Lecture

Link Layer Protocols in WSNs

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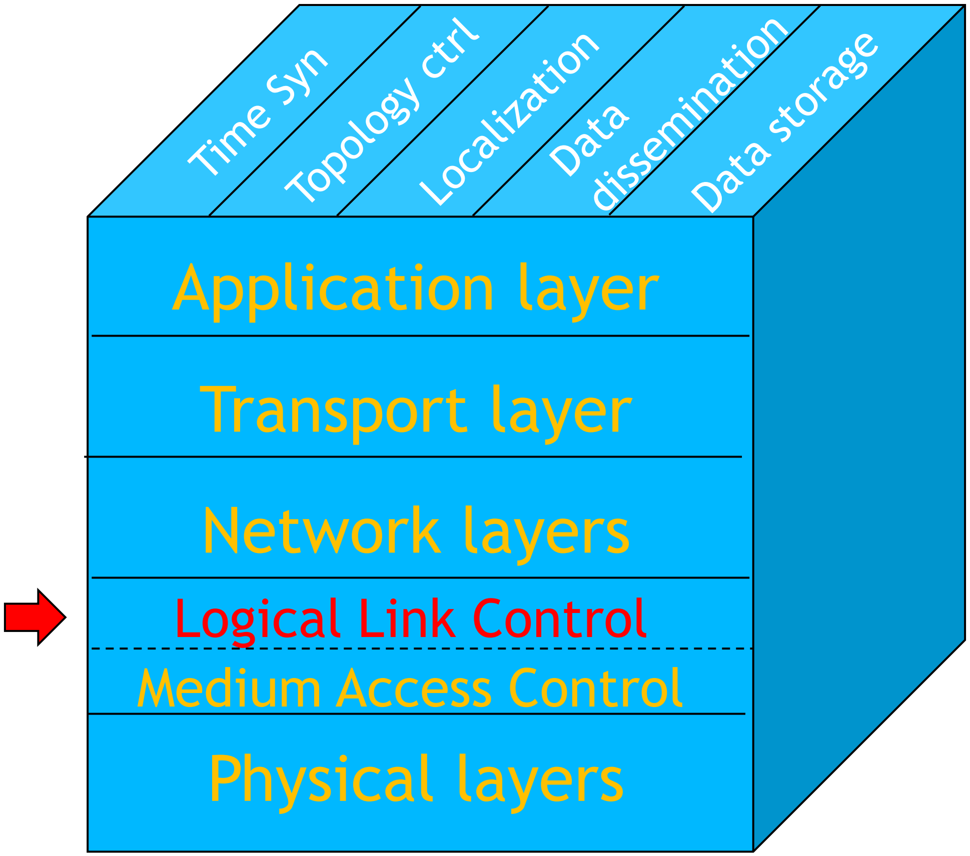
Relevant topics in WSN



Objective of this lecture

- The link layer has a task of ensuring a reliable communication link between neighbor nodes
  - Reliability in single hop link

- To achieve reliability over the time-variable wireless link, there are many mechanisms with different performance and energy consumption

- We will learn the relationship between reliability, error rate and energy consumption.

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Outline

- ***Error control***
- Framing
- Link management

Error control

- Error control has to ensure that data transport is
  - **Error-free** – deliver exactly the sent bits/packets
  - **In-sequence** – deliver them in the original order
  - **Duplicate-free** – and at most once
  - **Loss-free** – and at least once
- Causes: fading, interference, loss of bit synchronization, …
  - Results in bit errors, burst error
  - In wireless, even for stationary transmitter and receiver, bit error rate is time variable, average BER can be high – 10^{-2} … 10^{-4} possible!
- Approaches
  - ARQ: Reactive
  - Forward error control – FEC: Proactive

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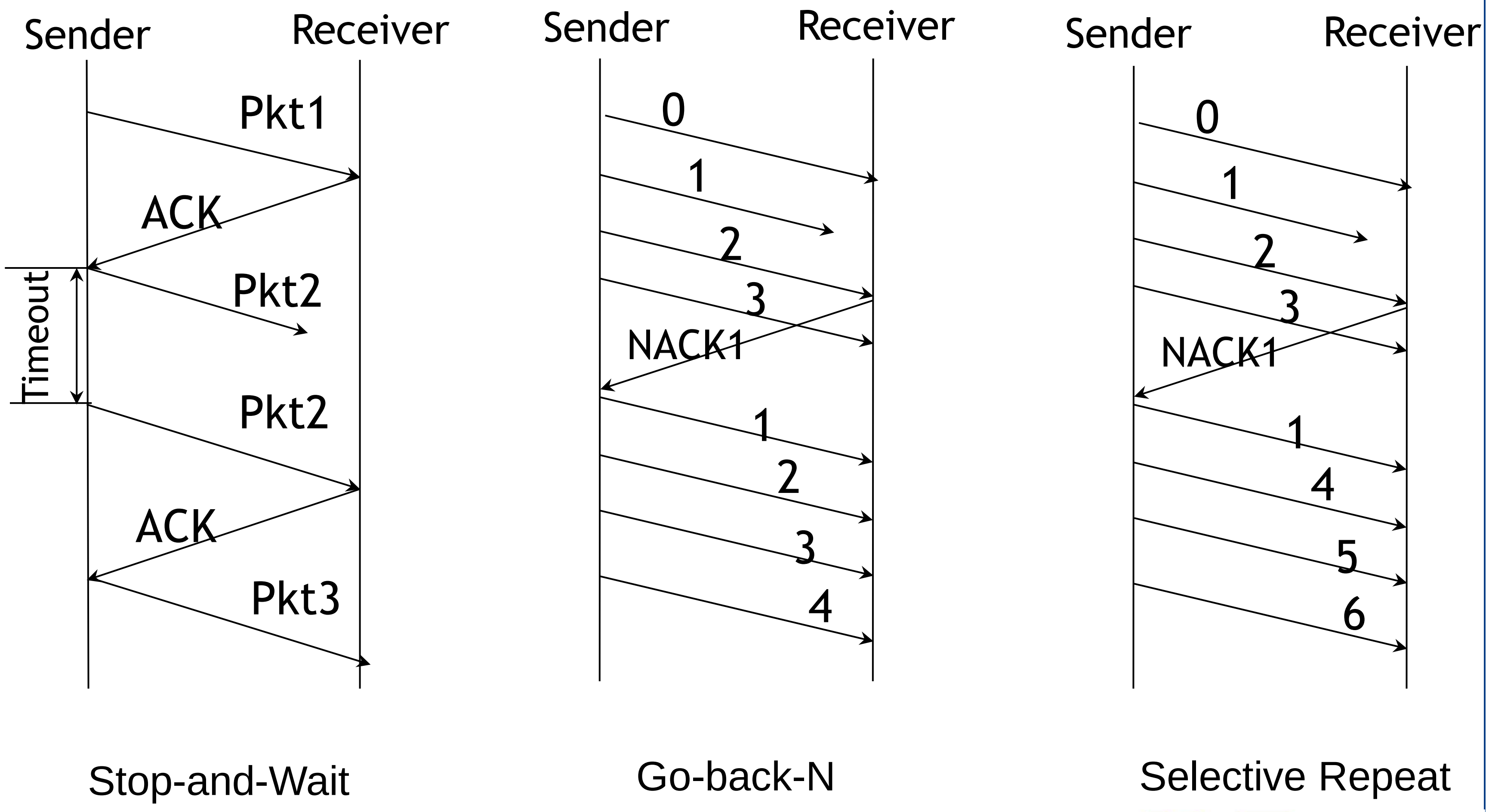
ARQ

- Basic procedure
  - Put header information around the payload
  - Compute a checksum and add it to the packet
    - Typically: Cyclic redundancy check (CRC), easy to implement,
  - Provide feedback from receiver to sender
    - Send ***positive*** or ***negative acknowledgement***
  - 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 maximum number of retransmission attempts?
    - If bounded, at best a semi-reliable protocols results

Standard ARQ protocols

- Stop-and-Wait (Alternating bit): at most one packet outstanding, single bit sequence number
- Go-back-N:
  - The transmitter sends up to N packets, keep buffer for op to N packets
  - The receiver accepts frame only in the sequence and drops frames that even are correctly received but do not have the expected sequence number.
  - The receiver acknowledges the last received packet in sequence and only needs to buffer this packet.
  - If a packet has not been acknowledged when timer goes off, transmitter retransmits all unacknowledged packets
- Selective Repeat: when timer goes off, only send that particular packet


Sender
Receiver
Pkt1
ACK
Timeout
Pkt2
Pkt2
ACK
Pkt3
Sender
Receiver
0
1
2
3
NACK1
1
2
3
4
Sender
Receiver
0
1
2
3
NACK1
1
4
5
6
Stop-and-Wait
Go-back-N
Selective Repeat

How to use acknowledgements

- Be careful about ACKs from different layers
  - A link layer ACK means
    I. Correctly receive the packet
    II. Has sufficient buffer space to process it further
    III. The accepted packet is in sequence or out-of-sequence
  - A MAC ACK (e.g., S-MAC) only indicates condition (I) and for stop-and-wait or selective repeat (II) and (III) are often implied.
  - Depending on the implementation, if all three conditions are met, the MAC layer ACK can be used simultaneously as link layer ACK. Otherwise, extra link layer ACK are required.
- Do not (necessarily) acknowledge every packet – use cumulative ACKs
  - E.g. windowed feedback with selective repeat and instantaneous feedback with selective repeat
  - Tradeoff: throughput, delay, energy, buffer size

When to retransmit

- Assuming sender has decided to retransmit a packet – when to do so?
  - In a BSC channel, any time is as good as any
  - In fading channels, try to avoid bad channel states – postpone transmissions

- How long to wait?
  - Example solution: Probing protocol
  - Idea: reflect channel state by two protocol modes, "normal" and "probing"
  - When error occurs, go from normal to probing mode
  - In probing mode, periodically send short packets (acknowledged by receiver) – when successful, go to normal mode

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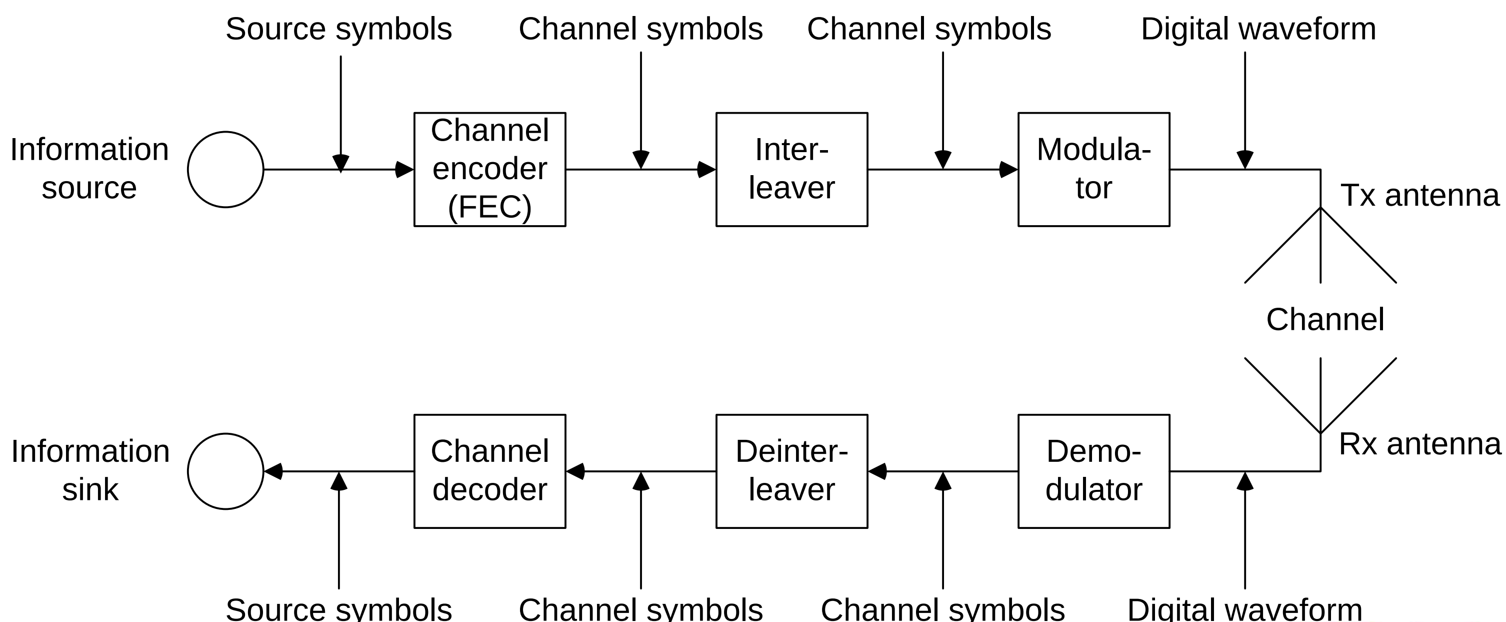
Forward error control

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



Block-coded FEC

- Level of redundancy: ***blocks of symbols***
  - Block: k p-ary source symbols (not necessarily just bits)
  - Encoded into n q-ary channel symbols
- Injective mapping (***code)*** of p^k source symbols into q^n channel symbols
- ***Code rate***: $(k \log_2(p)) / (n \log_2(q))$
  - When p=q=2: k/n is code rate

Popular block codes

- Popular examples
  - Reed-Solomon codes (RS)
  - Bose-Chaudhuri-Hocquenghem codes (BCH)
- Energy consumption
  - E.g., BCH encoding: negligible overhead (linear-feedback shift register)
  - BCH decoding: depends on block length *n*, and the number of correctable bits *t*, as

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

    - $E_{dec:}$ Energy Consumption for Decoding
    - $E_{add:}$ Energy Consumption for Addition
    - $E_{mult:}$ Energy Consumption for Multiplication
  - Similar for RS codes

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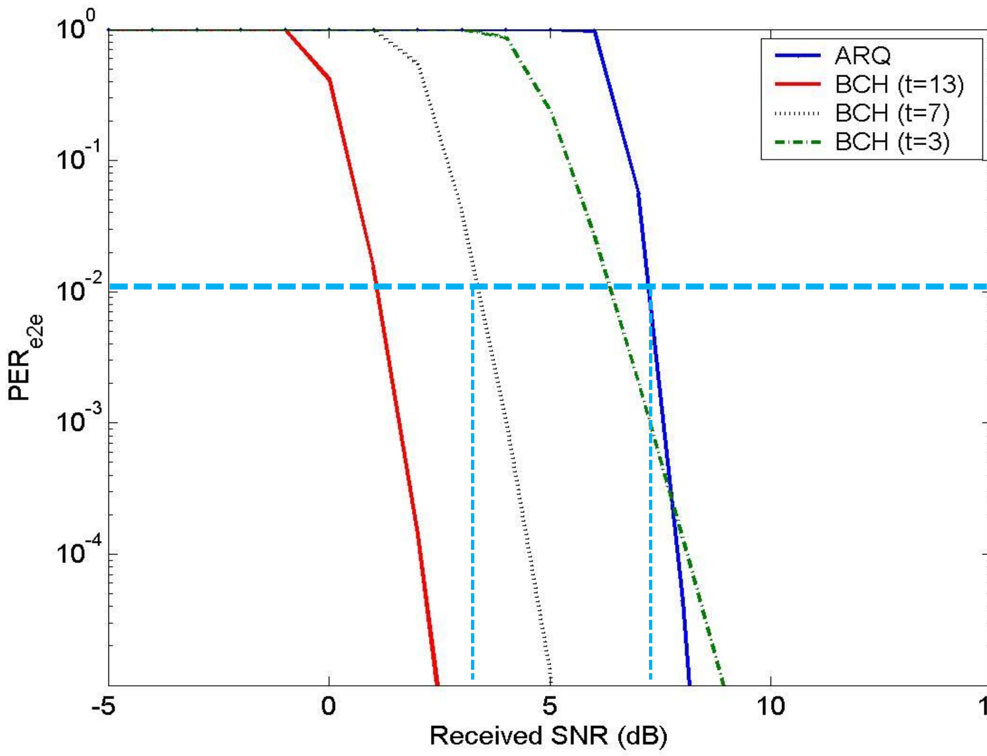
Error Resiliency

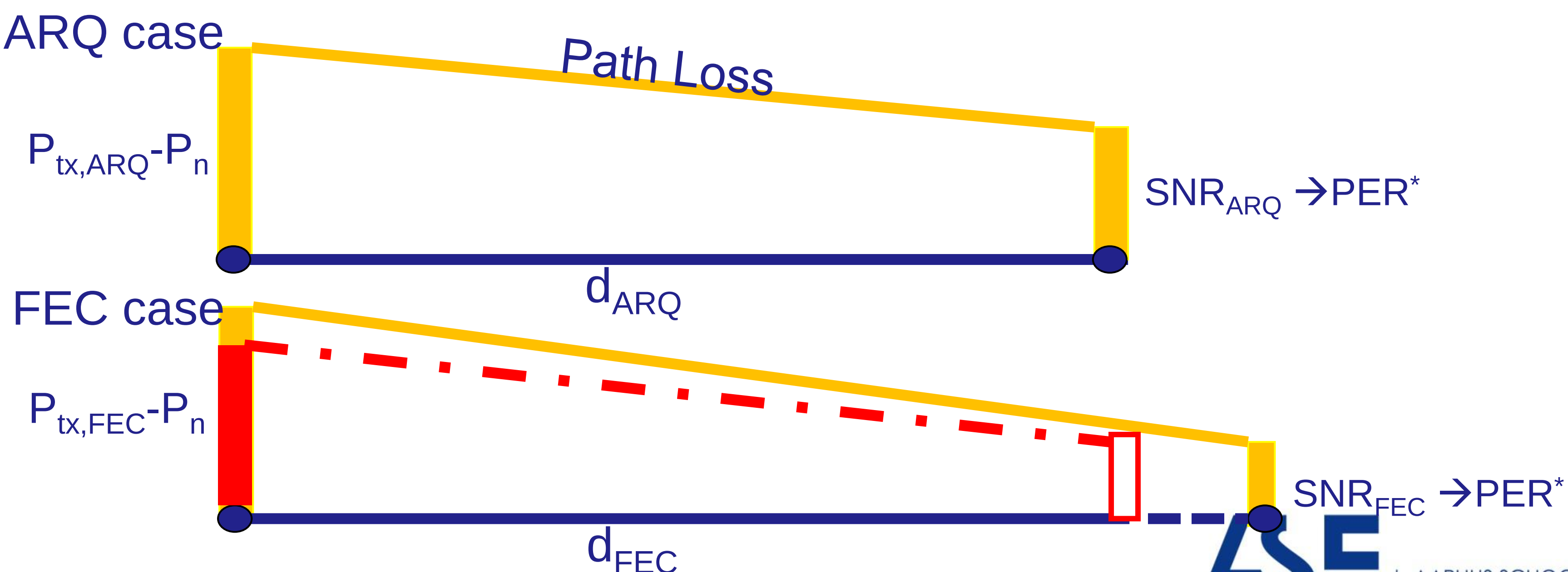
- Packet Error Rate (PER) is a function of signal to noise ratio (SNR), i.e., channel quality

- As error correction capability (t) increases, error resiliency improves



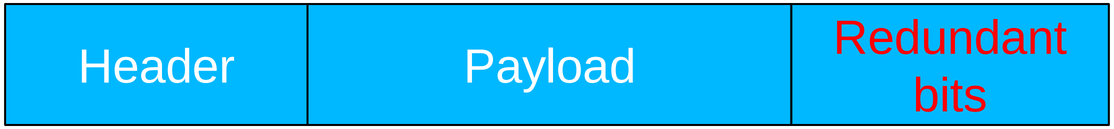
Error Resiliency

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



FEC Cost

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



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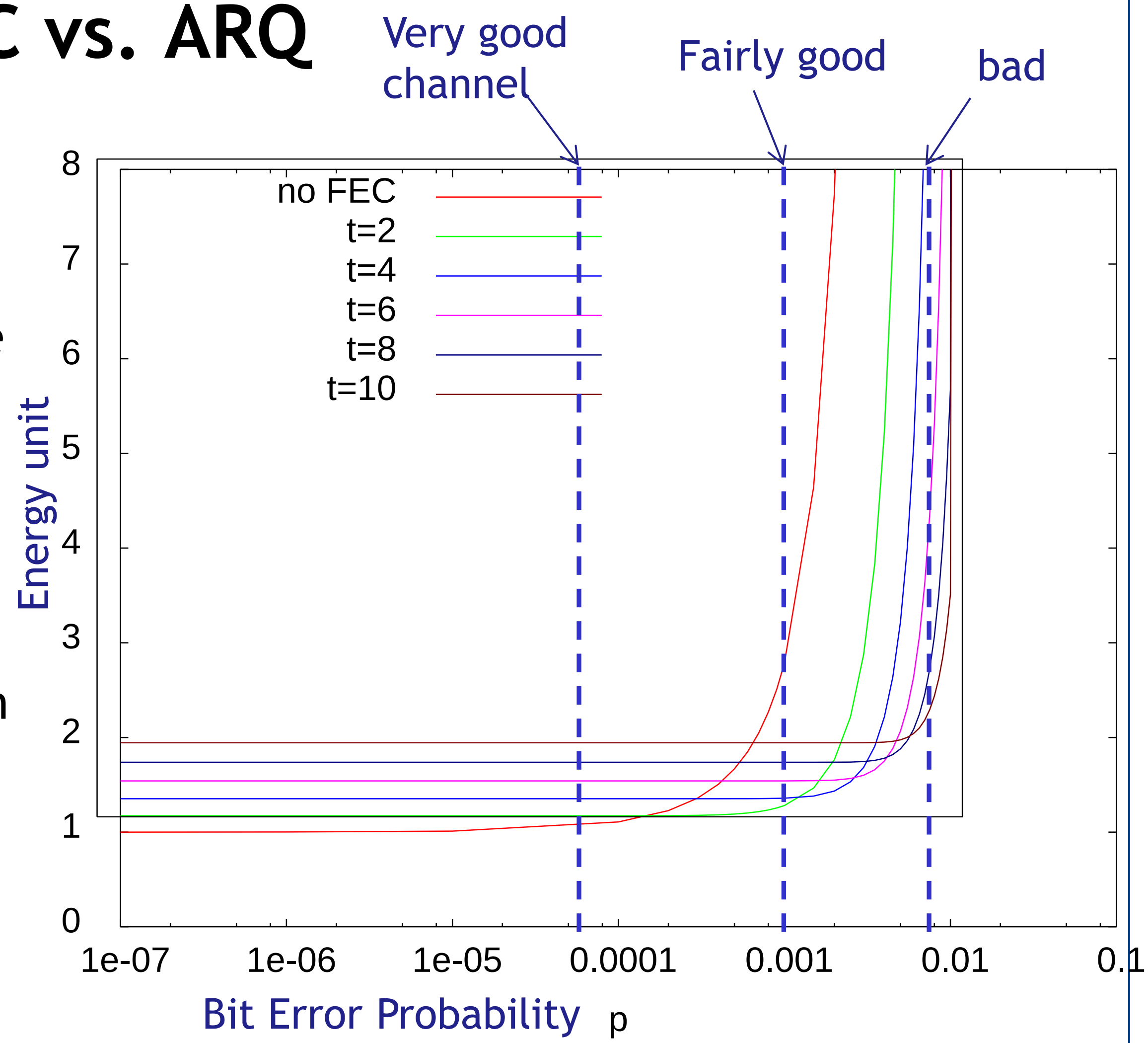
Comparison: FEC vs. ARQ

- FEC
  - Constant overhead for each packet
  - Not (easily) possible to adapt to changing channel characteristics
- ARQ
  - Overhead only when errors occurred (expect for ACK, always needed)
- Both schemes have their uses ***hybrid schemes***



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Error Control through Power Control

- Further controllable parameter: transmission power
  - Higher power, lower error rates by improving SNR
    - Results in less FEC/ARQ necessary
  - Lower power, higher error rates – higher FEC necessary
- Problem:
  - Higher power: energy consumption and interference are increased
- Tradeoff!

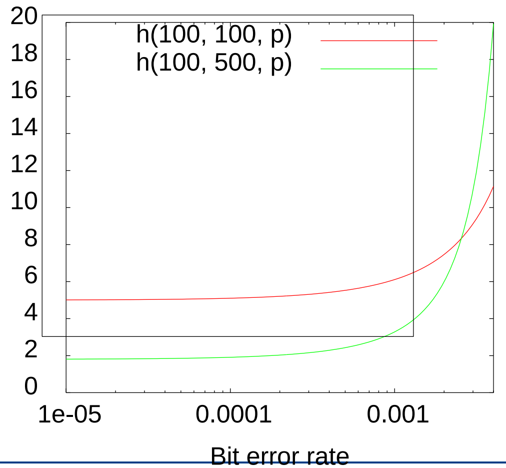
Outline

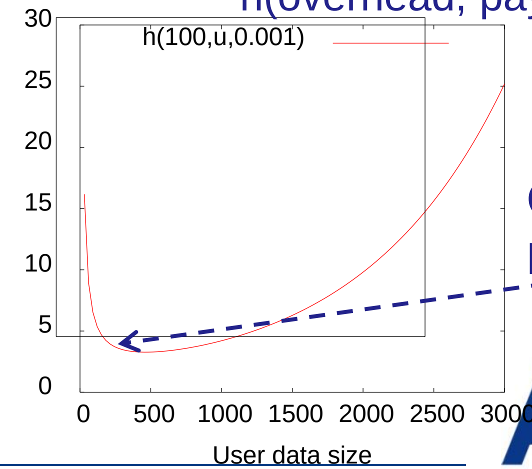
- Error control
- ***Framing***
- Link management

Frame, packet size

- Small packets:
  - low packet error rate,
  - high overhead
- Large packets:
  - high packet error rate,
  - low overhead
- Depends on bit error rate, *energy consumption per successfully transmitted bit*

Notation:
h(overhead, payload size, BER)





Optimal payload size

Dynamically adapt frame length

- For known bit error rate (BER), optimal frame length is easy to determine
- Problem: how to estimate BER?
  - Collect channel state information at the receiver (RSSI, FEC decoder information, …)
  - Example: Use number of attempts T required to transmit the last M packets as an estimator of the packet error rate (assuming a BSC)
- Second problem: how long are observations?
  - If the period is too short, not enough data to obtain an accurate estimate of bit error probability
  - If the period is too long, it takes too much time
  - Try to use the estimation as a short-term prediction

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Intermediate checksum schemes

- Basic idea: Retransmitting whole packet is waste resource. Can we only retransmit those parts of a packet where errors actually occurred?
  - User data is partitioned into a number of chunks
  - Append checksum for each individual chunk and also for frame header
  - If receiver detects error in the frame header, it discards the whole frame
  - If the header is correct, the receiver checks each chunk and buffers the correct ones. The faulty chunks need to be retransmitted.

Traditional framing

Intermediate checksum framing

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Outline

- Error control
- Framing
- *Link management*

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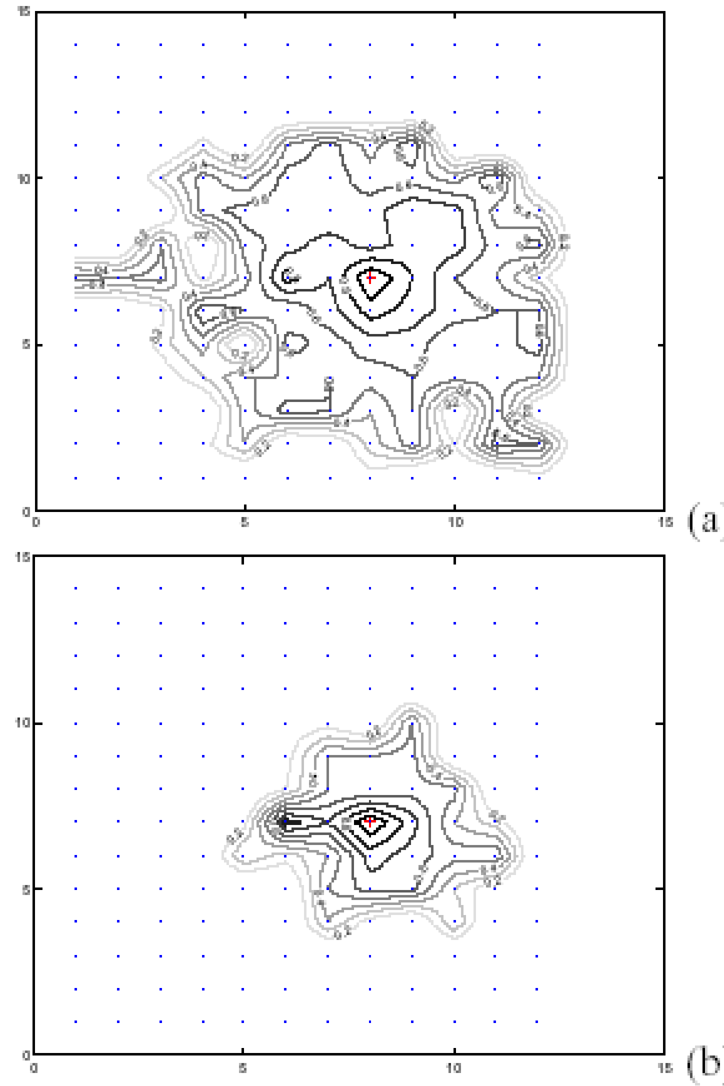
Link management

- Goal: a link should be established to decide to which neighbors that are *more or less* reachable
  - Quality of a link is time variable.
  - The quality can only be estimated,
    - either actively by sending probe packets and evaluating the responses
    - or passively by overhearing and judging neighbors' transmissions.
- ***Neighborhood table*** of each node cannot only store neighboring nodes but also the associated link qualities
  - Partially automatically constructed by MAC protocols
  - Cheap Sensor node might not have enough memory to store neighborhood table.

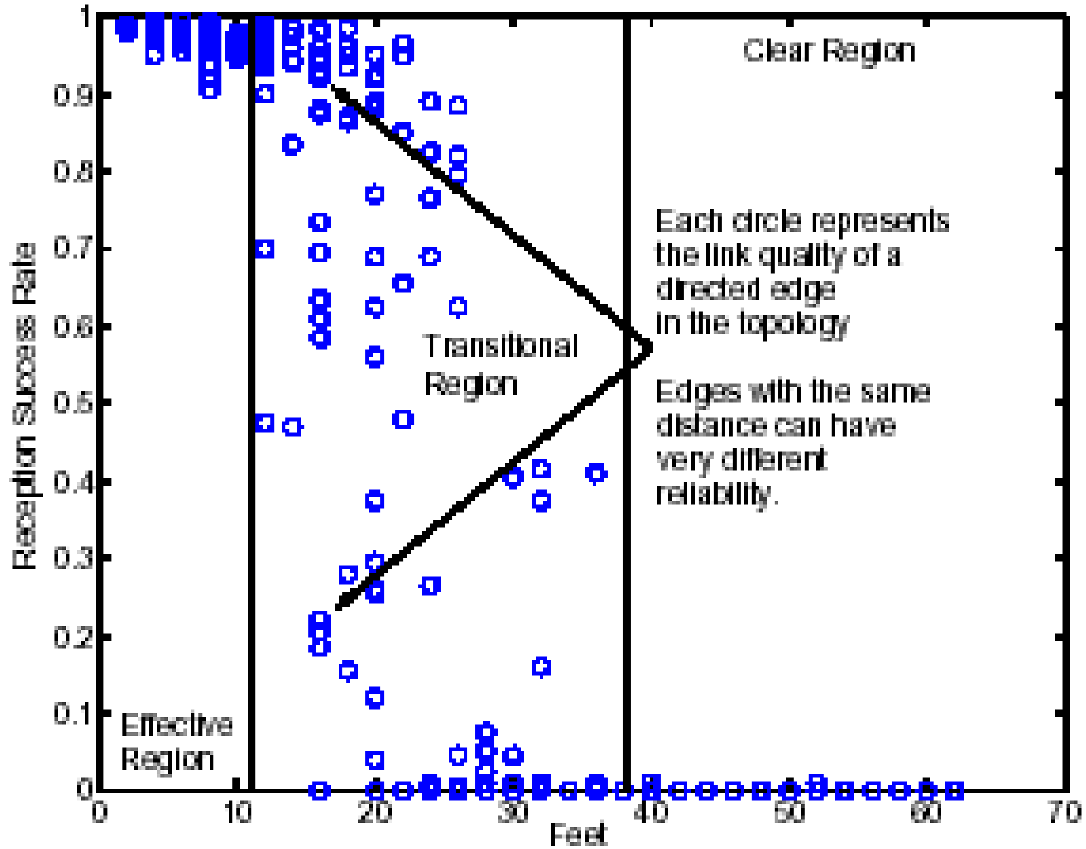
Link quality characteristics

- Expected: simple, circular shape of “region of communication” – not realistic
- Instead:
  - Correlation between distance and loss rate is weak; iso-loss-lines are not circular but irregular
  - Asymmetric links are relatively frequent (up to 15%)
  - Significant short-term PER variations even for stationary nodes



Three regions of communication

- ***Effective region***: PER consistently < 10%
- ***Transitional region***: anything in between, with large variation for nodes at same distance
- ***Poor region***: PER well beyond 90%

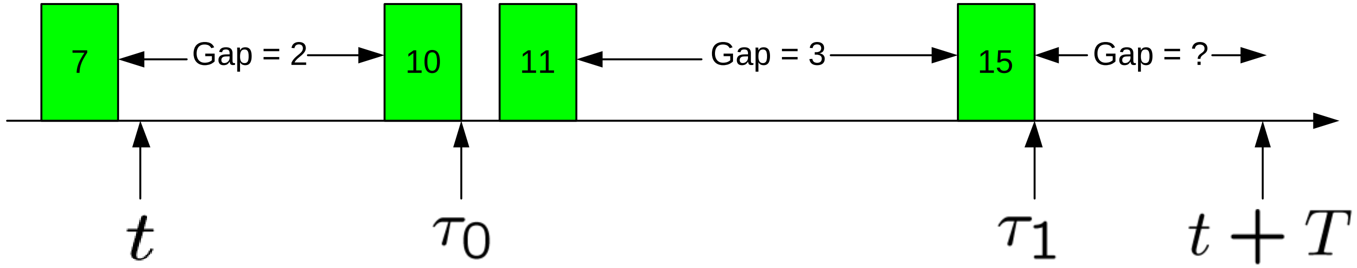


Link quality estimation

- How to estimate, on-line, in the field, the actual link quality?
- Requirements
  - Precision – estimator should give the statistically correct result
  - Agility – estimator should react quickly to changes
  - Stability – estimator should not be influenced by short/transient fluctuations
  - Efficiency – Active or passive estimator

Cont…

- Active estimator: The node sends out special measurement packets and collect response from its neighbors.
- Passive estimator: the node overhears the transmission of its neighbors and estimates the loss rates from observing the neighbor’s sequence numbers, packet loss are detected from gaps in the received numbers.
    - If neighbors generates sufficient traffic within a certain amount of time, i.e., with a minimum generated message rate, passive estimator is feasible.
    - Specially when transmission cost much more energy than receiving, passive estimator is preferable.



An illustration of a passive estimator

WMEWMA (Window Mean with EWMA)

- Best compromise between stability and agility
- It has two tuning parameters, $\alpha \in (0, 1)$ and observation period T
- $\hat{P}_n$ is predictions at time $t_n = t + n \cdot T$
- Here the number of received packets in interval $(t_{n-1},\ t_n\ ]$: r_n
- The number of lost packets during interval $(t_{n-1},\ t_n]$: f_n

$$\mu_n = \frac{r_n}{r_n + f_n};\ \hat{P}_n = \alpha\mu_n + (1-\alpha)\hat{P}_{n-1}$$

Summary

- In WSNs, Link layer needs to deal with the relatively specific issues
  - Careful choice of error control mechanisms – tradeoffs between FEC & ARQ & transmission power & packet size …
  - Link estimation and characterization

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