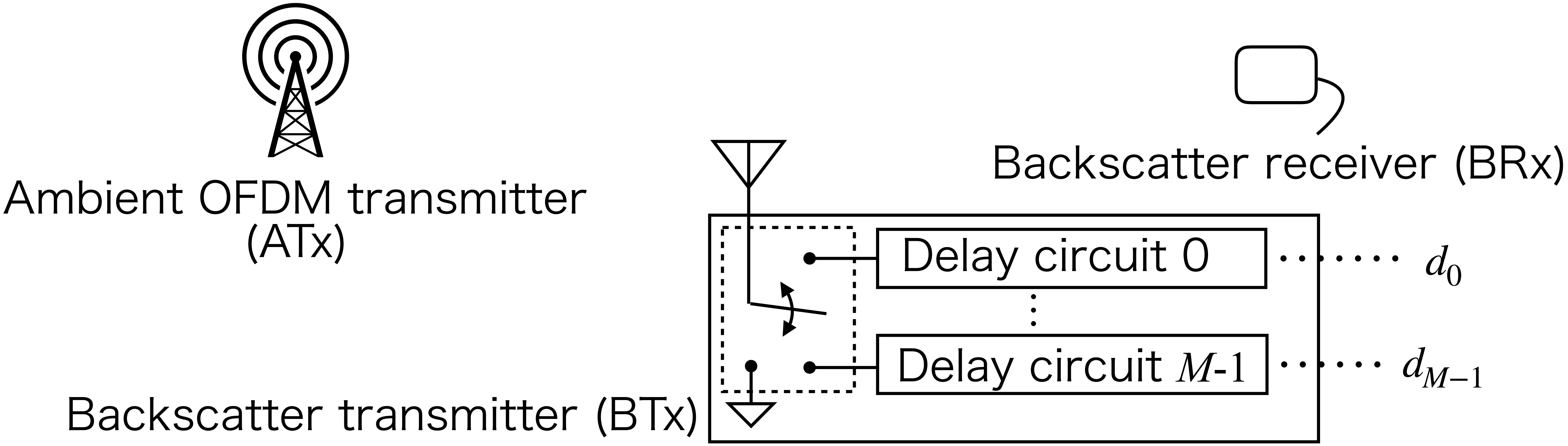
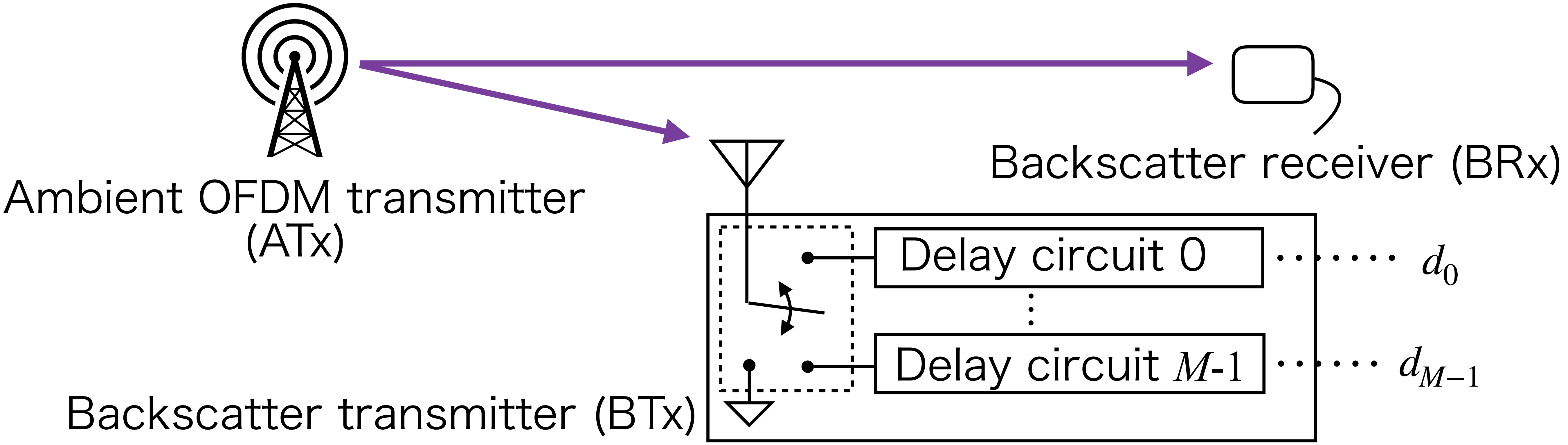
System Model

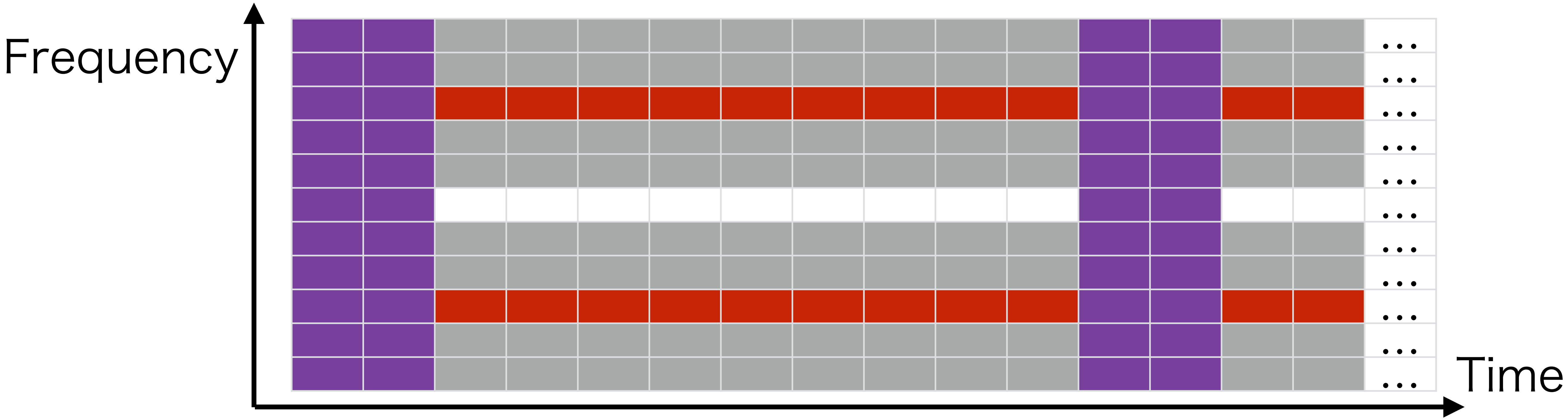


- d_n : delay of time sample (for n-th delay circuit)

System Model

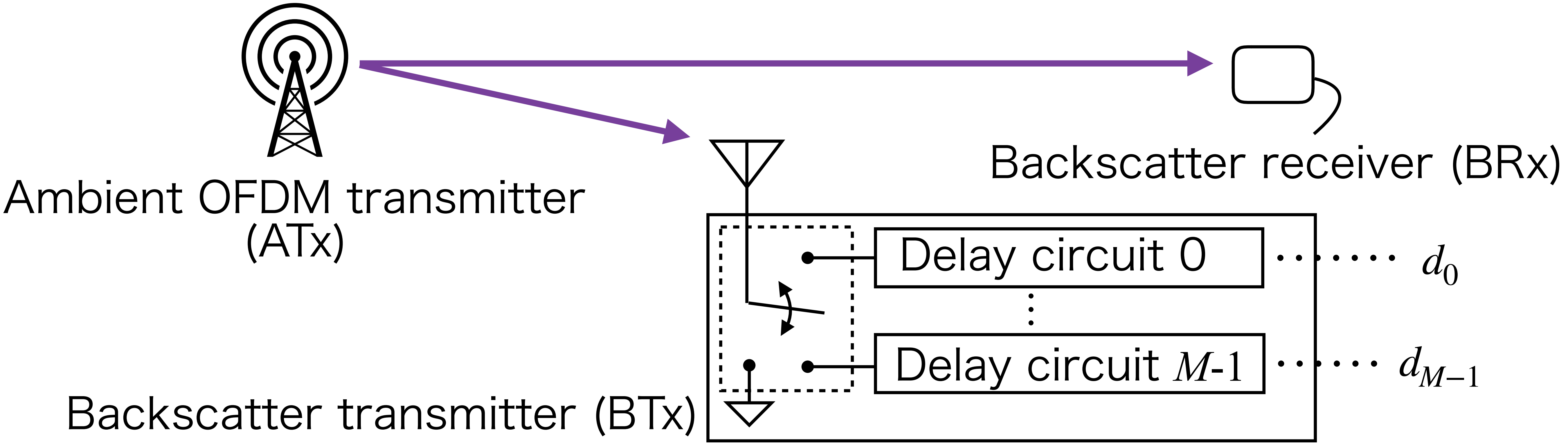


Example of ATx's frame structure based on IEEE 802.11



🟪 : Pilot signal in preamble 🟥 : Pilot signal in payload ▨ : Information

System Model



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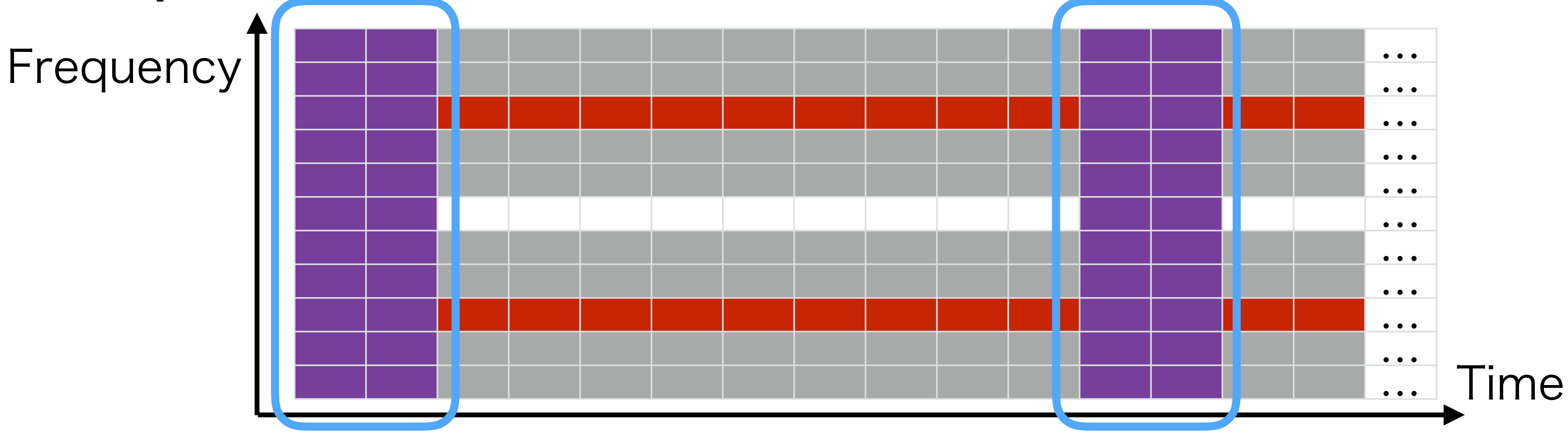

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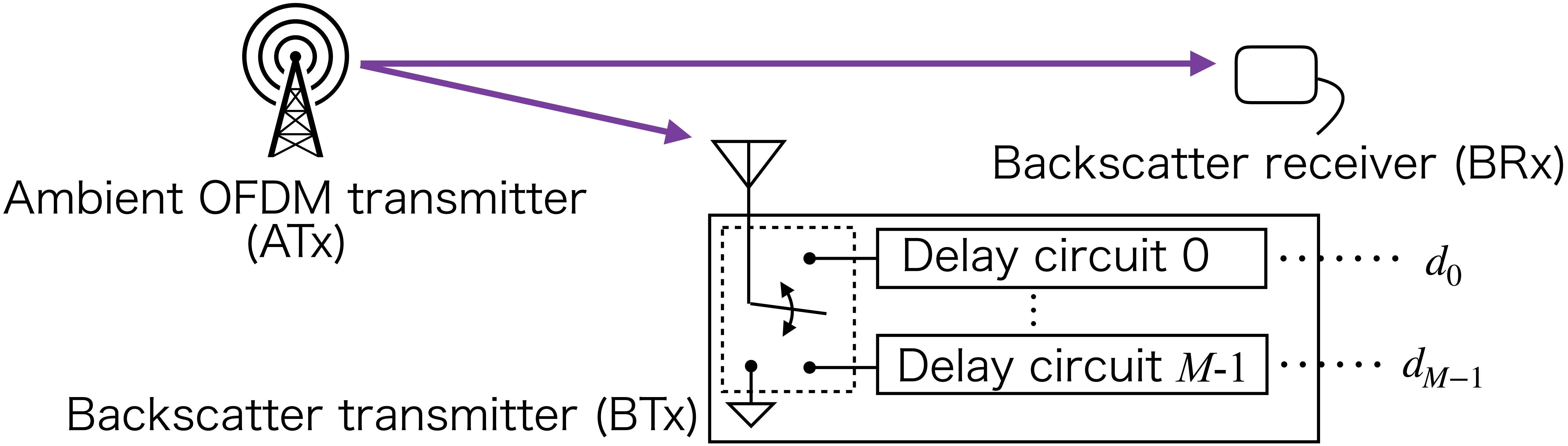
Channel Estimation and Signal Model



Ambient OFDM transmitter (ATx)

Backscatter receiver (BRx)

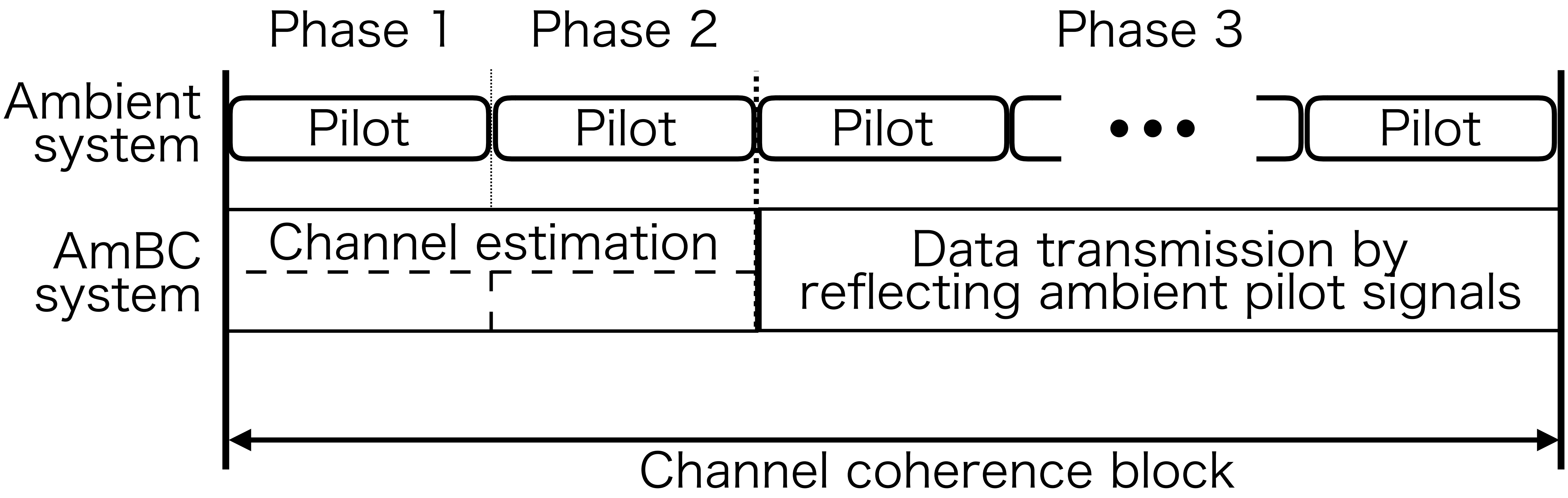
Backscatter transmitter (BTx)

Delay circuit 0 ······ d_0

⋮

Delay circuit M-1 ······ d_{M-1}

Transmission protocol



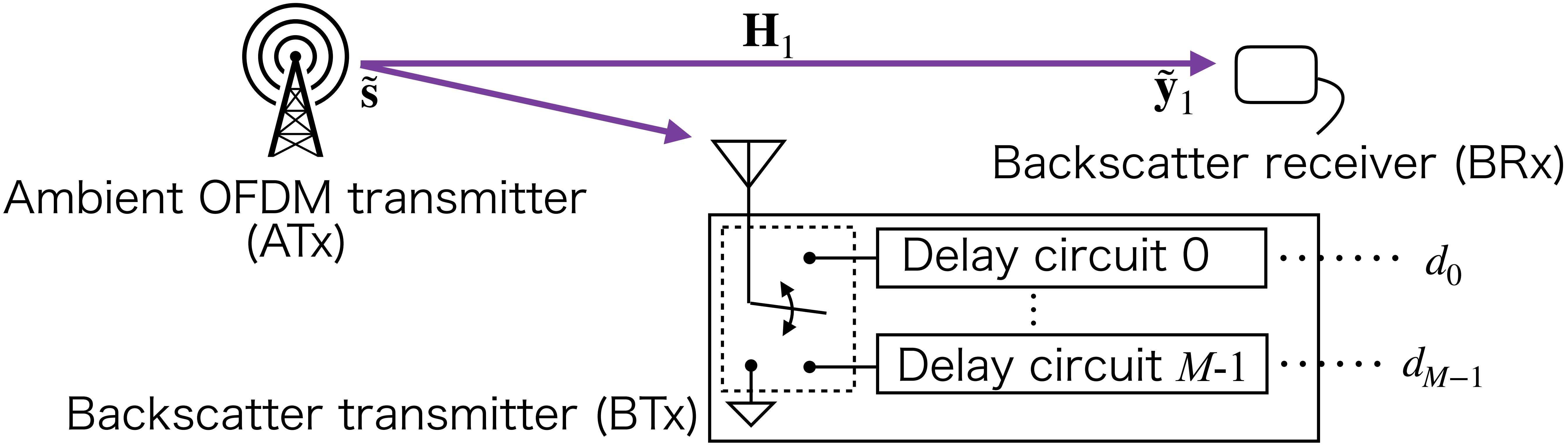
Phase 1 Phase 2 Phase 3

Ambient system: Pilot | Pilot | Pilot | ••• | Pilot

AmBC system: Channel estimation | Data transmission by reflecting ambient pilot signals

Channel coherence block

Channel Estimation and Signal Model



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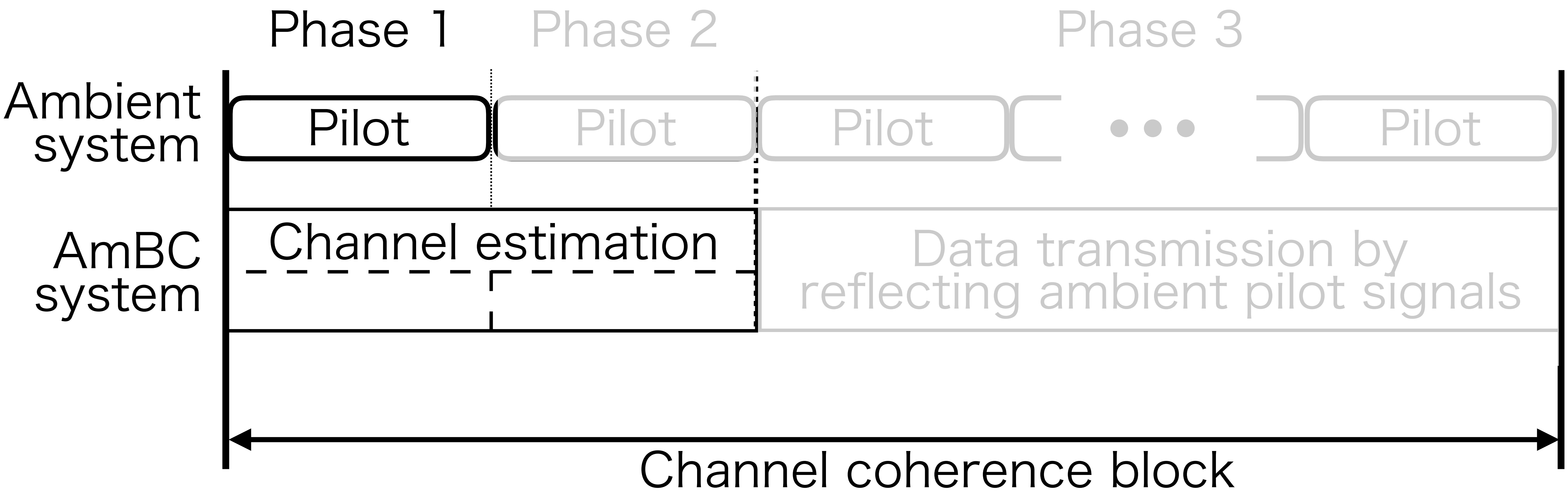

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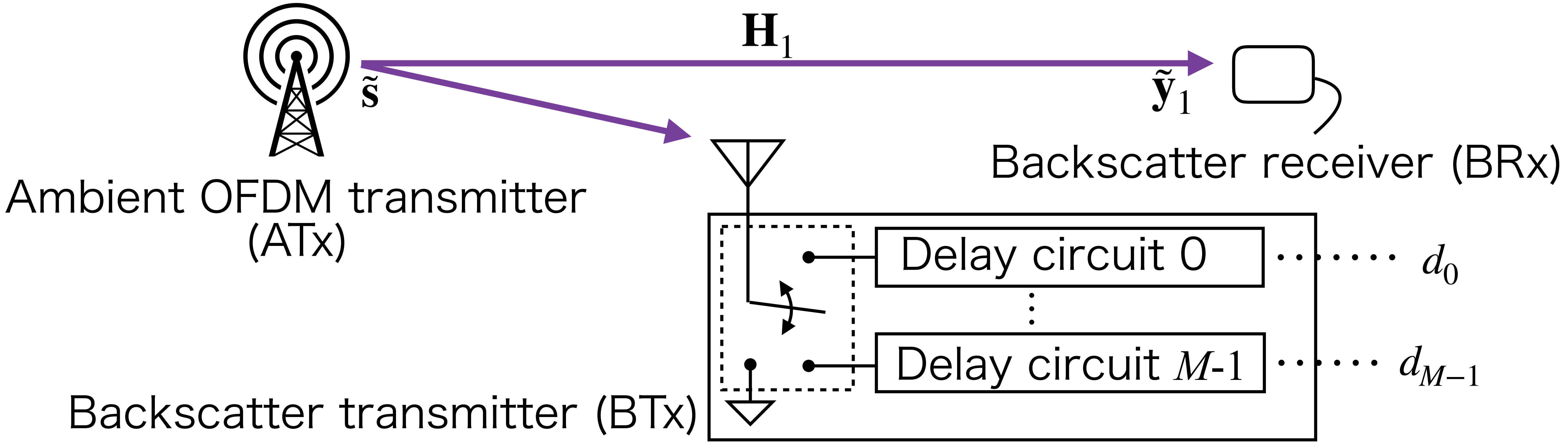
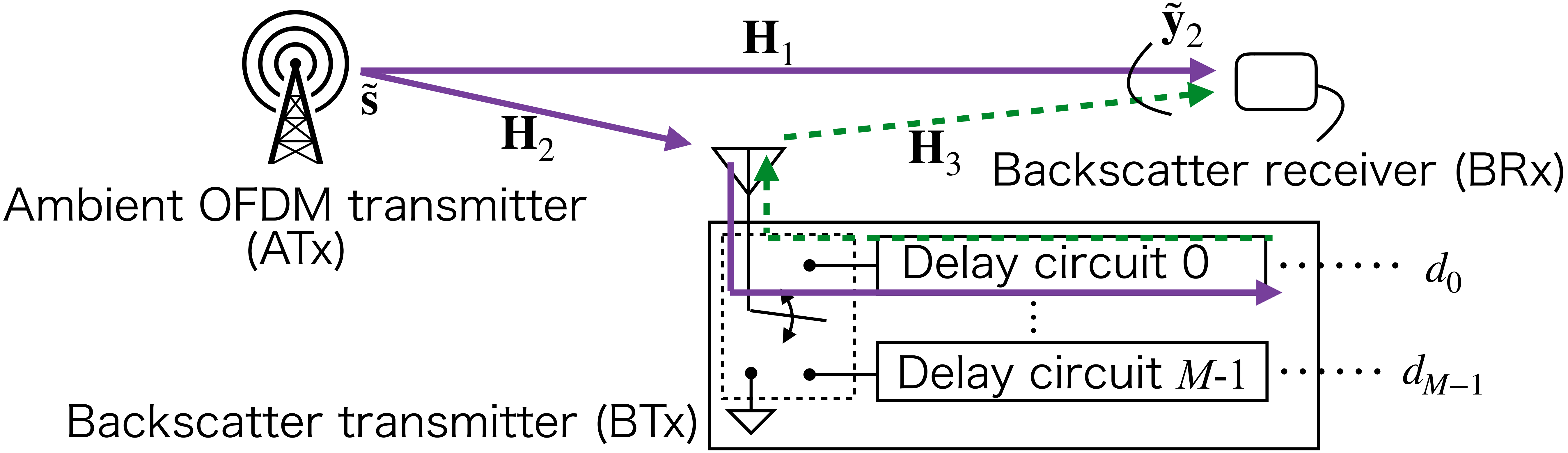


Received signal of BRx in phase 1

$$\tilde{\mathbf{y}}_1 = \mathbf{W}\mathbf{H}_1\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}} + \mathbf{v}_{\mathrm{P}1} \in \mathbb{C}^{N\times 1}$$

- N : the number of subcarriers
- $\mathbf{W} \in \mathbb{C}^{N\times N}$: discrete Fourier transform matrix
- $\mathbf{H}_1 \in \mathbb{C}^{N\times N}$: channel matrix between ATx and BRx
- $\tilde{\mathbf{s}} \in \{+1, -1\}^{N\times 1}$: pilot sequence
- $\mathbf{v}_{\mathrm{P}n}$: additive while Gaussian noise (AWGN) vector in phase n

Channel Estimation and Signal Model



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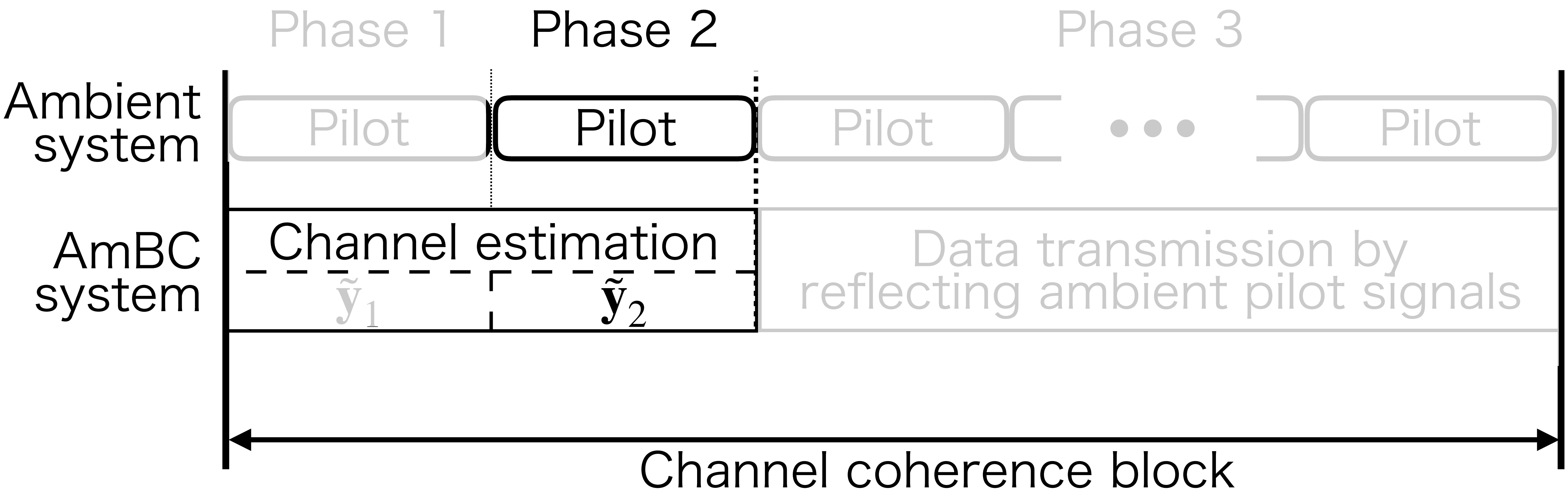

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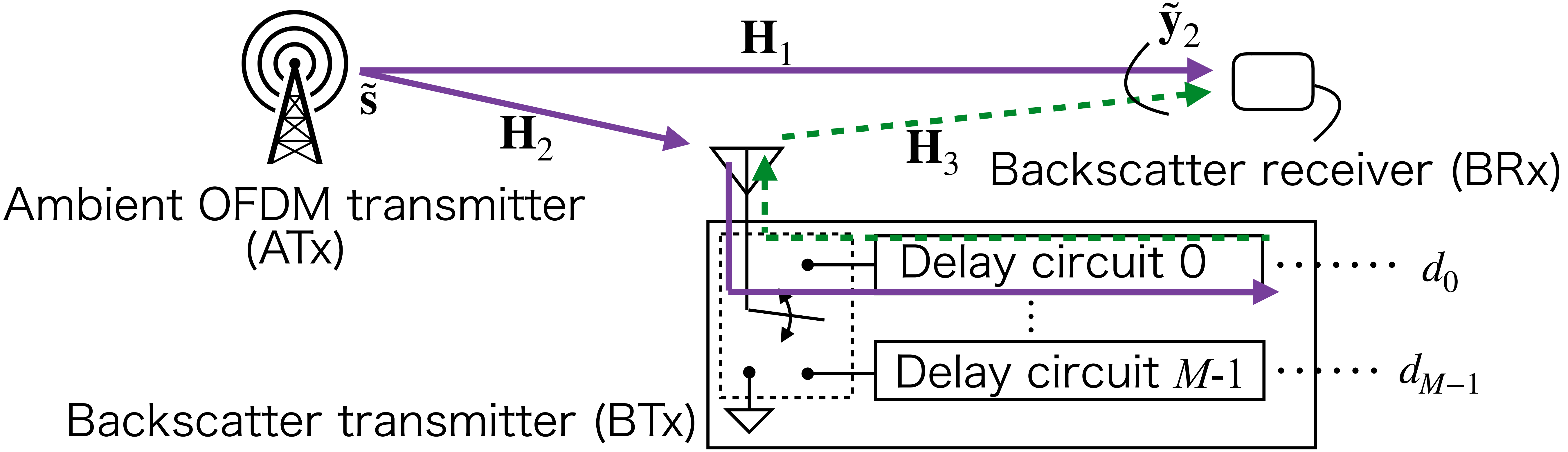

Received signal of BRx in phase 2

$$\tilde{\mathbf{y}}_2 = \underline{\mathbf{W}\mathbf{H}_1\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}}} + \underline{\alpha\mathbf{W}\mathbf{H}_3\mathbf{T}^{d_0}\mathbf{H}_2\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}}} + \mathbf{v}_{\mathrm{P}2}$$

- $\mathbf{H}_2 \in \mathbb{C}^{N\times N}$: channel matrix between ATx and BTx
- $\mathbf{H}_3 \in \mathbb{C}^{N\times N}$: channel matrix between BTx and BRx
- $\alpha \in \mathbb{C}$: reflection coefficient
- $\mathbf{T} \triangleq \begin{bmatrix} 0 & 0 & \dots & 0 & 1 \\ 1 & 0 & \dots & 0 & 0 \\ 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & 1 & 0 \end{bmatrix} \in \{0,1\}^{N\times N}$

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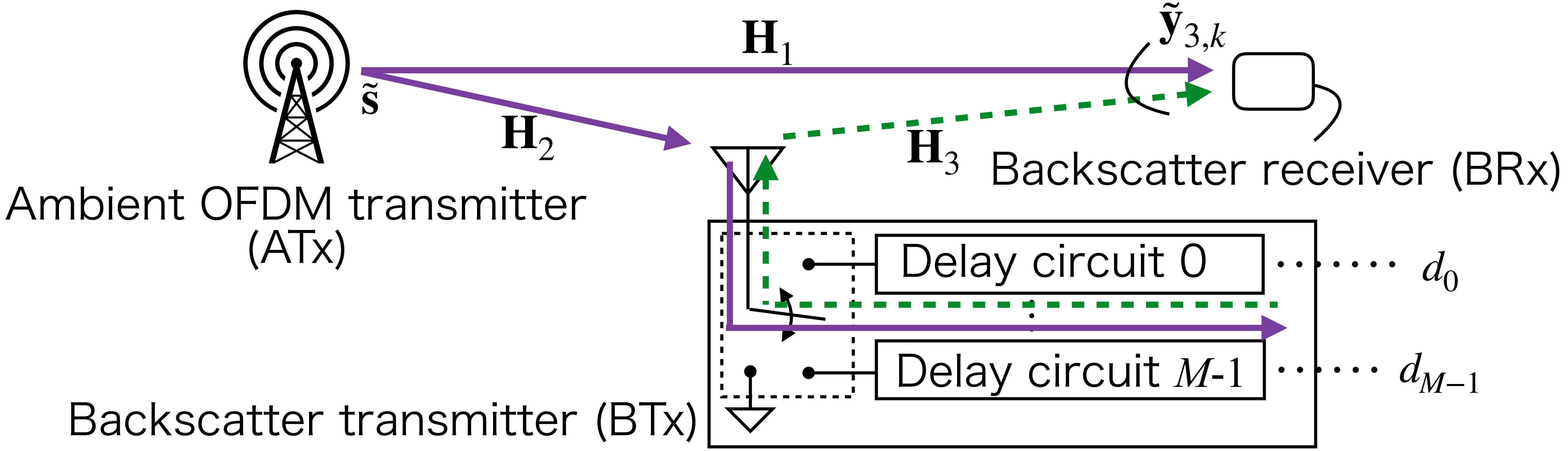

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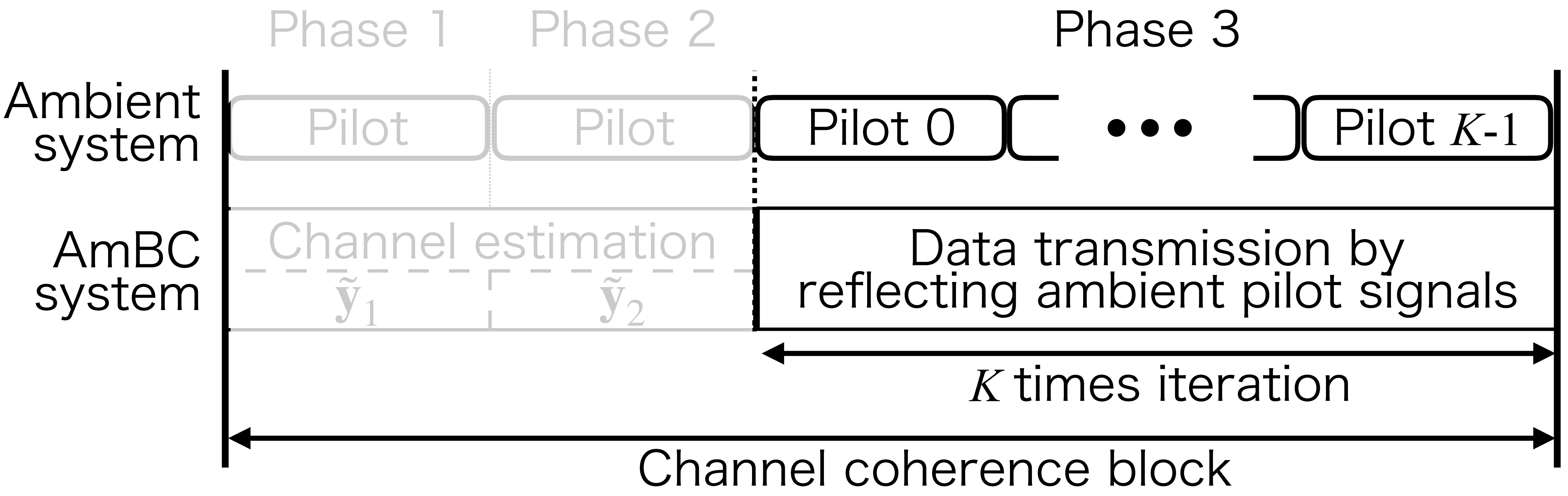

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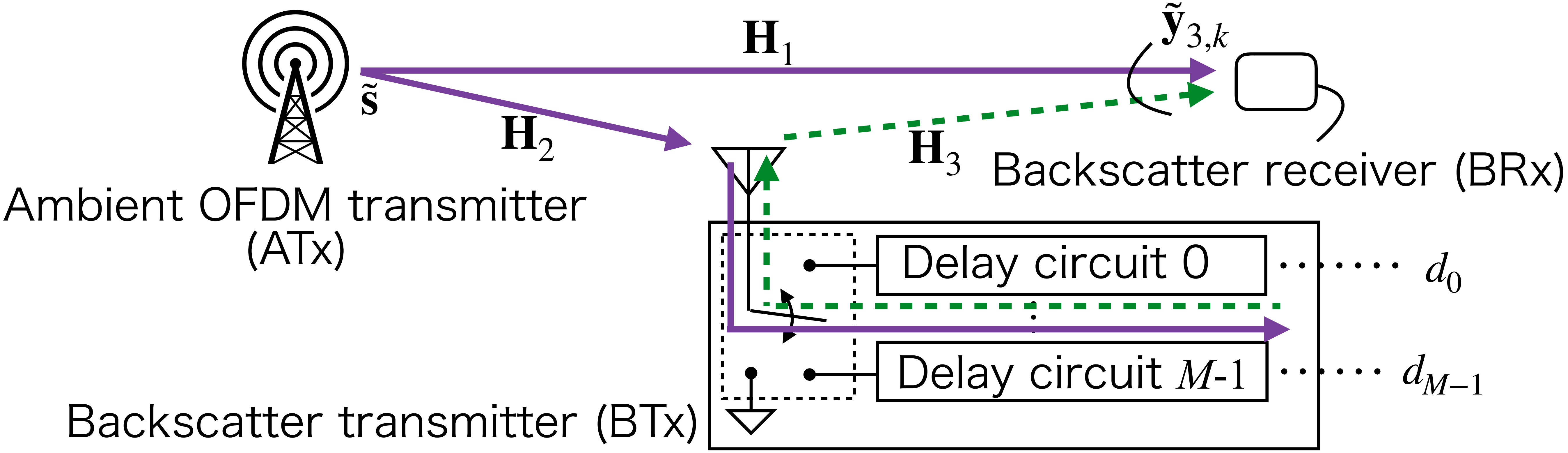
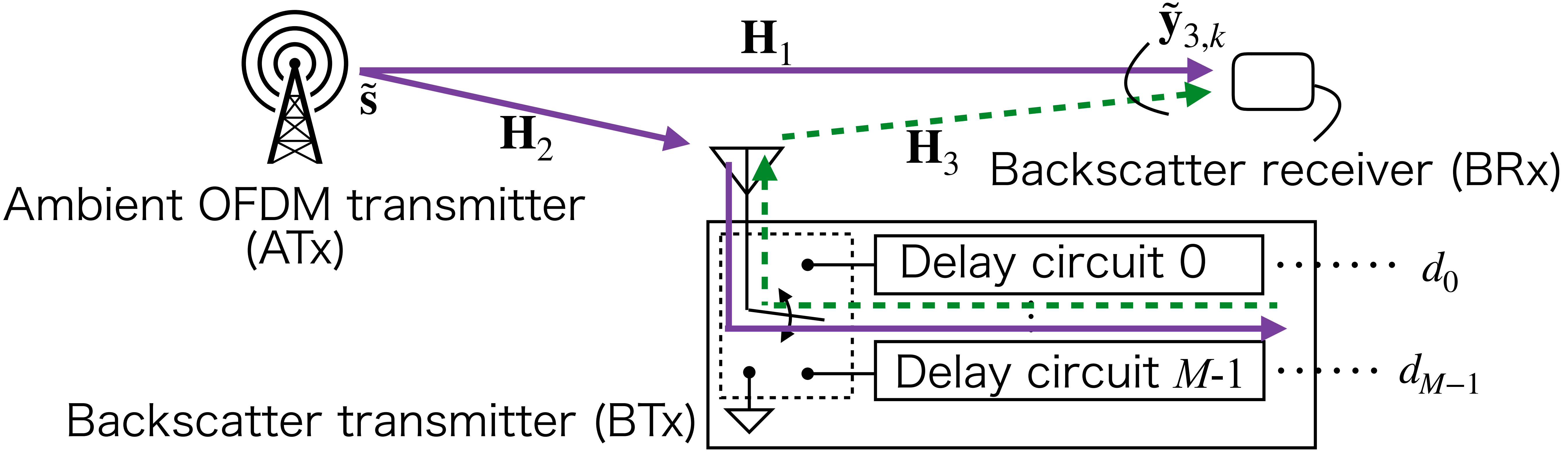


Received signal of BRx in phase 3

$$\tilde{\mathbf{y}}_{3,k} = \underline{\mathbf{W}\mathbf{H}_1\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}}} + \underline{\alpha\mathbf{W}\mathbf{H}_3\mathbf{T}^{d_i}\mathbf{H}_2\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}}} + \tilde{\mathbf{v}}_k$$

- k : index of OFDM pilot symbol
- $\tilde{\mathbf{v}}_k$: AWGN vector

Channel Estimation and Signal Model



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Delay-shift keying:
BTx reflects signals with a different delay for different information.

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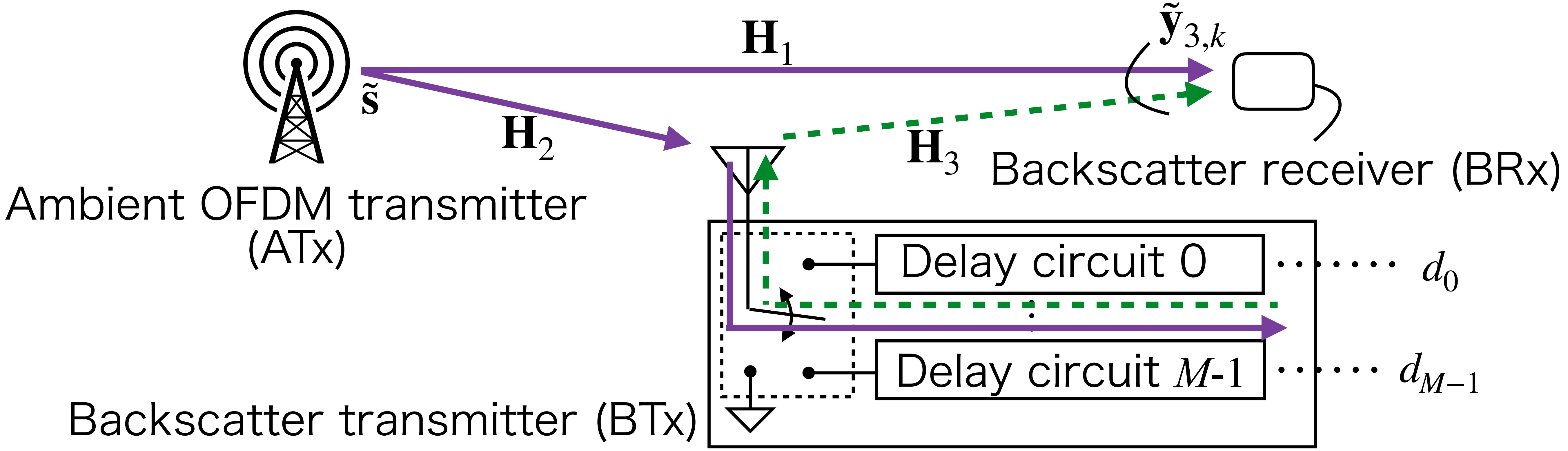

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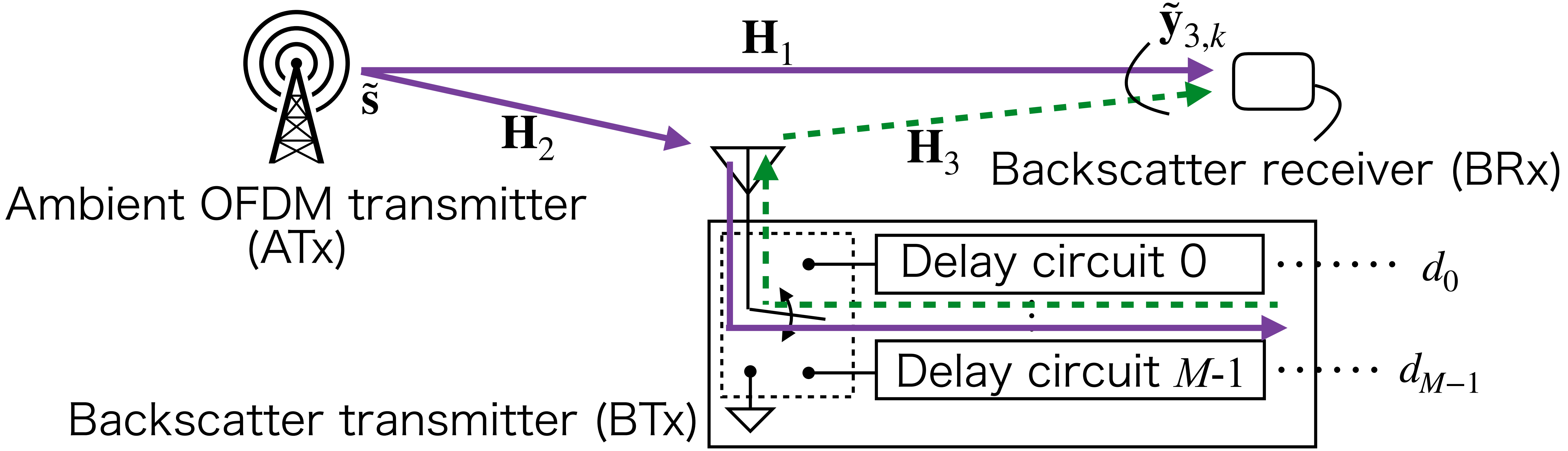
ML detector

$$\widehat{d_m} = \mathop{\arg\min}_{d_m \in \{d_0,\ldots,d_{M-1}\}} \sum_{k=1}^{K} \left\| \tilde{\mathbf{y}}_{3,k} - \mathbf{W}\mathbf{H}_1\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}} - \alpha\mathbf{W}\mathbf{H}_3\mathbf{T}^{d_m}\mathbf{H}_2\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}} \right\|_2^2$$

Channel Estimation and Signal Model



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Assuming the perfect channel estimation.

Performance Analysis

Different Looks of DSK

- Time domain
  - Different propagation delays.
- Frequency domain
  - Different phase rotations over subcarriers.
- To minimize SER, the optimal delay alphabet should be determined by deriving pairwise error probability of DSK.

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Pairwise error probability over AWGN channel

$$Q\left(\sqrt{\frac{K \cdot \mathrm{SNR}}{2}\mathbf{W}(\mathbf{T}^{d_i} - \mathbf{T}^{d_j})\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}}}\right)$$

- $Q(\,\cdot\,)$: Q-function
- $i, j \in \{0, \ldots, M-1\}, i \neq j$

Pairwise error probability over fading channel (upper bound)

$$\left(\prod_{\ell=1}^{L_2}\frac{1}{\lambda_\ell}\right)\left(\frac{K}{4L_2}\mathrm{SNR}\right)^{-L_2}$$

- λ_ℓ: eigenvalue of Gram matrix of distance between two alphabets [3]

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[3] D. Tse and P. Viswanath, Fundamentals of Wireless Communication, 1st ed. sity Press, 2005.

Definition of SNR and Parameters

Received signal to noise power ratio (SNR)

$$\mathrm{SNR} = \frac{\mathbb{E}_{\mathbf{H}_2,\mathbf{H}_3}\left[\left\| \left(\alpha \mathbf{W}\mathbf{H}_3\mathbf{T}^{d_m}\mathbf{H}_2\mathbf{W}^{\mathrm{H}}\tilde{\mathbf{s}}\right) \right\|_2^2\right]}{\mathbb{E}_k\left[\left\| \tilde{\mathbf{v}}_k \right\|_2^2\right]}$$

Assumption

- Channel matrix $\mathbf{H}_3$ is set the identity matrix.
- Power delay profile is set an exponential function [4].

Simulation parameters

The number of subcarriers	N	64
The number of multi paths between ATx and BTx	L_2	1
The number of pilot OFDM symbols for AmBC	K	1
The number of delay circuits	M	2
Delay alphabet	$\{d_0, d_1\}$	{0, 2}

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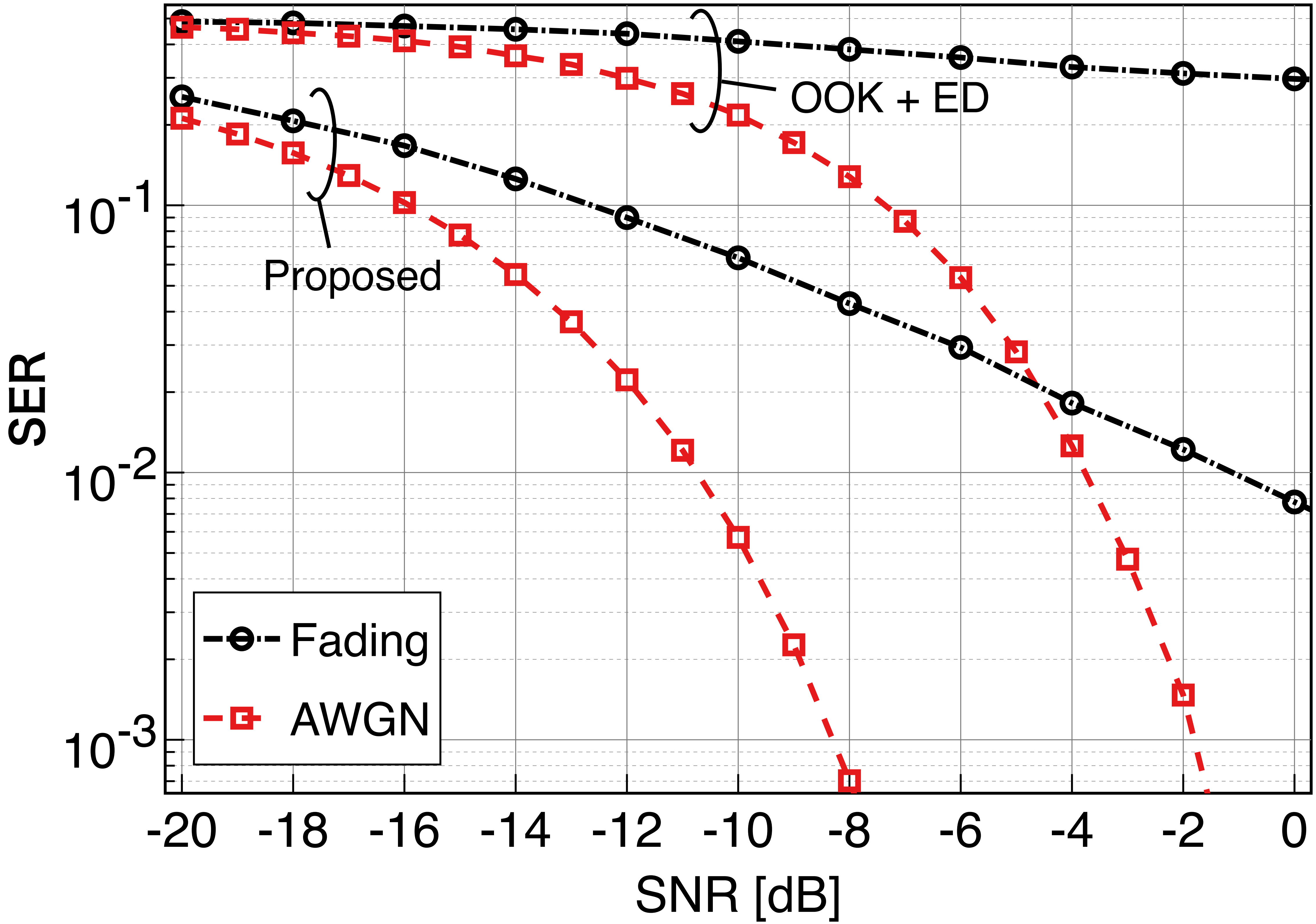
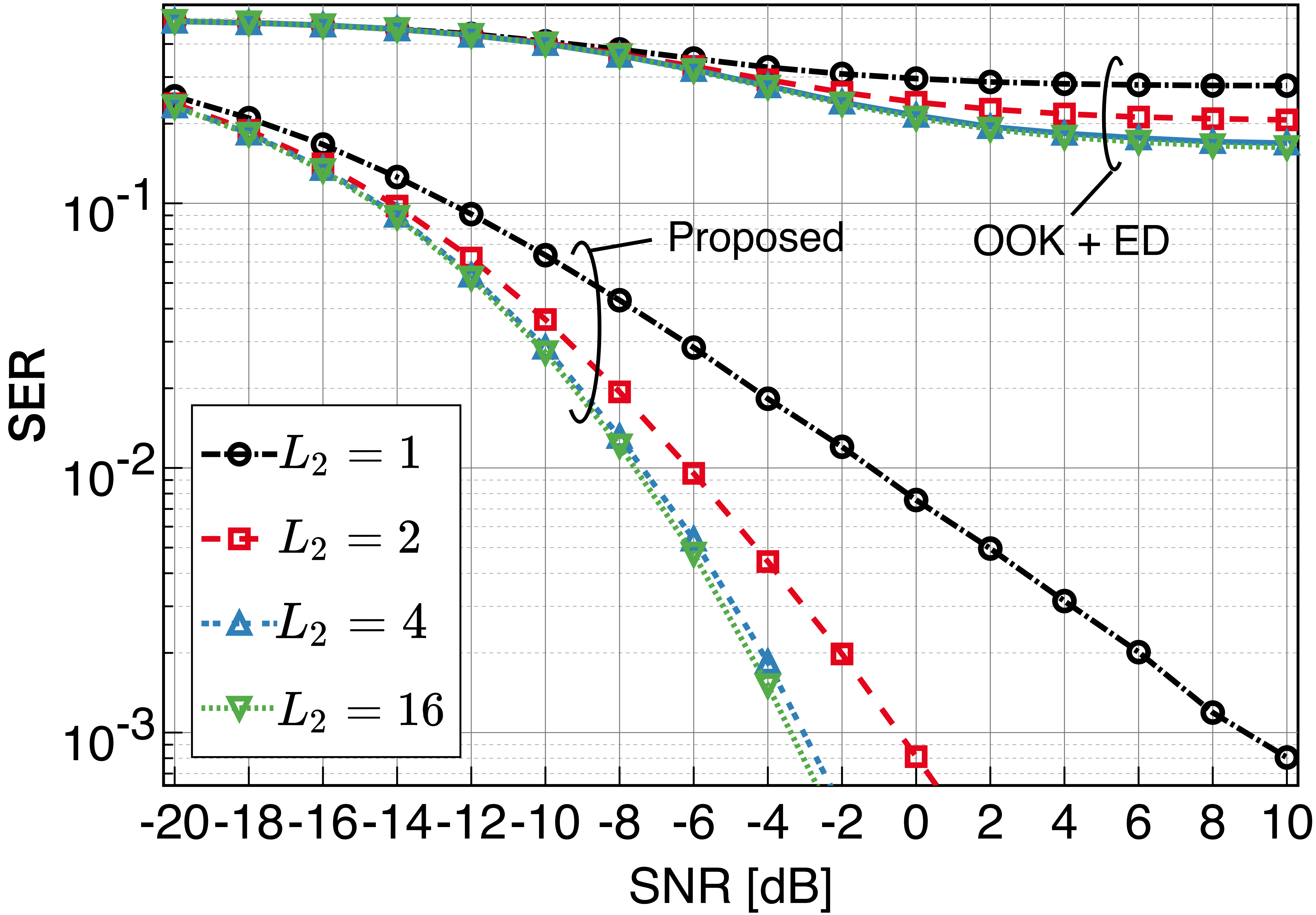
[4] A. F. Molisch, Wireless Communications Second Edition, 2nd ed. Wiley, 2011.

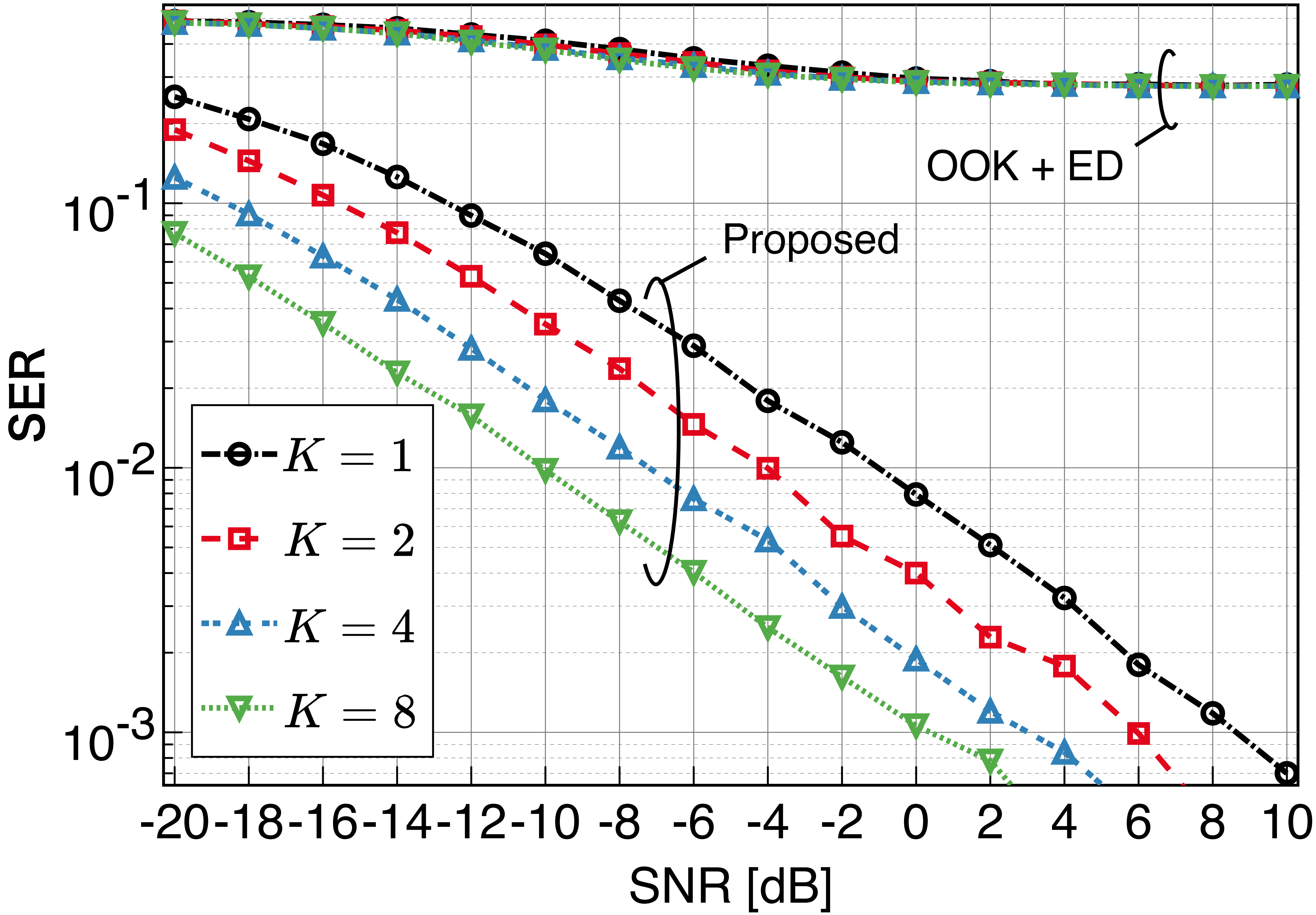
SERs for AWGN and fading channels



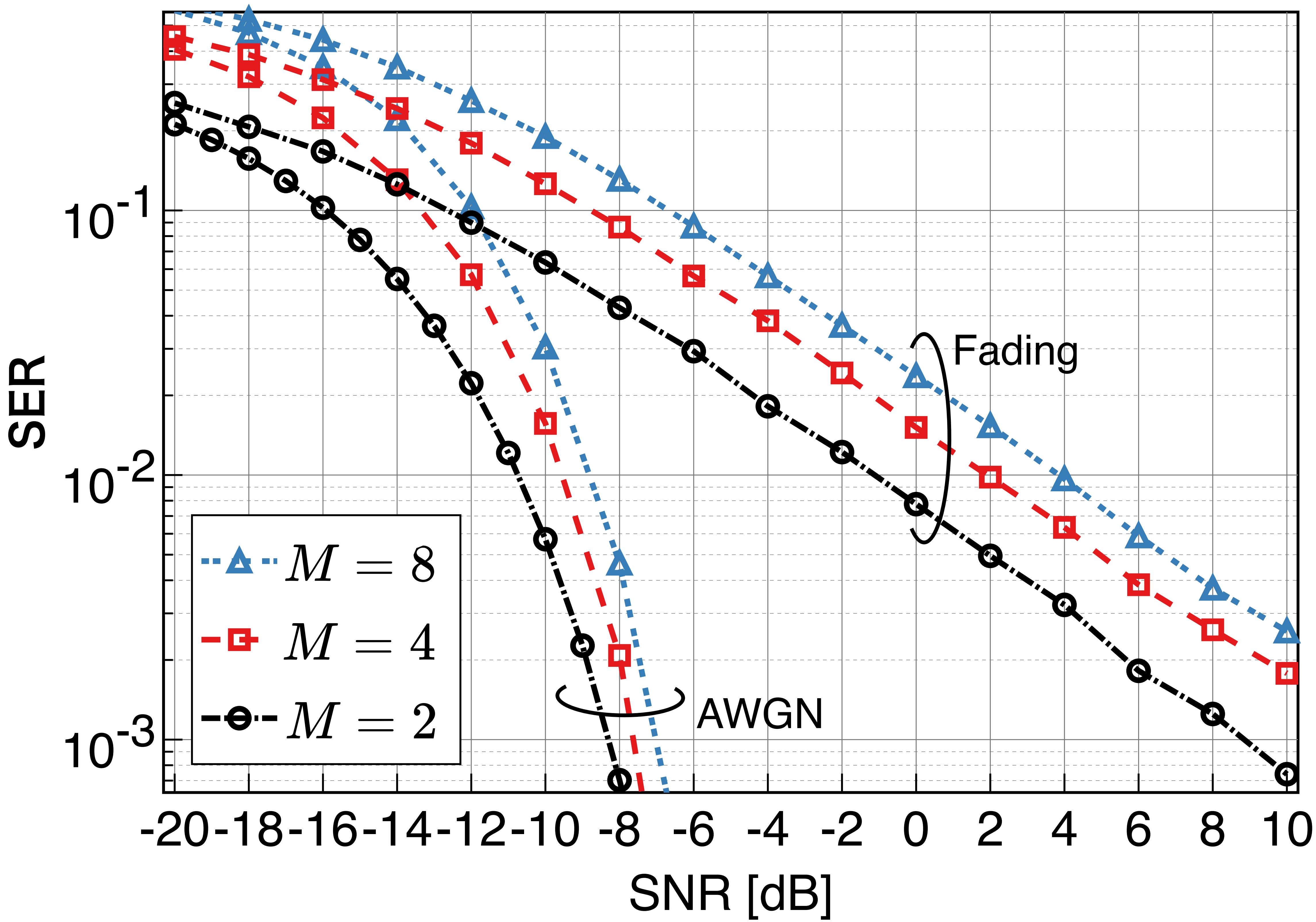
SERs over fading channels with different L_2



SERs for different K over fading channels



SERs for different M over fading channels



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