CSCE 438/838: Internet of Things

Error Control

Purpose

- Error-free
- In-sequence
- Duplicate-free
- Loss-free

Wireless Errors

- Causes: Fading, interference, loss of bit synchronization
  - Results in bit errors, sometimes bursty
  - For low power wireless communication → sometimes quite high average bit error rates (BERs) (10^{-2} … 10^{-4} possible!)

Error Control Approaches

- Automatic Repeat reQuest (ARQ)
- Forward Error Correction (FEC)
- Hybrid ARQ (Type I and II)

ARQ

- Basic procedure
- Put header information before the payload
- Compute a checksum and add it to the end of the packet
  - Typically: Cyclic redundancy check (CRC),
    → quick, low overhead, low residual error rate
- Provide feedback from receiver to sender
  - Send *positive* or *negative acknowledgement* (*ACK/NACK*)

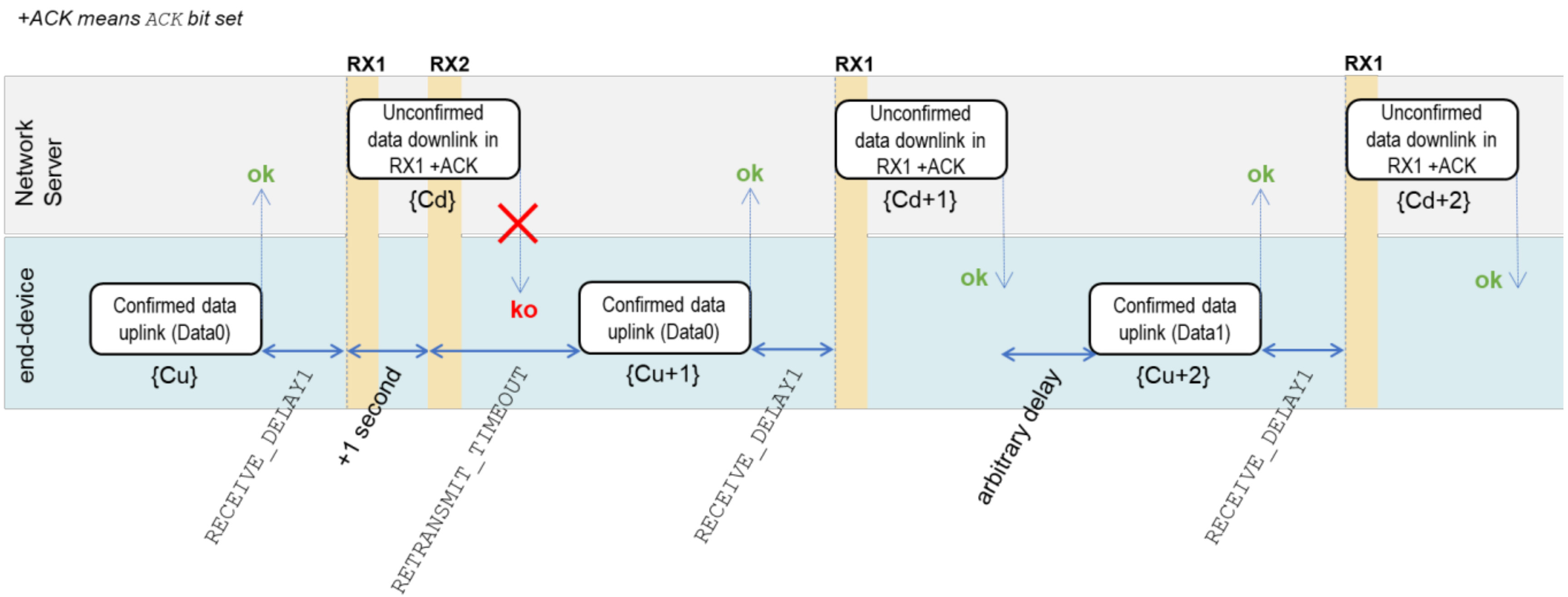
ARQ

- Sender uses timer to detect that ACKs have not arrived
  - Assumes packet has not arrived
  - Optimal timer setting?
- If sender infers that a packet has not been received correctly, sender can retransmit it
  - What is the maximum number of retransmission attempts?

Standard ARQ protocols

- Alternating bit – at most one packet outstanding, single bit sequence number
- Go-back-N – send up to N packets, if a packet has not been ACKed when timer goes off, retransmit all packets after the first unacknowledged packet
- Selective Repeat – when timer goes off, only send the unacknowledged packet(s)

Confirmed Packets



- Uplink
- NS successfully receives Data0
- NS sets ACK bit in its packet and sends during RX1
- Downlik packet is lost
- End-user waits for RETRANSMIT_TIMEOUT sec and retransmits
- NS ACKs

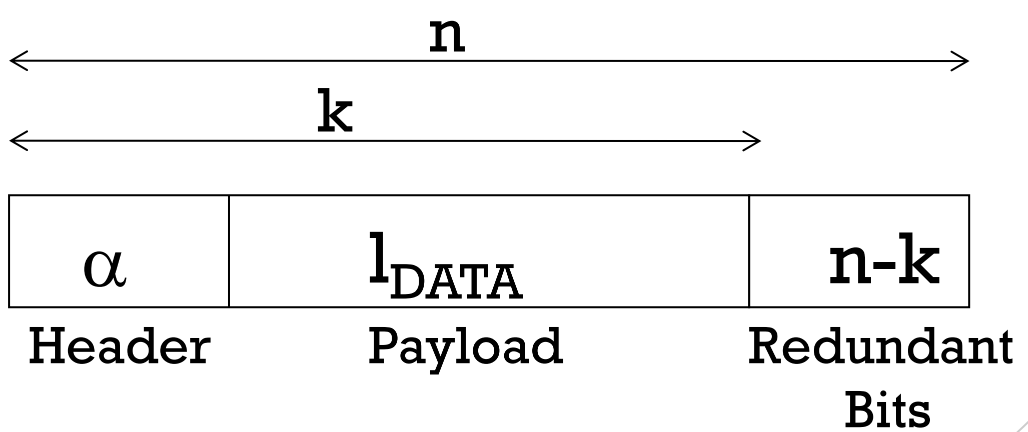
Source: LoRa Alliance

When to Retransmit ?

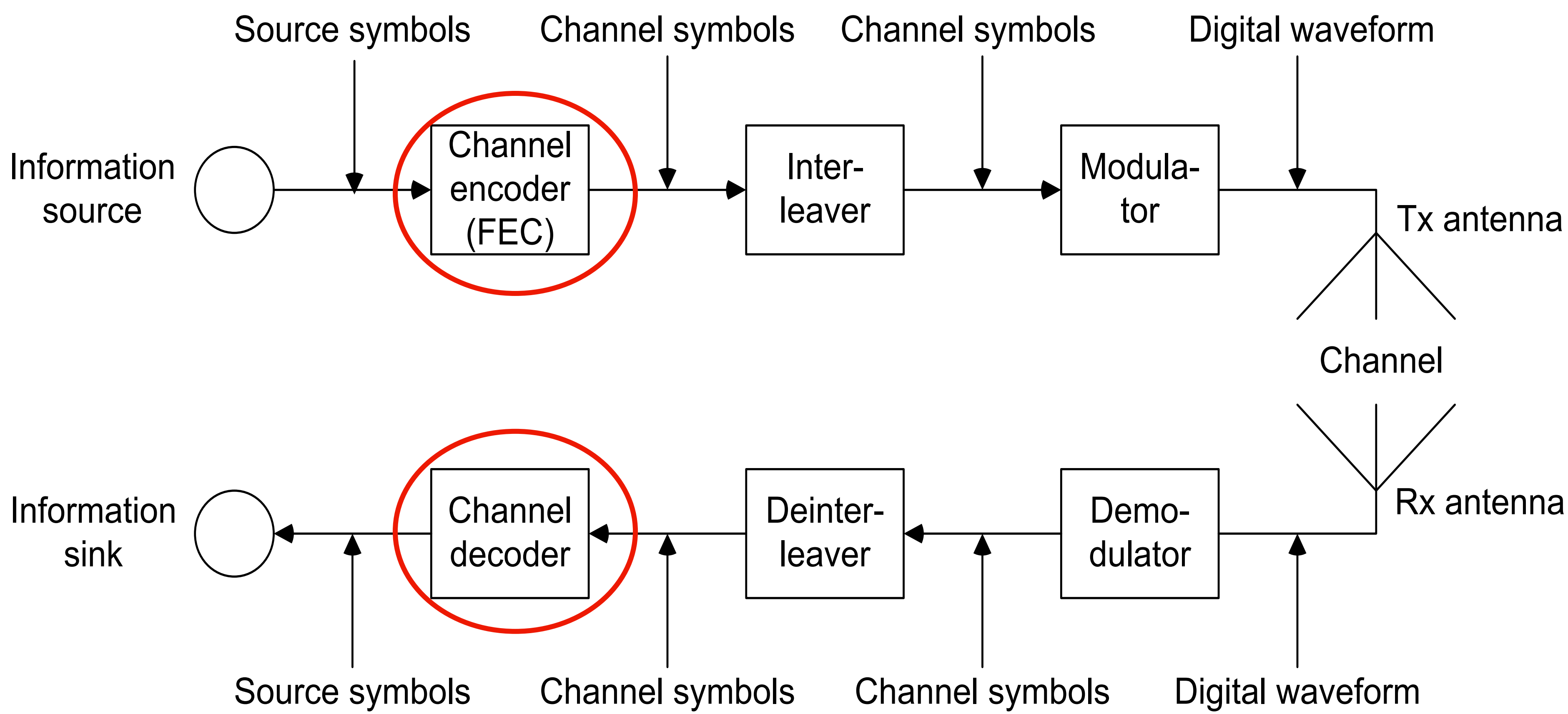
- Assuming sender has decided to retransmit a packet – when to do so?
  - For a good channel, any time is as good as any
  - For fading channels, try to avoid bad channel states – postpone transmissions
  - Instead (e.g.): send a packet to another node if in queue (exploit multi-user diversity)
- REMARK: If the previous packet was corrupted then the channel was bad

Forward Error Control (FEC)

- Idea: Endow symbols in a packet with additional redundancy to withstand a limited amount of random permutations
- Additionally: interleaving – change order of symbols to withstand burst errors



Forward Error Control



Popular Block Code FECs

- Reed-Solomon Codes (RS)
- Bose-Chaudhuri-Hocquenghem Codes (BCH)

Energy Consumption of Block Codes

- Encoding: Negligible overhead (linear-feedback shift register)
- Decoding: Depends on block length (n) and Hamming distance (t)

$$E_{dec} = (2nt + 2t^2)(E_{add} + E_{mult})$$

Eng. Consumption for addition

Eng. Consumption for multiplication

Convolutional Codes

- Code rate: ratio of k user bits mapped onto n coded bits
- Constraint length k determines *coding gain*
- Energy consumption
  - Encoding: cheap
  - Decoding: Viterbi algorithm, energy & memory depends exponentially (!) on constraint length

Last Class

- Error control, ARQ, FEC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BATH ROOM

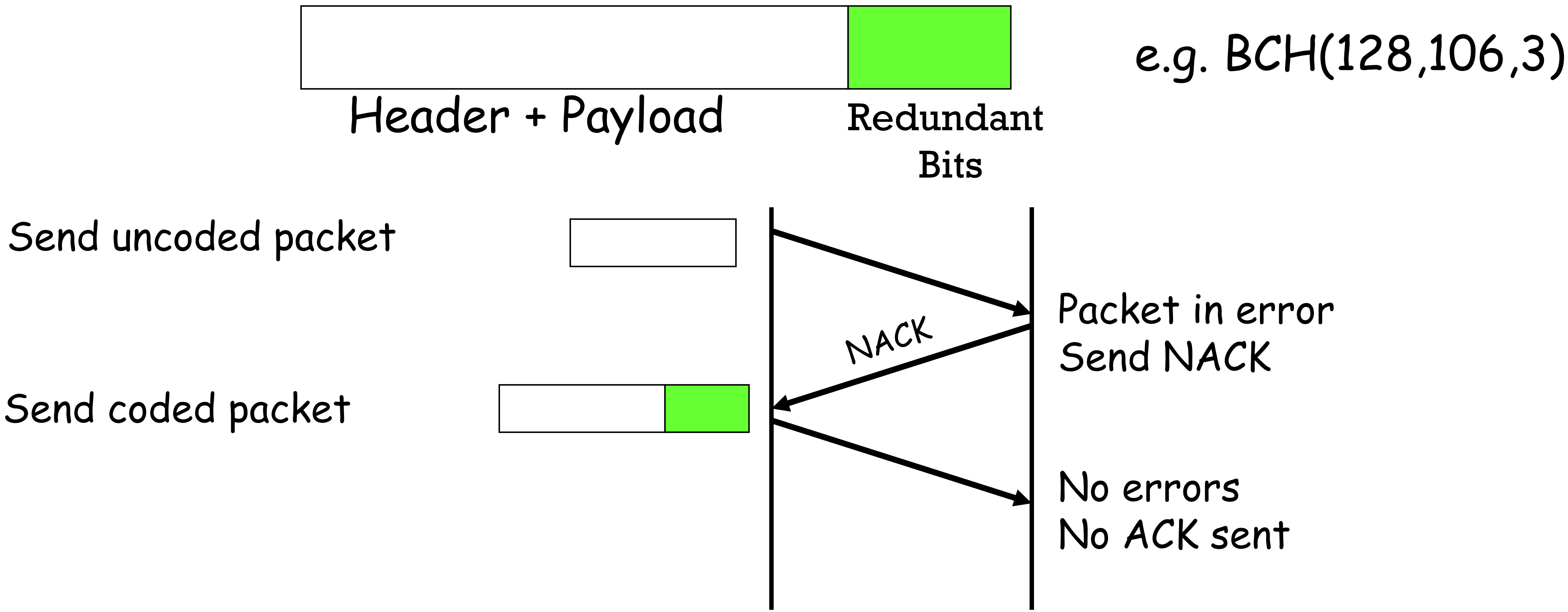
Hybrid ARQ (HARQ)

- ARQ
  - Efficient when channel is good - No redundant bits are sent
  - Inefficient when channel is bad – whole packet is sent again
- FEC
  - Inefficient when channel is good – Redundant bits sent anyway
  - Efficient when channel is bad – No retransmissions
- Hybrid ARQ
  - Marry ARQ and FEC
  - Get advantages from both techniques

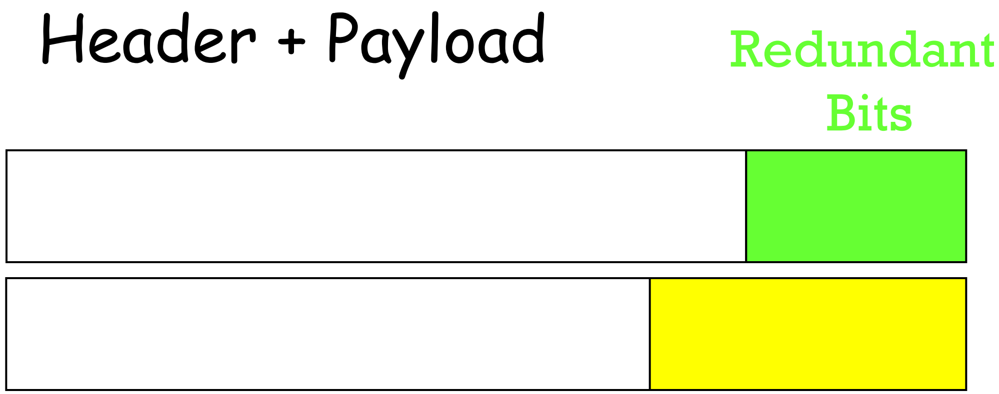
Hybrid ARQ

- Send uncoded or lightly coded packet first
- If in error, retransmit with a stronger code
- Two types based on retransmission technique
  - HARQ Type I
  - HARQ Type II

Hybrid ARQ Type I (HARQ-I)



Hybrid ARQ Type I (HARQ-I)

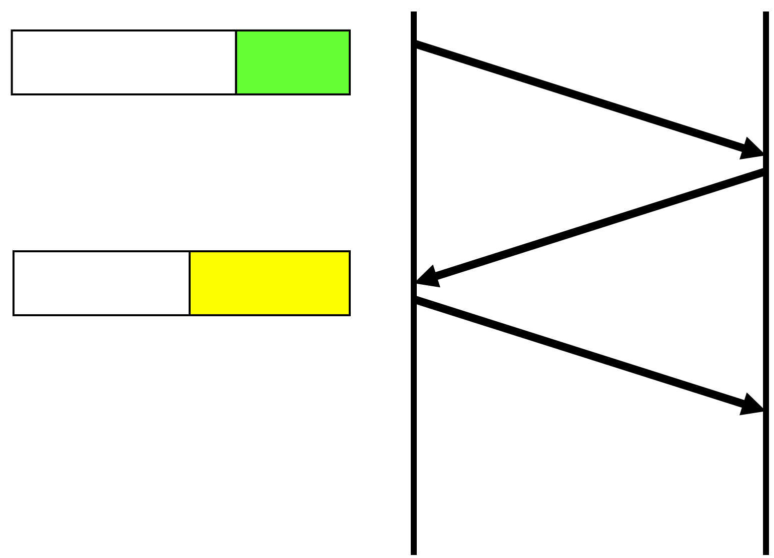


e.g. BCH(128,106,3)

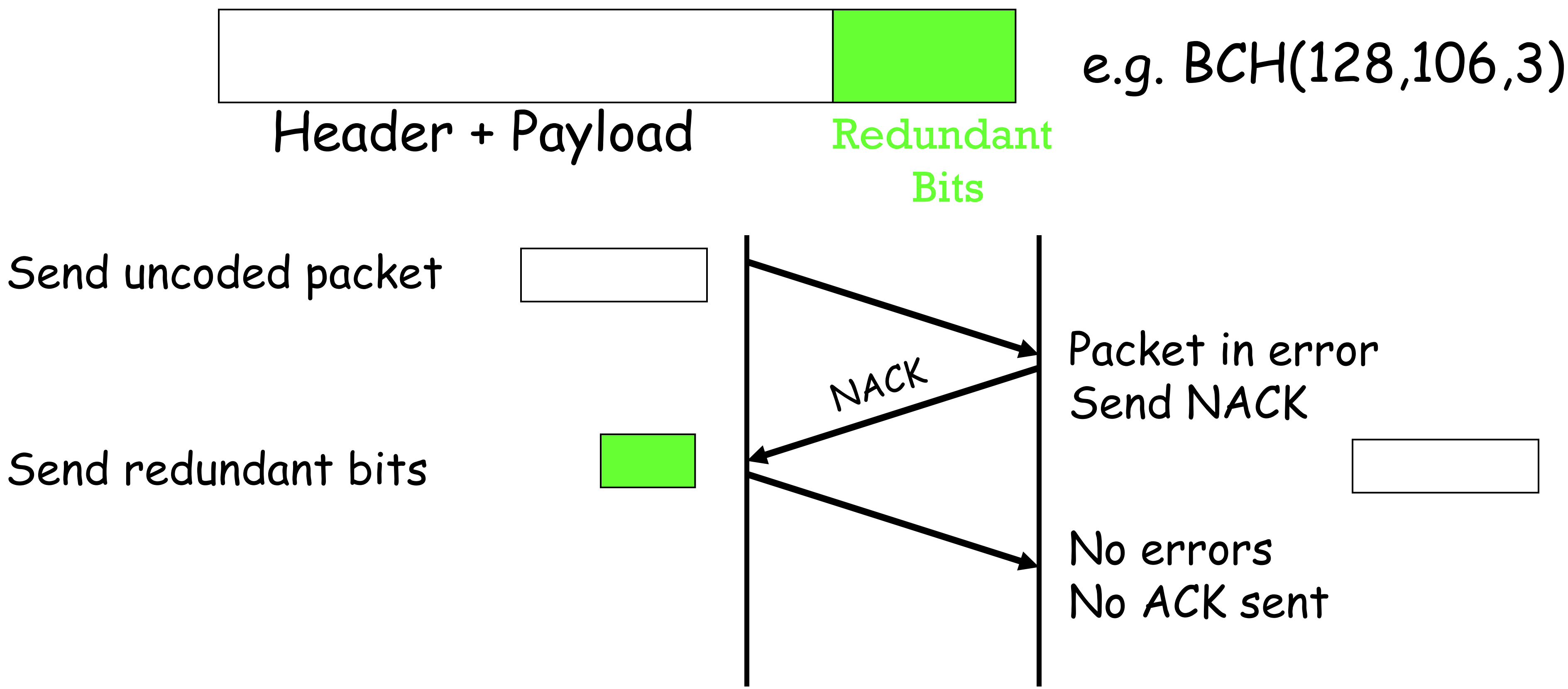
e.g. BCH(128,78,7)

Send lightly coded packet

Send more powerful coded packet



Hybrid ARQ Type II (HARQ-II)



Hybrid ARQ

- Type I – Does not require previous packet to be stored
- Type II – Reduces bandwidth usage

Error Control through Transmit Power Control

- Higher transmission power reduces the packet error rate by improving SNR.

→ Energy consumption and interference is increased

- Radio should support different power levels

Questions?

Cross-Layer Comparison: FEC, ARQ, HARQ

M. C. Vuran and I. F. Akyildiz, "Error Control in Wireless Sensor Networks: A Cross Layer Analysis, *IEEE Trans. on Networking*, *vol. 17, no. 4, pp. 1186-1199, April 2009.*

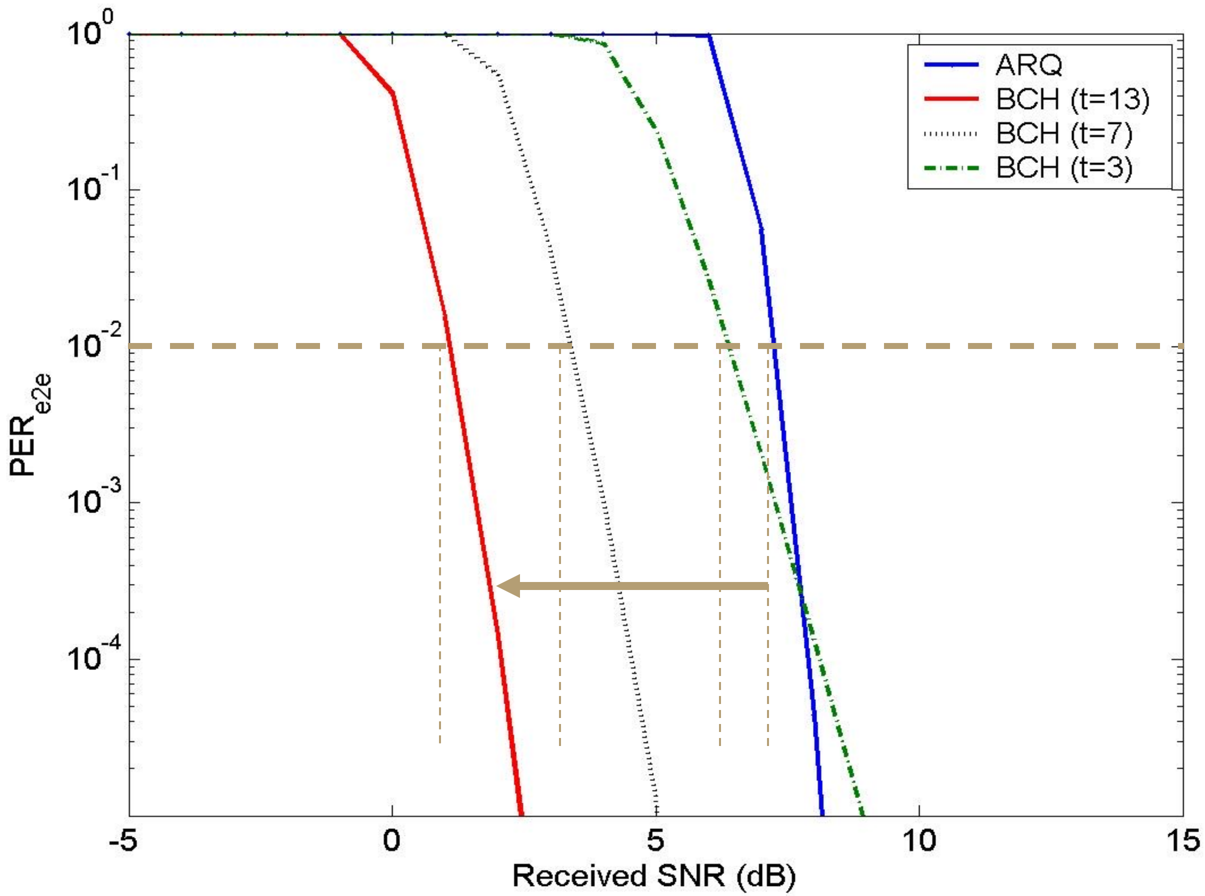
- Investigate the tradeoffs between ARQ, FEC, and HARQ in terms of
  - Energy consumption
  - Latency
  - Packet error rate
- Jointly considers
  - Broadcast wireless channel
  - Multi-hop communication
  - Realistic channel model
  - 2-D topology
  - Realistic hardware models (Mica2 and MicaZ)

Cross-Layer Effects

- Multi-hop communication affects
  - End-to-end packet error rate
  - Energy consumption
  - Latency
- Broadcast wireless channel
  - Nodes other than communicating parties are affected (overhearing)
- Wireless channel
  - Channel characteristics drastically influence BER performance

Cross-layer analysis of error control is necessary

Error Resiliency

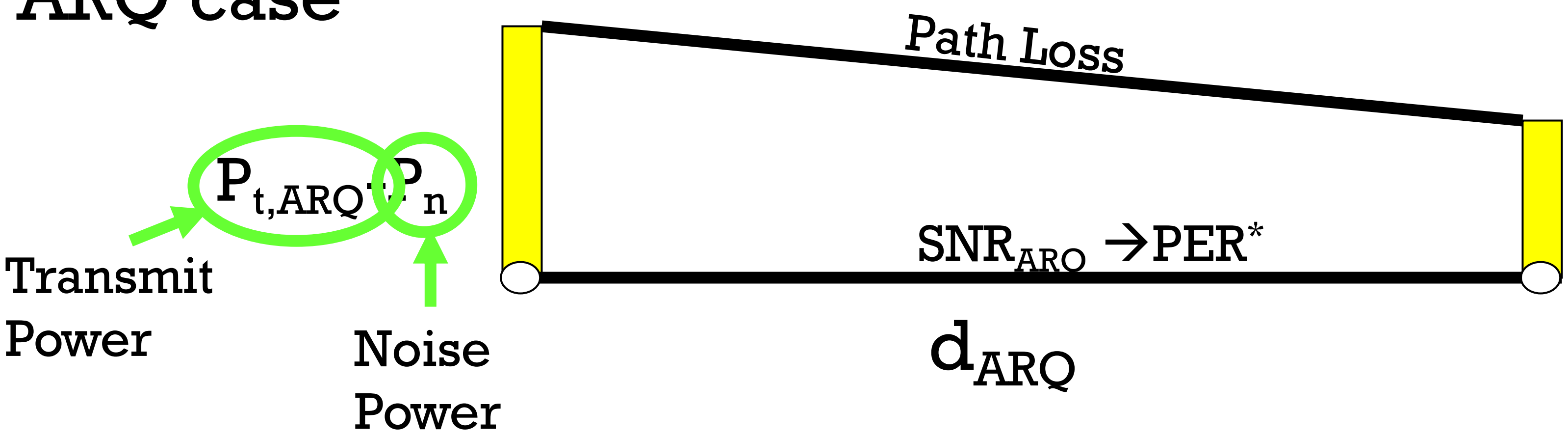


- Packet Error Rate (PER) is a function of signal to noise ratio (SNR), i.e., channel quality
- ARQ vs. FEC: FEC codes provide the same PER with lower SNR, i.e., lower channel quality
  - For PER*, $SNR_{ARQ} > SNR_{FEC}$
- As error correction capability, t, increases, error resiliency improves

Error Resiliency

- How can error resiliency be exploited in multi-hop IoT?

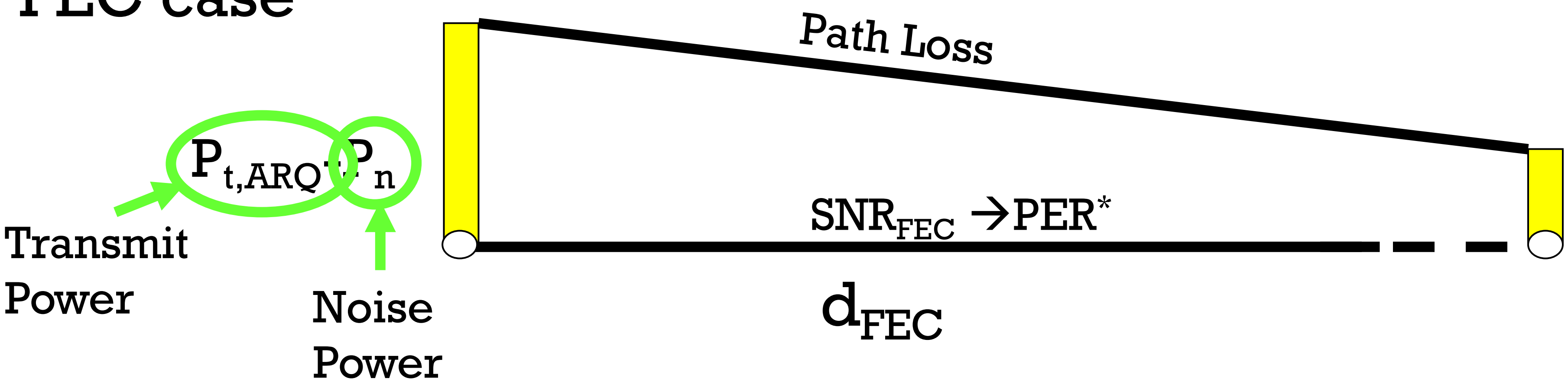
ARQ case



Error Resiliency

- How can this be exploited in multi-hop IoT?
  - Hop-length Extension (increase hop length for FEC)
    - $P_{t,FEC} = P_{t,ARQ}$, $d_{FEC} > d_{ARQ}$

FEC case



Error Resiliency

- How can this be exploited in multi-hop IoT?
  - Hop-length Extension (increase hop length for FEC)
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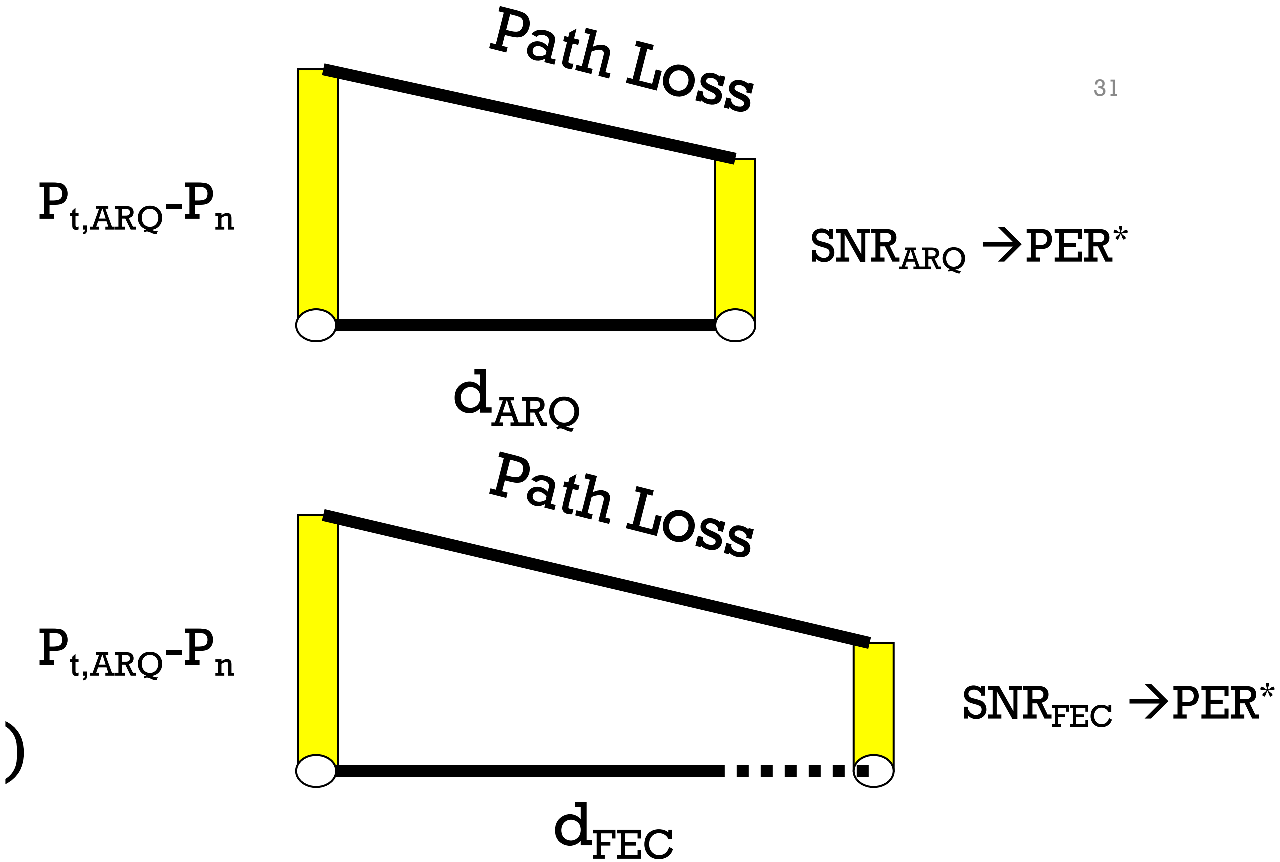
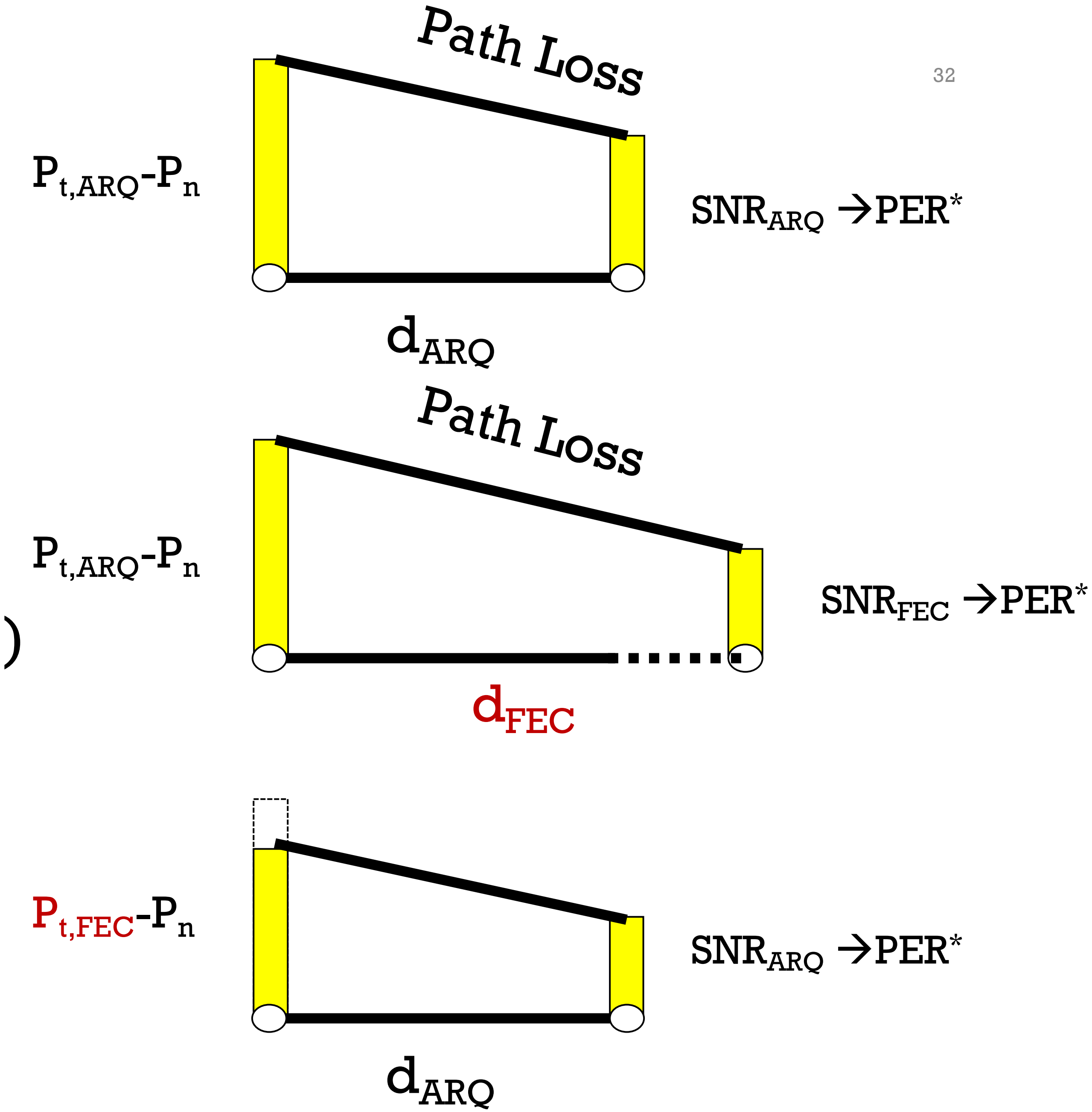


Error Resiliency

- How can this be exploited in multi-hop IoT?
  - Hop-length Extension (increase hop length for FEC)
    - $P_{t,FEC} = P_{t,ARQ}$, $d_{FEC} > d_{ARQ}$
  - Transmit Power Control (decrease transmit power)
    - $P_{t,FEC} < P_{t,ARQ}$, $d_{FEC} = d_{ARQ}$



Cost

- FEC codes improve error resiliency at the cost of
  - Encoding/decoding (energy + latency)
  - Tx/Rx longer packets (energy + latency)

α	l_{DATA}	n-k
Header	Payload	Redundant Bits

Network Model

- Channel-aware routing
  - Next hop j is selected if received SNR, $\psi_j > \psi_{Th}$ (SNR threshold)
- Contention-based medium access
  - RTS-CTS-DATA(-ACK) exchange
- Duty cycle operation
  - Nodes are active δ fraction of the time

Cross-layer Analysis

- Channel model

$$P_r(d) = P_t - PL(d_0) - 10\eta log\left(\frac{d}{d_0}\right) + X_\sigma$$

Received Power

Transmit Power

Path loss

Path loss exponent

Log-normal Shadow fading

Cross-layer Analysis

- SNR threshold for a target BER
- Per-hop and end-to-end energy consumption
- End-to-end latency
- Decoding latency and energy
- Hardware-based BER

Numerical Evaluations

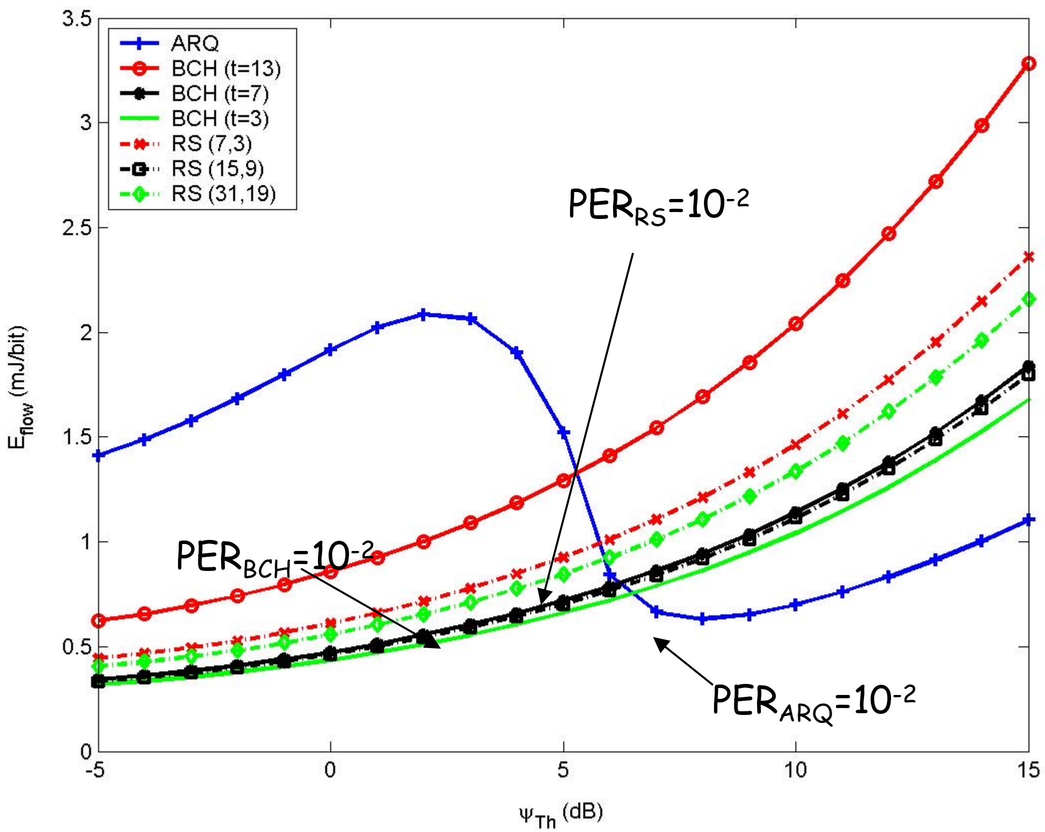
D	300 m	l_C	8 bytes
P_t	0, -5, -15 dBm	l_D	38 bytes
PL_{d0}	55 dB	t_{cycle}	250 ns
P_n	-105 dBm	I_{proc}	8 mA
η	3	V	3 V
σ	3.8		
	Mica2	MicaZ	
e_{rx}	21 mJ	59.1 mJ	
e_{tx} (P_t=0)	24 mJ	52.2 mJ	
e_{tx} (P_t=-5)	21.3 mJ	42 mJ	
e_{tx} (P_t=-15)	16.2 mJ	29.7 mJ	
$t_{bit} = 1/R$	62.4 μs	4 μs	
N	N/A	16 chips	
K	N/A	2	

- Energy consumption, latency and PER are found for Mica2 and MicaZ, and ARQ, FEC, and HARQ schemes

Numerical Evaluations

- FEC Codes
  - BCH (n,k,t) - (128,50,13), (128,78,7), (128,106,3)
  - RS (n,k,t) – (7,3,2), (15,9,3), (31,19,6)
- Hybrid ARQ (I & II) Notation:
  - HARQ-I (t1,t2) means:
    - Hybrid ARQ type I
    - t1: error correction capability for 1st transmission (t1 = 0 → uncoded packet)
    - t2: 2nd transmission
    - BCH codes are used for coded transmission

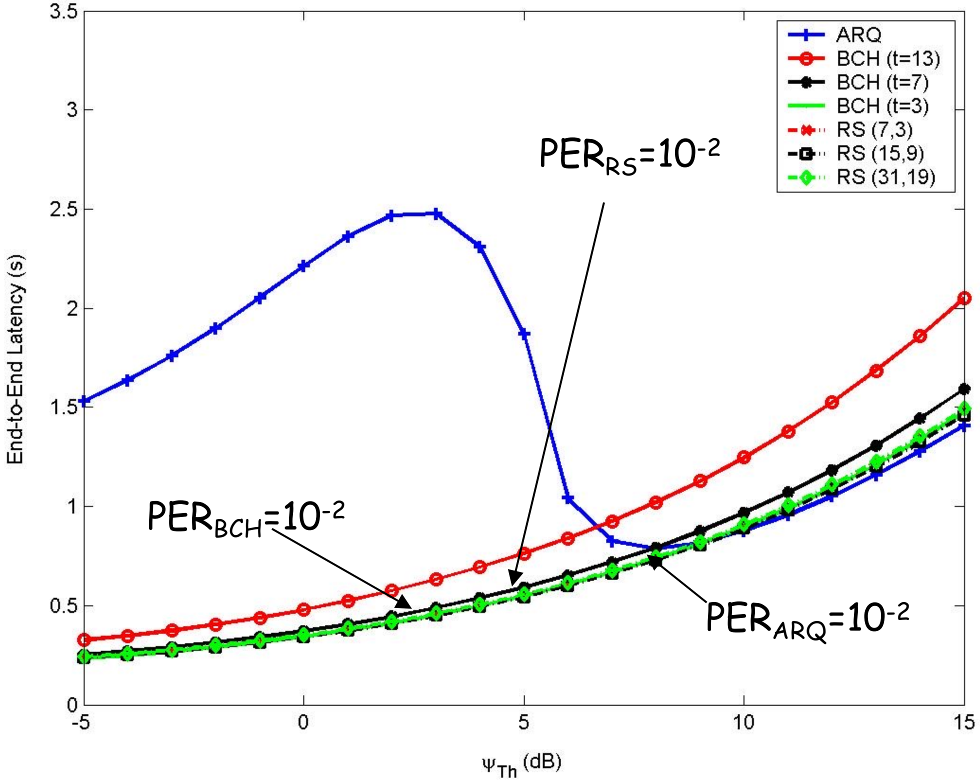
Hop Length Extension



Energy Consumption (MicaZ)

- Energy consumption vs. SNR threshold
- Lower SNR threshold leads to longer hop length
- BCH and RS achieve the same PER for lower SNR threshold compared to ARQ
- BCH (t=7) consumes less energy than ARQ
- RS (t=3) consumes more energy than ARQ

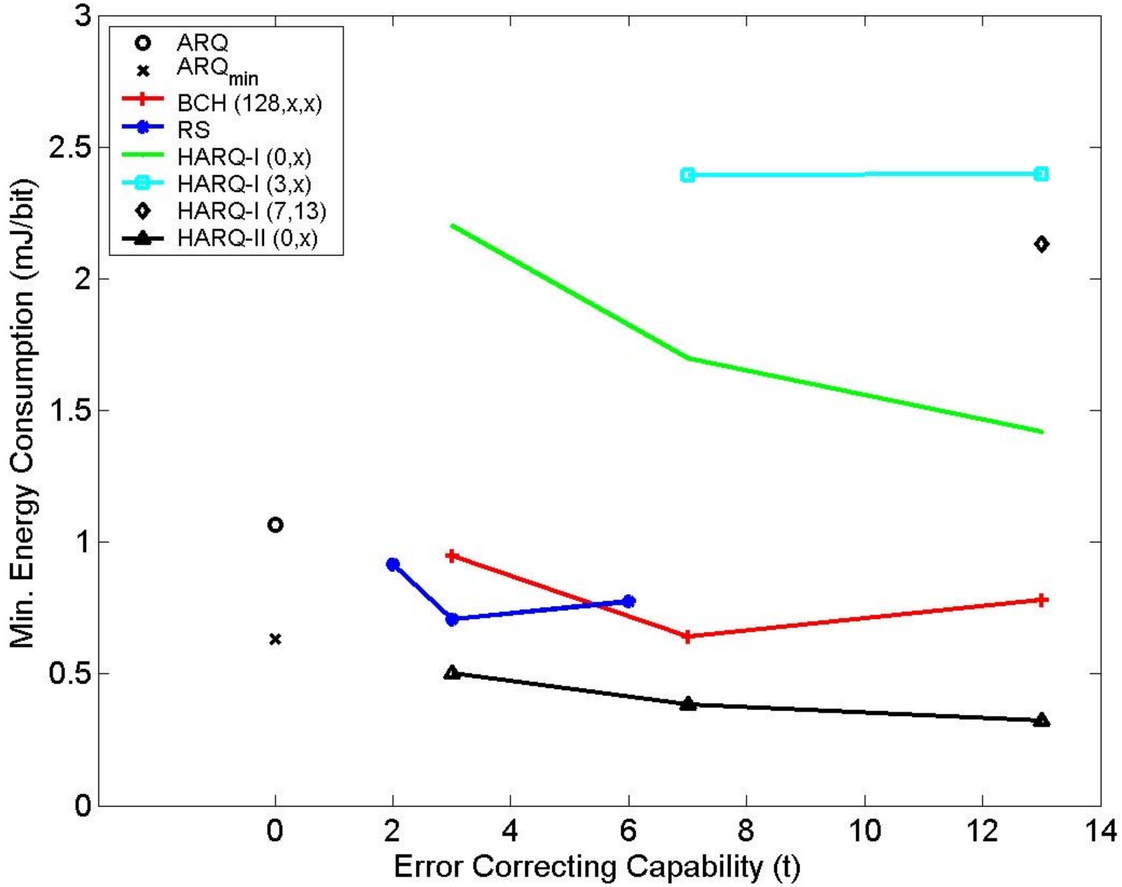
Hop Length Extension



Latency (MicaZ)

- Compared to ARQ, BCH and RS achieve lower latency for the same PER
- Lower SNR threshold → longer hops → less number of hops → lower latency

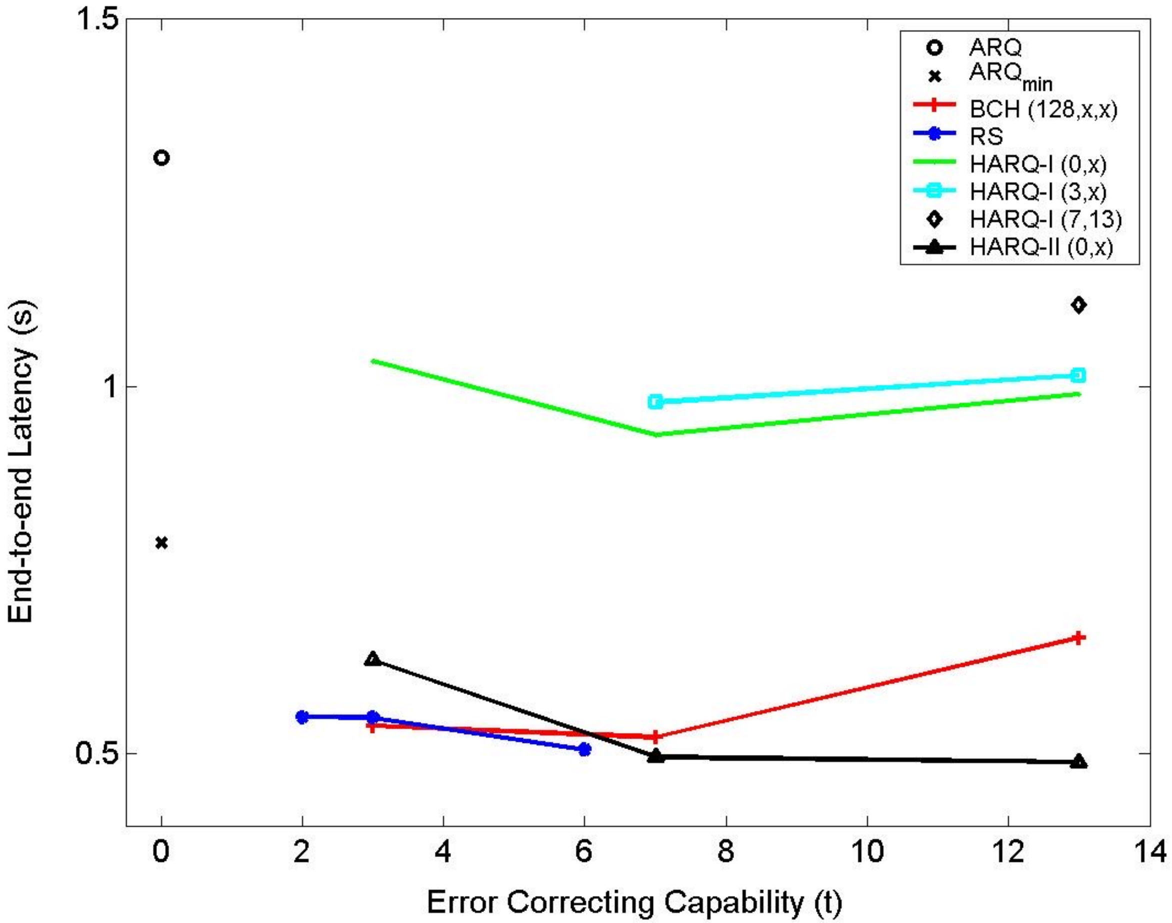
Hybrid ARQ



Energy Consumption (MicaZ)

- HARQ-II outperforms ARQ and FEC schemes
- HARQ-I is less energy efficient – whole packet is retransmitted
- For HARQ-II, energy efficiency improves if error correction capability (t) increases
- HARQ-II implementation cost is also lower than HARQ-I

Hybrid ARQ



- HARQ-II, BCH, and RS provide lower latency compared to ARQ
- HARQ-I latency is significantly higher
  – Retransmission + Encoding/Decoding overhead
- HARQ-II and RS most suitable for delay sensitive traffic

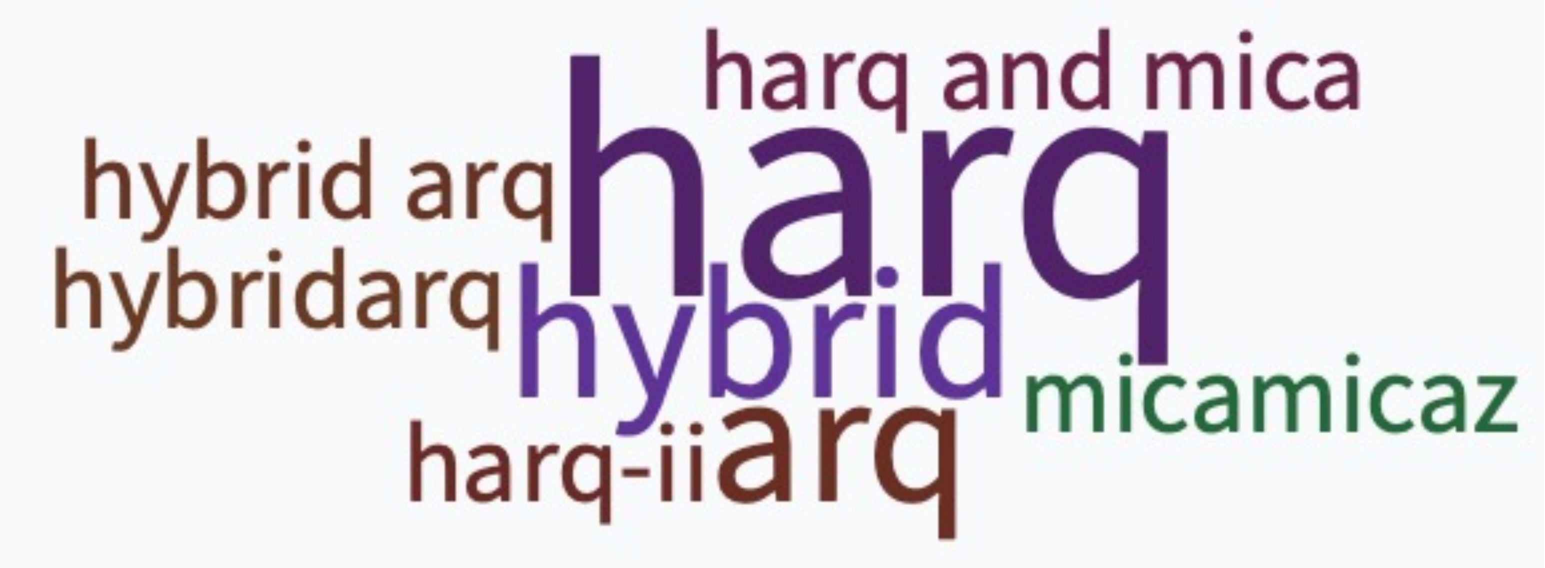
Conclusions

- A cross-layer analysis of ARQ, FEC, and HARQ
- Developed framework enables a generic analysis with various parameters (e.g. BCH, RS, Mica2, MicaZ)
- Careful selection of FEC parameters improve latency without hampering energy consumption (HARQ and RS suitable for multimedia traffic)
- Hardware support for FEC will improve performance

	Hop Length Ext.		Tx. Power Cont.	
	Energy	Latency	Energy	Latency
Mica2	HARQ I&II	HARQ I&II	BCH ($t \geq 1$)	ARQ
MicaZ	HARQ II	HARQ II	BCH ($t \geq 1$)	ARQ

Questions?

Which concept was the most intriguing? (one word)



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