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“Preamble-Free Frame Synchronization for Short-Packet Low-Latency Communications”

Javier Villares and Meritxell Lamarca

Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

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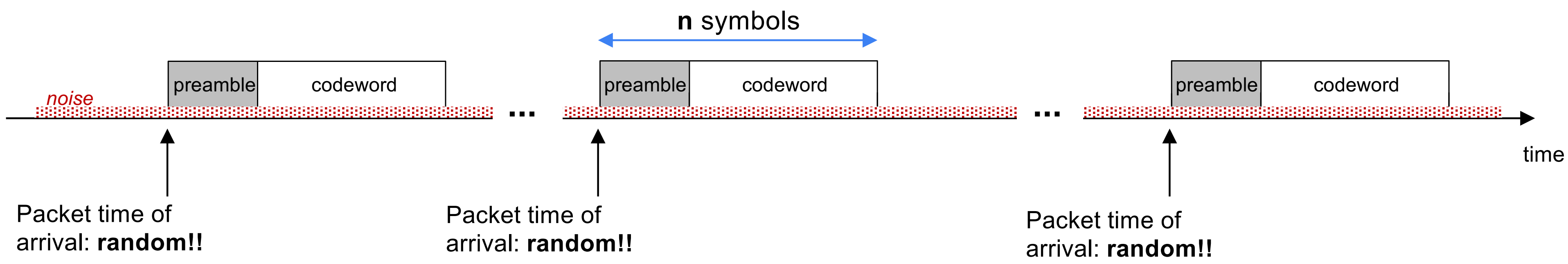
Problem Statement

Asynchronous packet-based digital link:

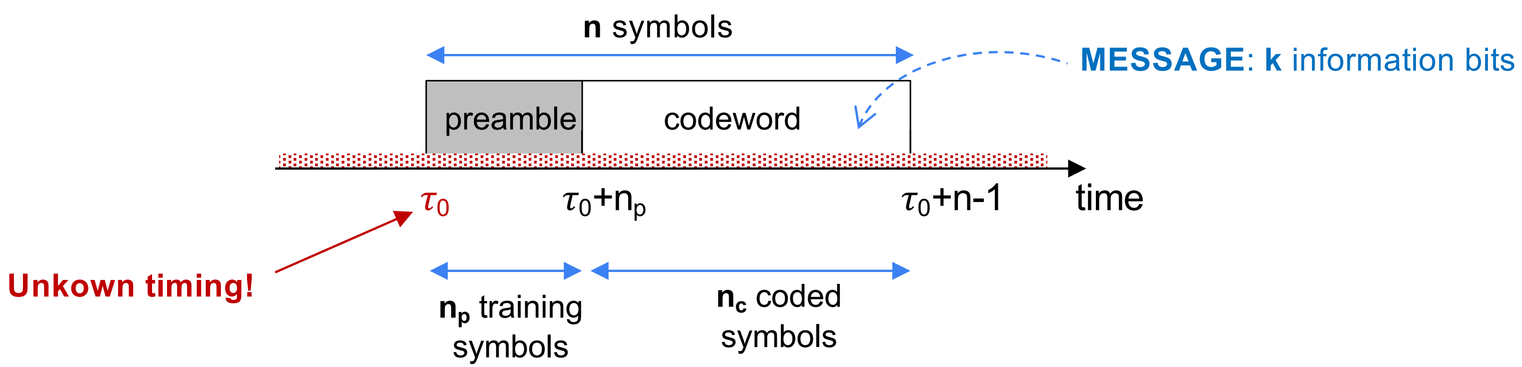


Low Latency ➔ SHORT packets
(n < 100)

SHORT preambles !!
Synchronization ??
Code-aided (CA) synchro

SHORT codewords !!
Reliability ??
Short-blocklength codes (Polar, TB-CC, …)

Problem Statement



OBJECTIVE:

Message decoding with minimum PER → **requires estimation of τ_0**

n : fixed (latency constraint)

k : fixed (bit rate constraint)

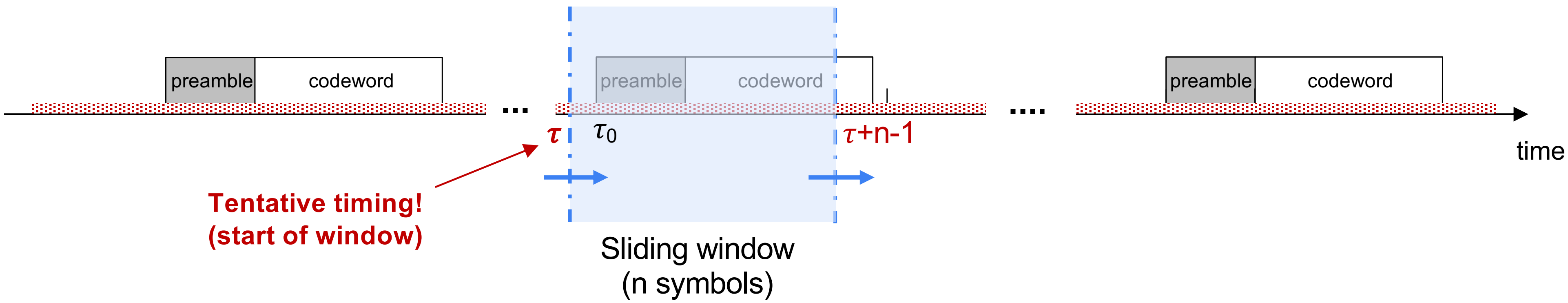
n_p : to be optimized

n_c = n - n_p

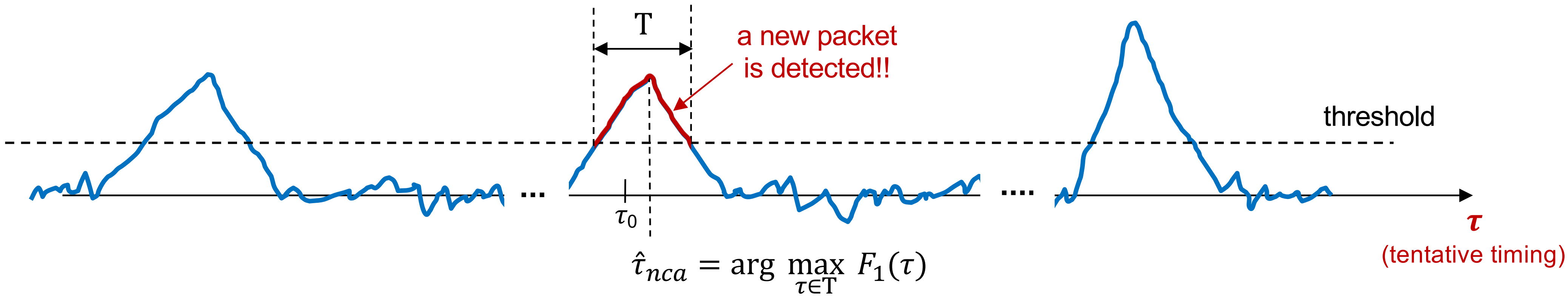
n_p ↑ → Improved synchronization

n_p ↑ → Degraded PER (**n_c** ↓)

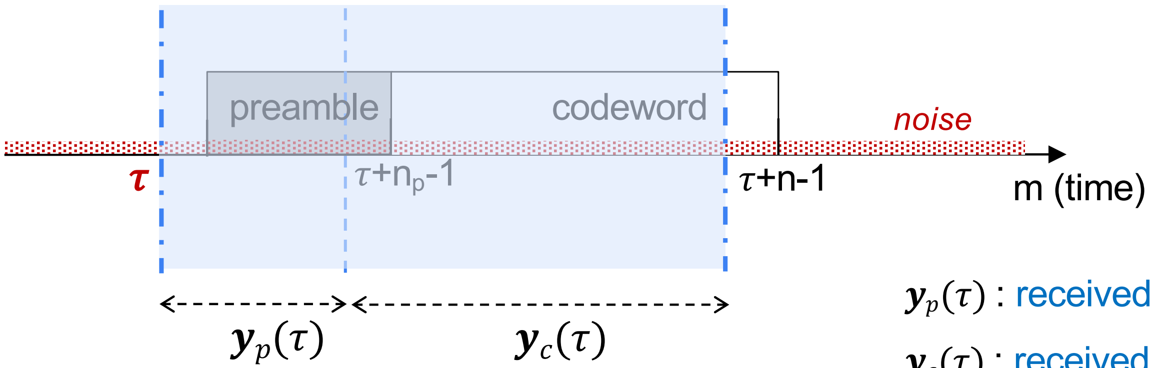
Synchronization (step 1)



Non-Code-Aided (NCA) synchronization metric $\longrightarrow$ $F_1(\tau)$



Synchronization (step 1)



$\boldsymbol{y}_p(\tau)$: received preamble samples assuming τ (length $\mathbf{n_p}$)

$\boldsymbol{y}_c(\tau)$: received codeword samples assuming τ (lenght $\mathbf{n_c}$)

(at the matched filter output)

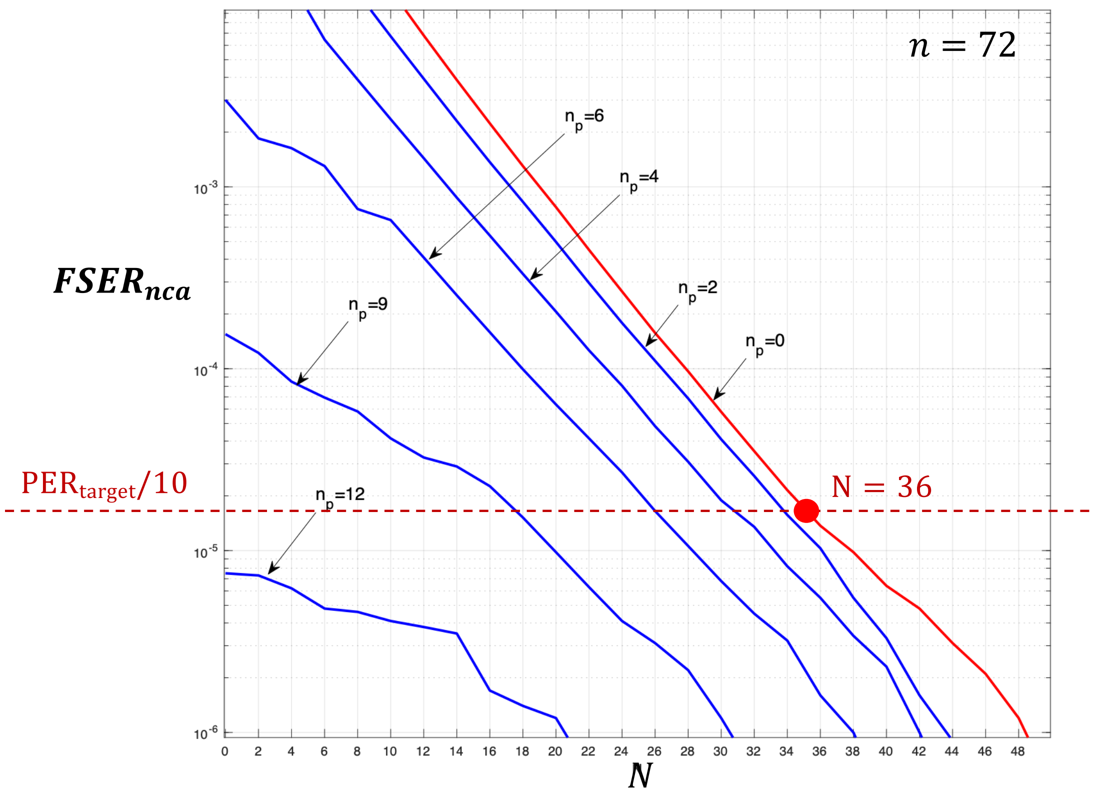
Non-Code-Aided (NCA) synchronization metric :

$$F_1(\tau) \doteq \underbrace{\frac{2}{\sigma_w^2}\Re\left\{\mathbf{y}_p^H(\tau)\mathbf{x}_p\right\}}_{\text{Preamble (Data-Aided)}} + \underbrace{\sum_{m=0}^{n_c-1}\ln\cosh\left(\frac{2\Re\{[\mathbf{y}_c(\tau)]_m\}}{\sigma_w^2}\right) + \sum_{m=0}^{n_c-1}\ln\cosh\left(\frac{2\Im\{[\mathbf{y}_c(\tau)]_m\}}{\sigma_w^2}\right)}_{\text{QPSK-modulated Codeword (Non-Data-Aided)}}$$

Classical Massey's metric [24] adapted for burst transmisión (Maximum Likelihood criterion). Good approximation: $\ln\cosh(x) \approx \|x\|_1$

Synchronization (step 1)

Non-Code-Aided (NCA) synchronization <u>performance analysis</u>:

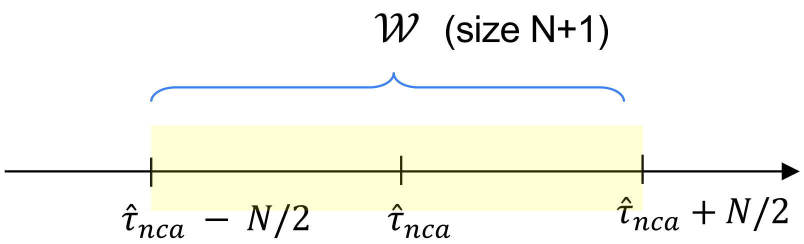


Frame Synchronization Error Rate

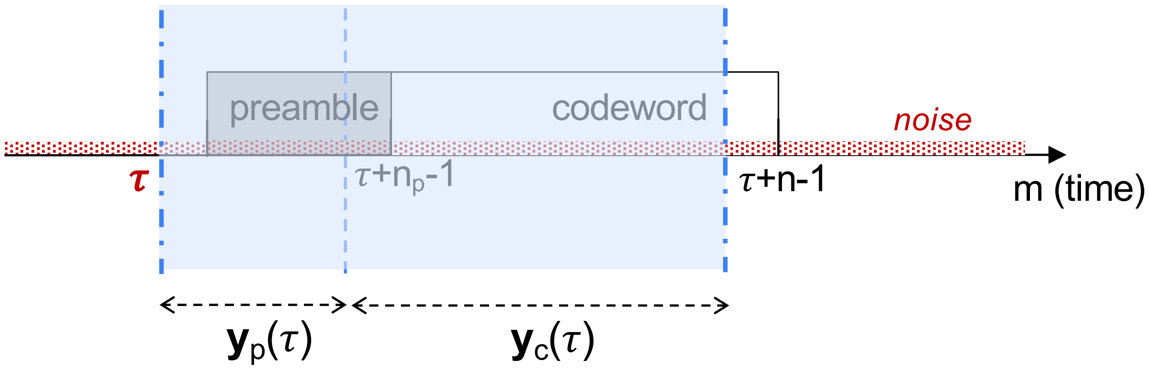
$$\boldsymbol{FSER_{nca}} = \text{Prob}\left(|\hat{\tau}_{nca} - \tau_0| > \frac{N}{2}\right)$$

$$= \text{Prob}\,(\tau_0 \notin \mathcal{W}) \quad < \text{PER}_{\text{target}}/10$$

Negligible!!



Synchronization (step 2)



Code-Aided (NCA) synchronization metric :

Preamble (Data-Aided) — Codeword (Code-Aided)

$$F_2(\tau) \doteq \Re\{\mathbf{y}_p^H(\tau)\mathbf{x}_p\} + \Re\{\mathbf{y}_c^H(\tau)\mathrm{f}_{\mathrm{enc}}[\hat{\mathbf{b}}(\tau)]\}$$

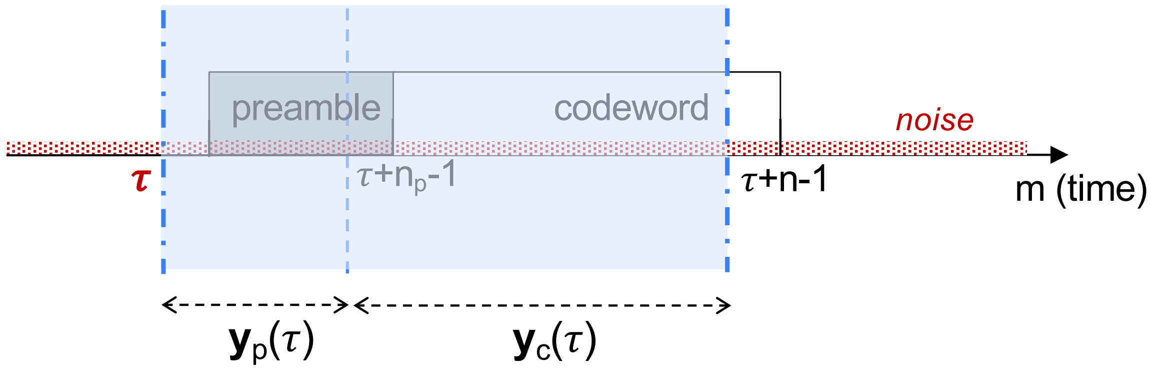
for $\tau \in \mathcal{W}$

__Joint__ Maximum Likelihood (ML) synchronization and decoding.

Reduced search window!!

$$\Rightarrow \boxed{\hat{\tau}_{ca} = \arg\max_{\tau\in\mathcal{W}} F_2(\tau)}$$

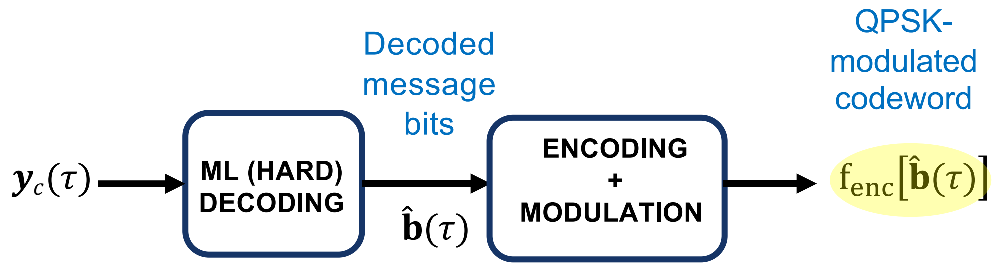
Synchronization (step 2)



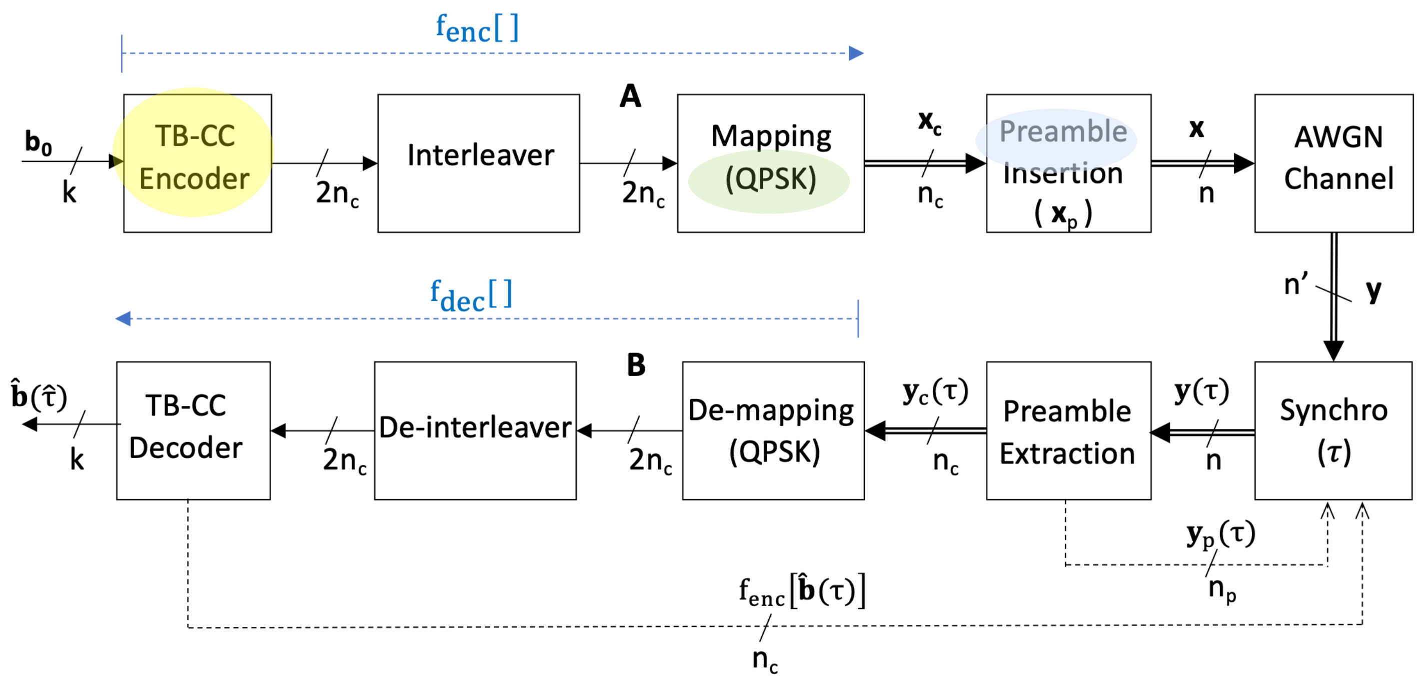
Code-Aided (NCA) synchronization metric :

$$F_2(\tau) \doteq \overbrace{\Re\{\mathbf{y}_p^H(\tau)\mathbf{x}_p\}}^{\text{Preamble (Data-Aided)}} + \overbrace{\Re\{\mathbf{y}_c^H(\tau)\mathrm{f}_{\mathrm{enc}}[\hat{\mathbf{b}}(\tau)]\}}^{\text{Codeword (Code-Aided)}}$$

Joint *Maximum Likelihood (ML) synchronization and decoding.*



Overall architecture

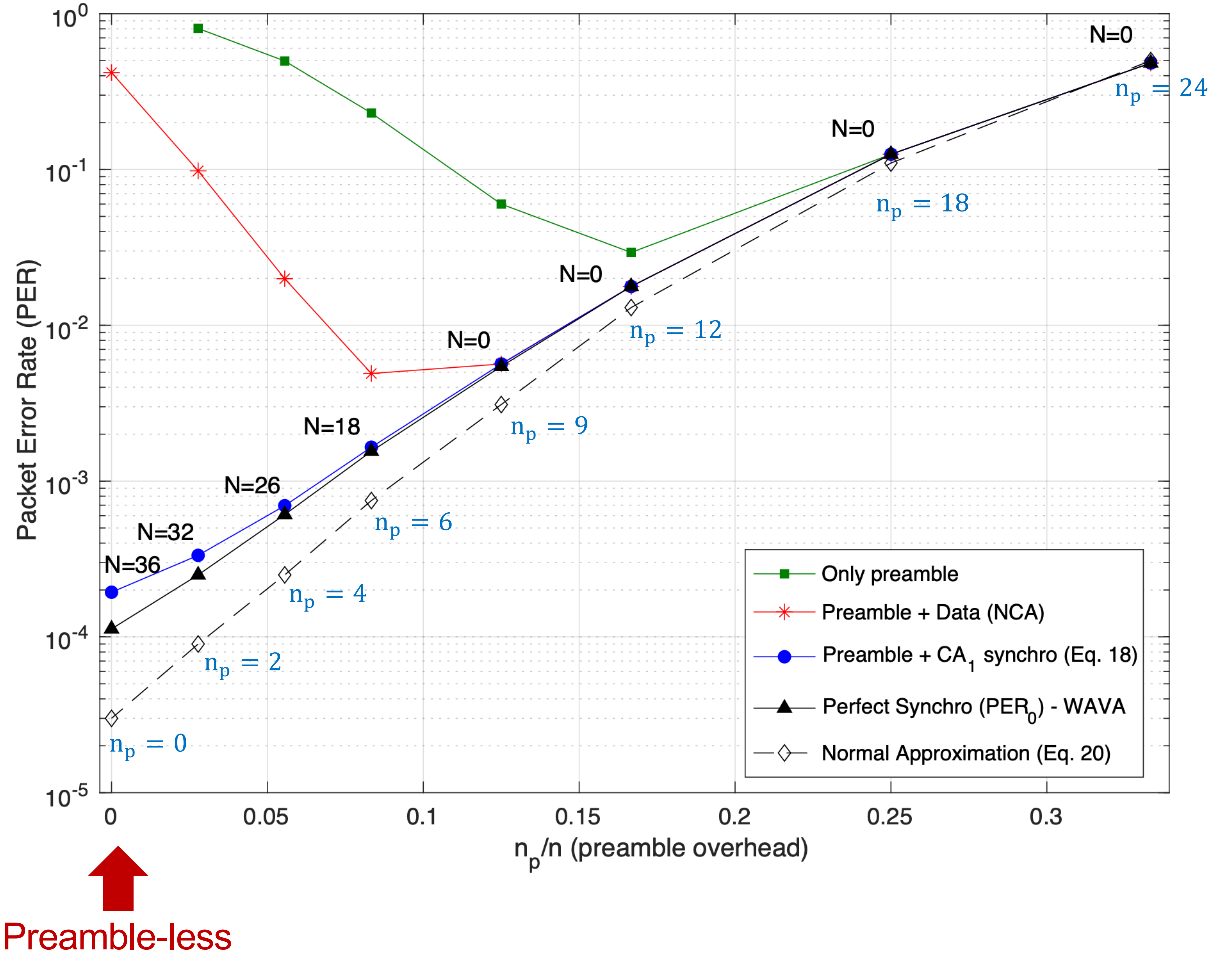


Code: **TB-CC** (large-memory Tail-Biting Convolutional Codes)

Modulation: **QPSK**

Preamble: complex-valued **Zadoff-Chu** sequence

Simulations



- Packet length: **n = 72** (fixed!)
- Message length: **k = 72** (fixed!)
- **TB-CC**

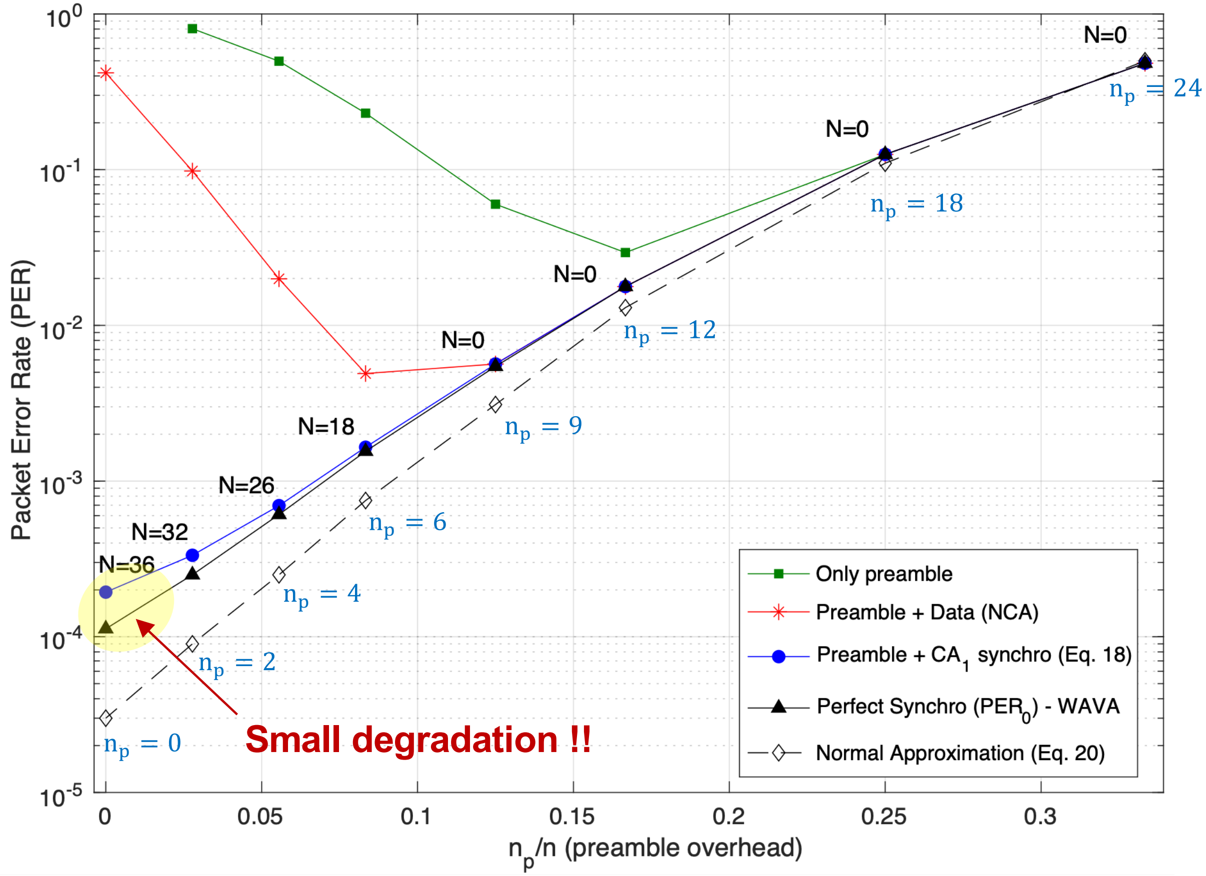
  ½-rate mother code: 5537_{oct} 6131_{oct}

  Memory = 11 bits (2048 states)

  Variable code rate (puncturing): $R_c = \frac{k}{2(n-n_p)}$

  Wrap-Around Viterbi decoder (WAVA) (iterations ≤ 4)
- AWGN channel (Eb/No = 3dB)
- Correct carrier phase/frequency synchronization
- Correct symbol (fine timing) sychronization.

Simulations (II)



Perfect synchro

Code Memory	FSER	PER_0	PER
4	1.8×10^{-5}	2.6×10^{-2}	2.6×10^{-2}
8	6.8×10^{-5}	1.0×10^{-3}	1.0×10^{-3}
11	8.0×10^{-5}	1.2×10^{-4}	1.8×10^{-4}
14	8.4×10^{-5}	5.0×10^{-5}	1.2×10^{-4}

Synchronization does not improve (actually degrades) if we increase the TB-CC memory.

⇩

For short packets and large code memory, synchronization degrades the overall PER.

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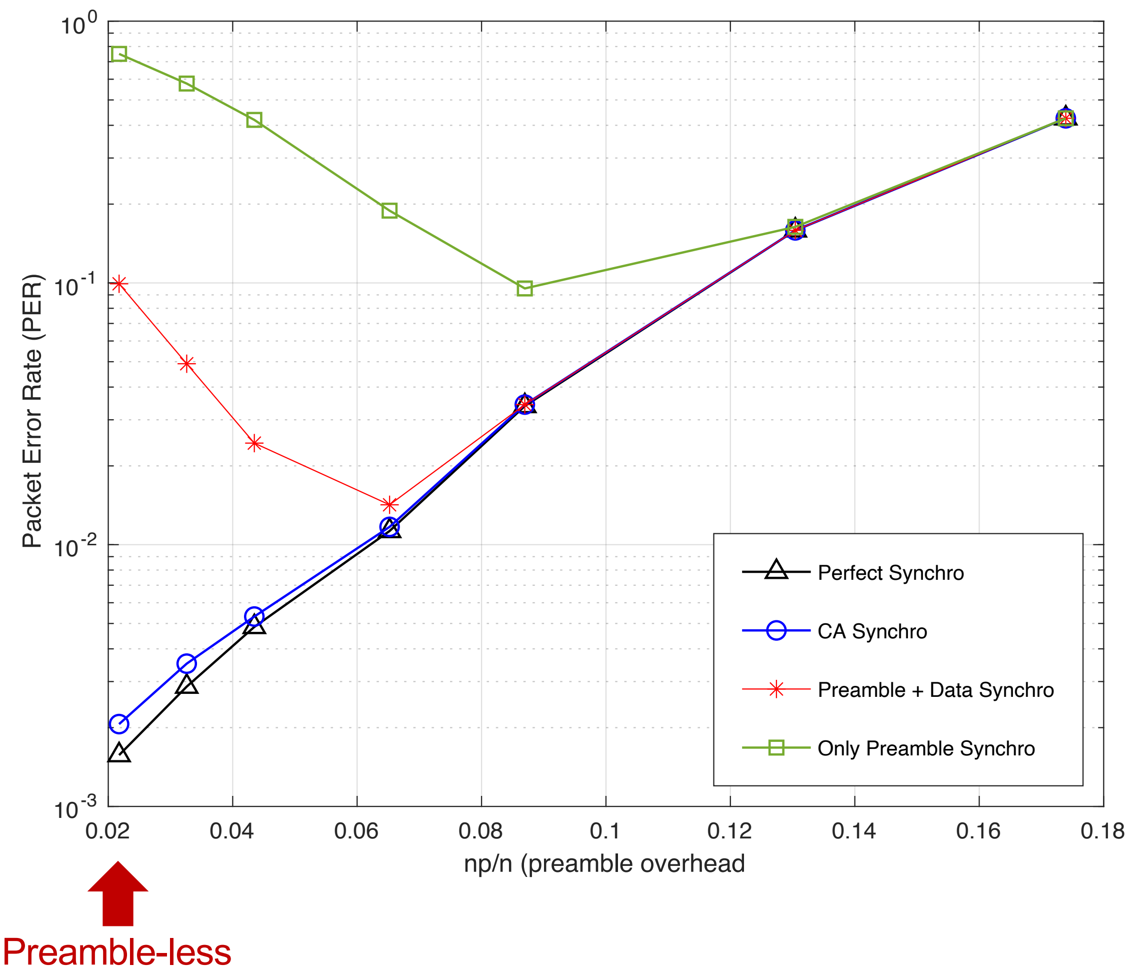
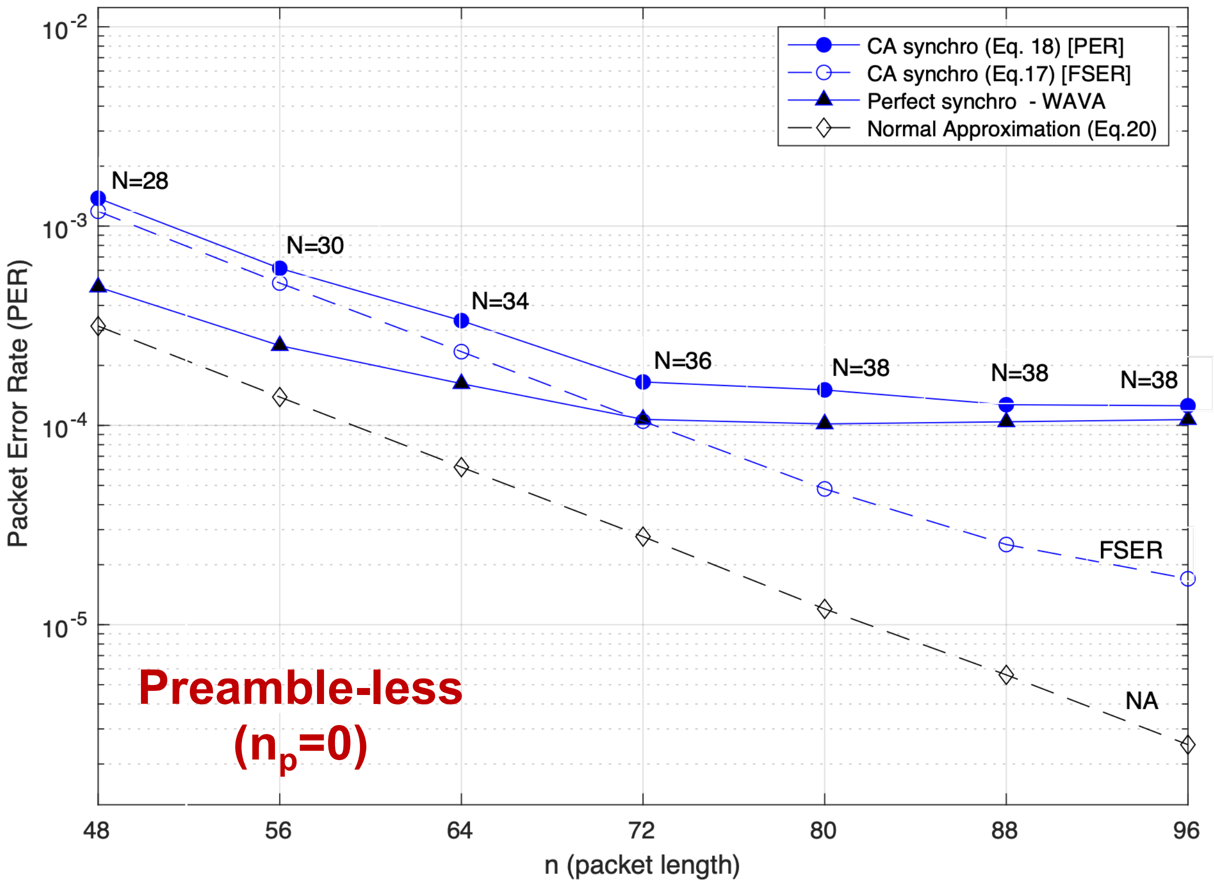
Simulations (III)



- Packet length: **n = 48** (fixed!)
- Message length: **k = 48** (fixed!)
- **TB-CC**

  ½-rate mother code: 5537_{oct} 6131_{oct}
  Memory = 11 bits (2048 states)
  Variable code rate (puncturing): $R_c = \frac{k}{2(n-n_p)}$
  Wrap-Around Viterbi decoder (WAVA) (iterations ≤ 4)
- AWGN channel (Eb/No = 3dB)
- Correct carrier phase/frequency synchronization
- Correct symbol (fine timing) sychronization.

Simulations (IV)



- Packet length: **n = 48-96** (variable!)
- Message length: **k = n**
- **TB-CC**
  ½-rate mother code: 5537_{oct} 6131_{oct}
  Memory = 11 bits
  No puncturing: $R_c = 1/2$ (fixed!!)
  Wrap-Around Viterbi decoder (WAVA)
  (iterations ≤ 4)
- AWGN channel (Eb/No = 3dB)
- Correct carrier phase/frequency synchronization
- Correct symbol (fine timing) sychronization.

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Conclusions and further work

- TB-CC are suited for short blocklength communications (n<72). Gap to Normal Approximation decreases for short packets ($n \leq 72$) and large memory ($m \geq 11$)
- Synchronization of TB-CC encoded packets can degrade the overall PER in that case (i.e, $n \leq 72$ and $m \geq 11$).
- **Preamble-less is optimal** in terms of PER for fixed packet and message lenghts (n and k fixed) even for very short packets (e.g., $48 \leq n \leq 72$).
- Preamble-less communications requieres **N+1 decodings** per packet. For E_b/N_0=3dB and n=k=72, TB-CC, we found that **N≥36**.
- **Complexity reduction** requires:
  - To reduce the number of decodings per packet (N+1). Parallelisation to not increase latency!
  - To reduce complexity of decodings