ECE 4880

Fall 2016

Chapter 10

Multiple Access and Air Protocols

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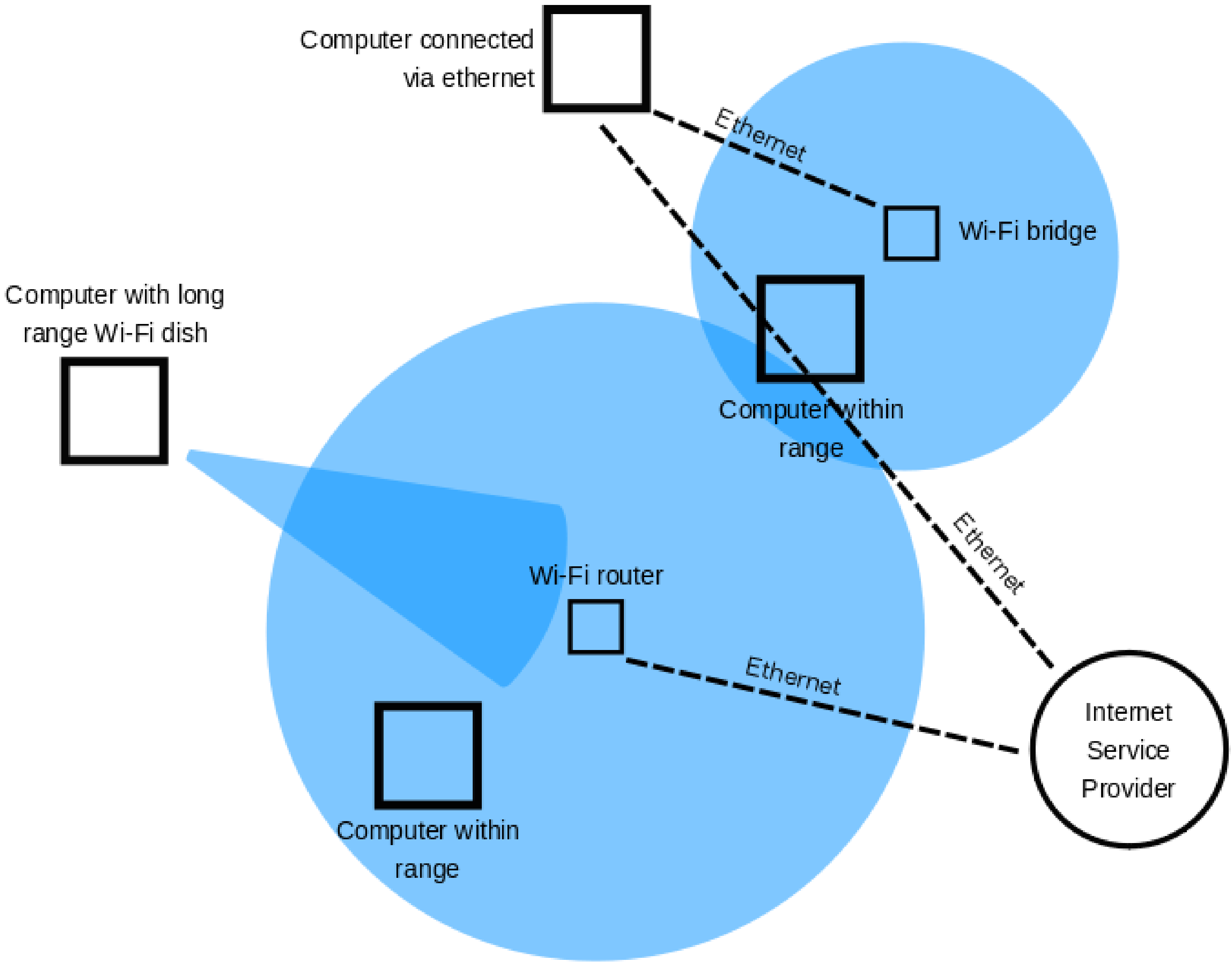
Goals

- Understanding time, frequency (channel and intermediate), and code division in radio transceivers
- Time division multiple access and Aloha protocol
- Frequency division and spread spectrum
- Orthogonal, error detection and error correction codes

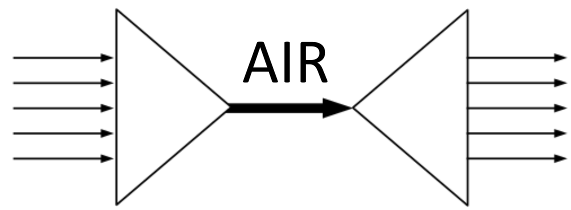
Multiple Access of Wireless Local Area Network (WLAN)

- If all signals are added together, the receiver cannot distinguish each source clearly.
- **Security and privacy** are major issues.
- A checksum or cyclic redundancy check (CRC) is used to detect if a correct message (header or ID) is heard by receiver.
- Within the WLAN (IEEE 802.11):
  - **Infrastructure**: base station; access points; hub owner
  - **Ad hoc**: peer-to-peer (P2P); independent basic service set (BSS)

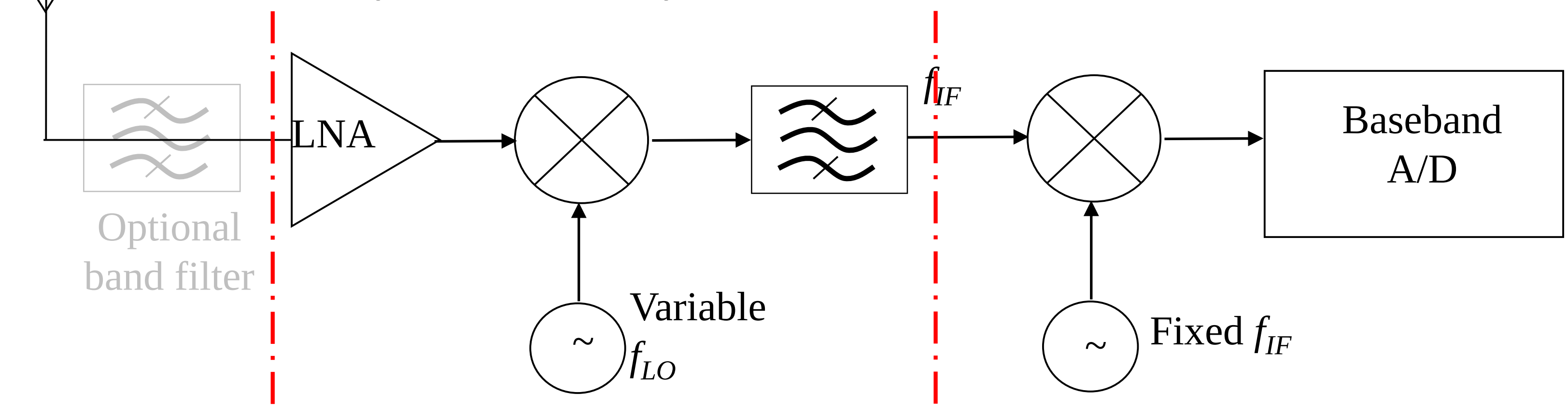
WLAN Example: Wi-Fi



Multiple Access from the Transceiver View



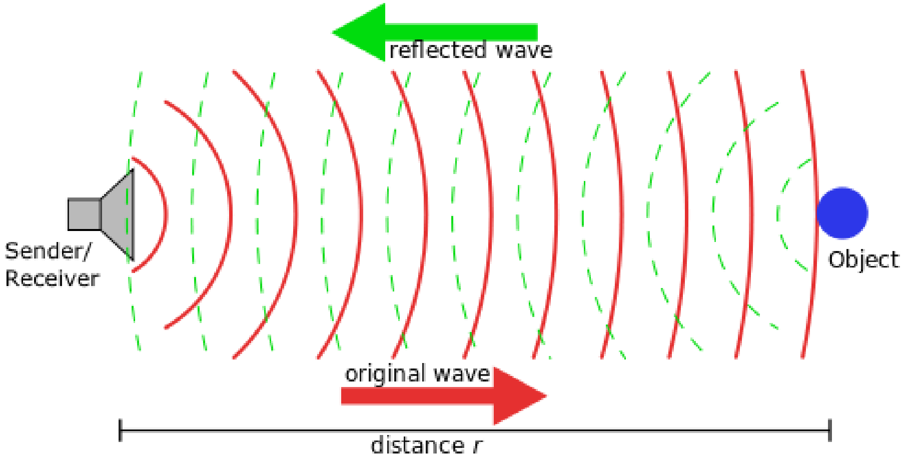
Superheterodyne receiver



Time Division Multiple Access (**TDMA**)	Frequency Division Multiple Access (**FDMA**)	Spread Spectrum (SS) and Code Division Multiple Access (**CDMA**)

Incoherent and Coherent Receivers

- When TX and RX are not together, the receiver is "incoherent" and "multi-static".
- In Radar and RFID systems, when the receiver is listening to the echo, the receiver is coherent and mono-static.



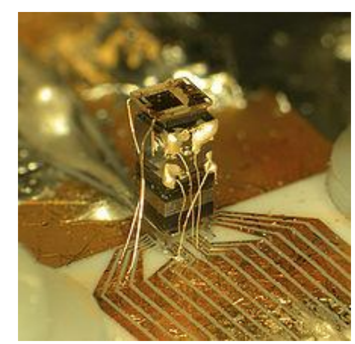
Time Division Multiplexing (TDM; TDMA)

- There is only one transmitter within WLAN at a time: Traffic control by the hub owner so that the “air space” is time-shared.
- Polling of all potential transmitters to agree on further efficient multiple-access protocols.
- The only possible method when the data rate of the transmission medium exceeds that of signals to be transmitted.
- Originally developed for telegraphy and telephony.
- Further improvement:
  - Synchronous digital hierarchy (SDH): require **global clock**
  - Statistical time-division multiplexing (STDM): Address (media control address: MAC) & data
  - Dynamic TDMA: Scheduling and Aloha

A Word on "Synchronization" of WLAN

- WLAN synchronization most often means the same frequency of LO_{RF_TX} and LO_{RF_RX}.
  - Local absolute frequency reference (crystal oscillator or atomic clock)
  - Master and slave (recapturing LO frequency from master in the infrastructure): Security concerns!
  - GPS synchronization (radio clock)
  - Listen to long-wave broadcast (USA: WWVB; EU: Allouis)
- Handshaking (flags and ACK) protocol is still needed for control. On IC, this is still similar to the asynchronous circuits.
  - Music analogy (the scale can be absolute, but dance steps for all parties have more requirements)

"Atomic" watch



Atomic clock

Allouis Longwave Tower

- 350 m tall
- 162kHz; 2MW transmitting; single quarter wavelength antenna (Geneva standard)
- At Allouis, France

WWVB Radio Station

- At Fort Collins, CO
- Four 122 m tower
- 60 KHz at 70kW
- Frequency precision < 10^{-12}

Aloha: Heritage from Ethernet

- An invention by Robert Metcalfe in 1974 in Harvard (almost flunked) and then Xerox.
- In 1979, Metcalfe formed 3Com and developed Ethernet with Digital, Intel and Xerox (called DIX).
- 3Com developed Network Interface Card for all later computers including Apple and PC.
- Communication markets shift quickly, and 3Com has tried Chinese market (Huawei), but eventually purchased by HP in 2010.

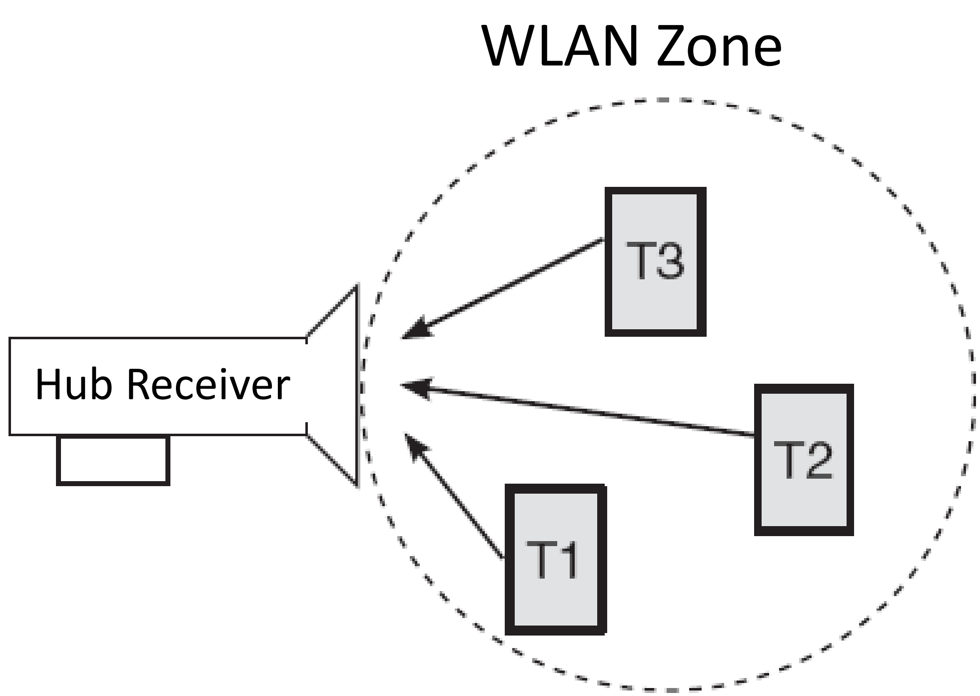
"Every success takes a unique combination of timing, invention, talent, and effort. Failure, it just needs one thing terribly wrong."

--- Adapted from Sun Tze.

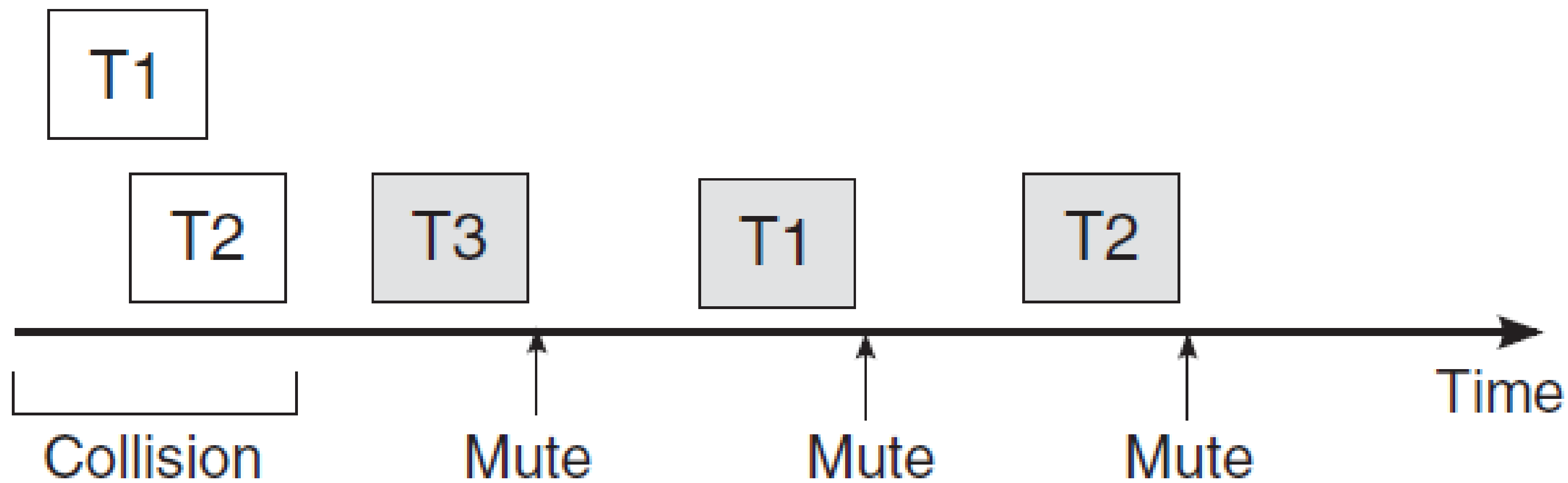
Bob Metcalfe
National Medal, 2003

Pure Aloha (PA)

- The hub receiver listens to a potential “Channel”.
- If a header is received correctly, the receiver sends ACK
- If a collision is detected, it sends NACK, and all transmitters (lack of a valid ACK) transmit headers again after a random delay.

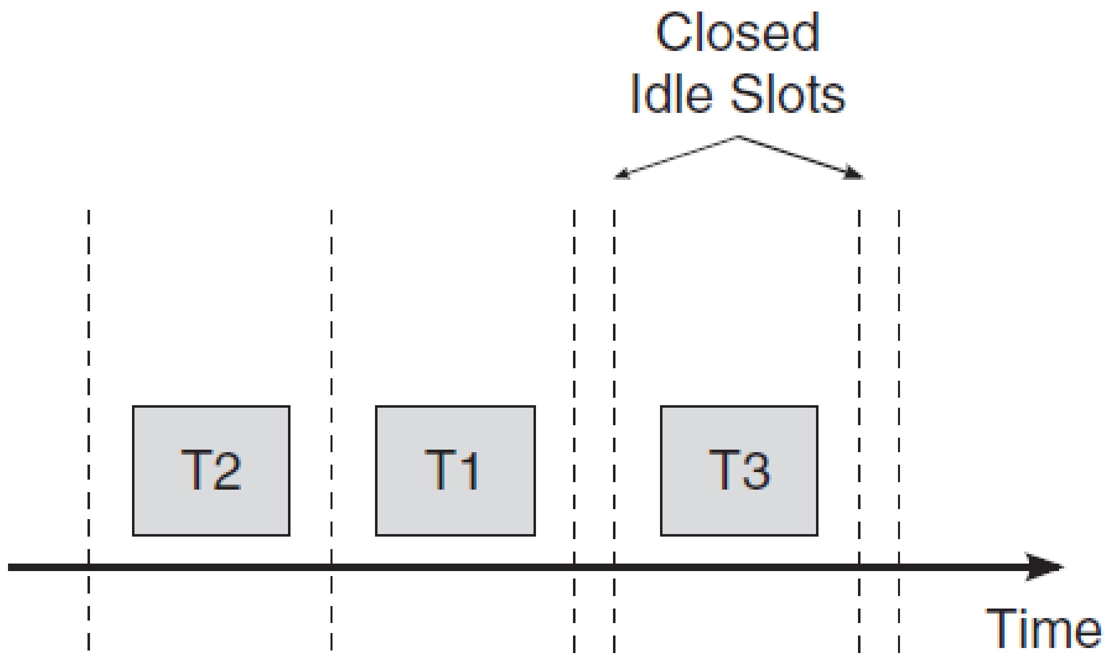


Pure Aloha with Muting



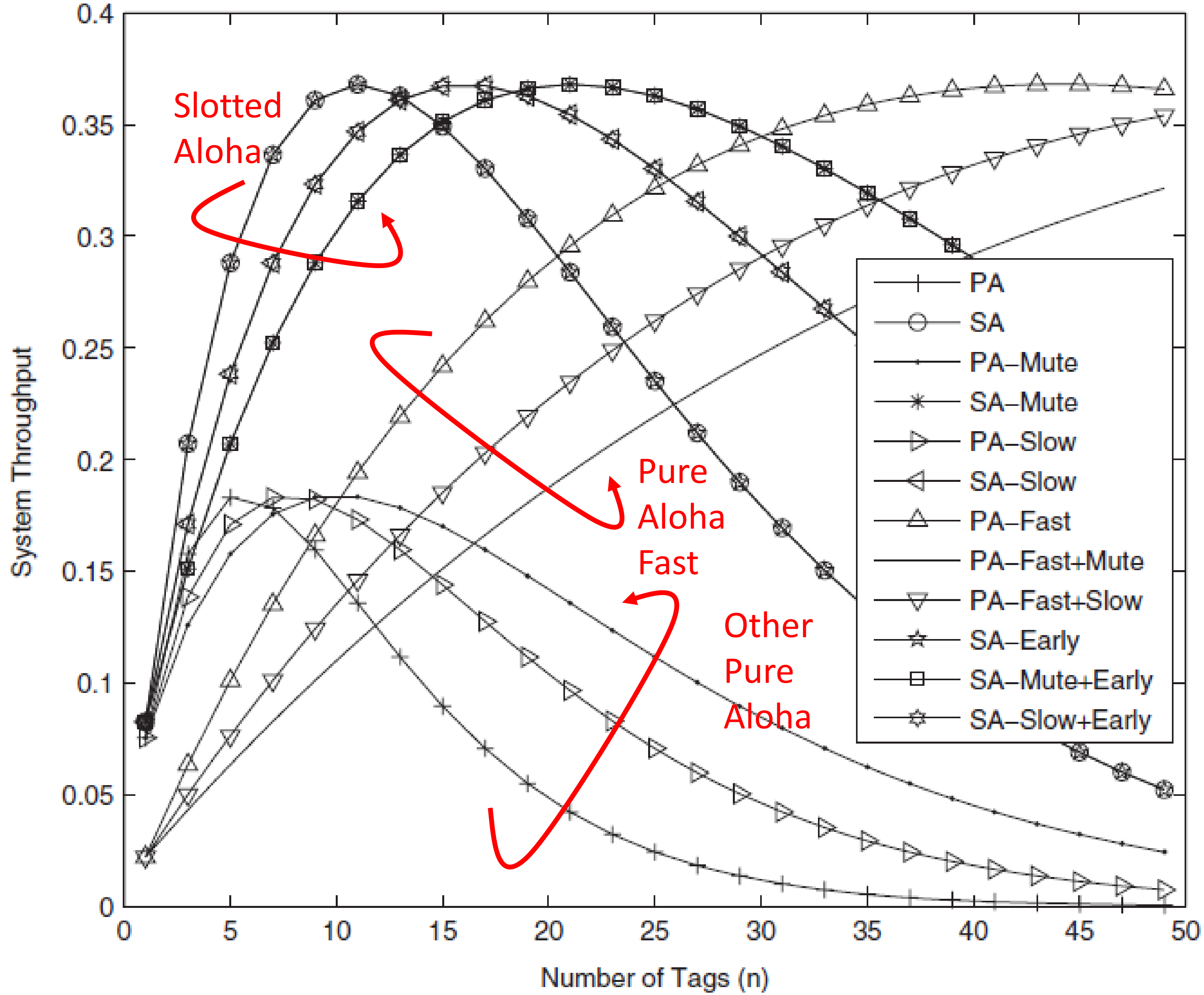
- After ACK is detected, the transmitter will be muted until further command (such as reset).
- Successfully read units will not cause further collision until the polling is finished.

Slotted Aloha

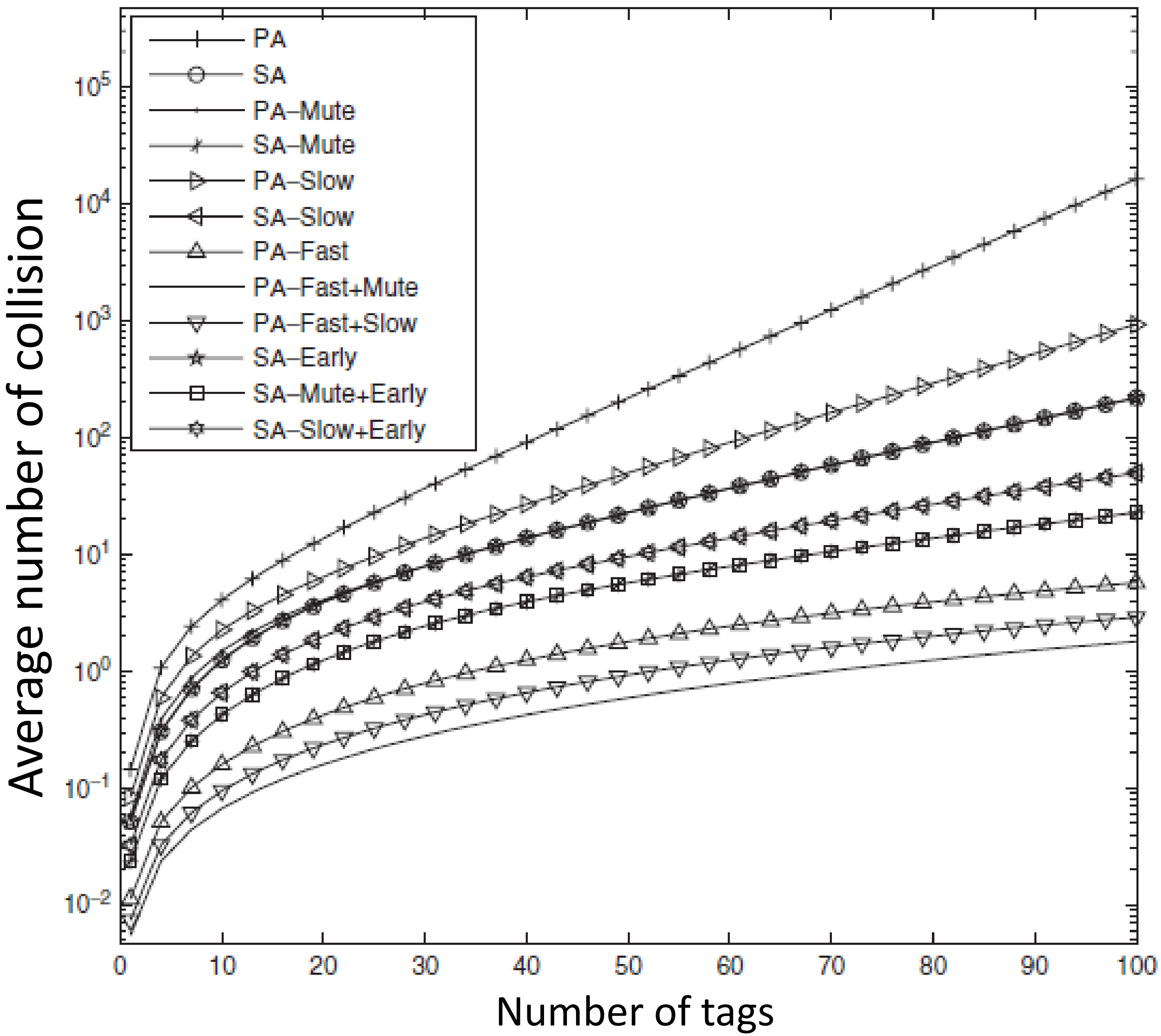


- Pure Aloha has a high probability of partial collision
- Slotted Aloha synchronize transmitters: the hub owner broadcasts slot frame rates.
- Slot can have an “Early End” (to shorten an idle slot) by adding START_SLOT and END_SLOT commands.

System Performance of Aloha Variants



Average Number of Collision



Frequency Division Multiple Access (FDMA)

- Synchronization of the **LO carriers** in transmitters and receivers.
- Only one transmitter is allowed on each channel.
- Channel availability monitoring: listen before talk (LBT)
- Carriers and subcarriers for supergroups and groups.
- Number of channels vs. number of users
  - Pigeonhole theory

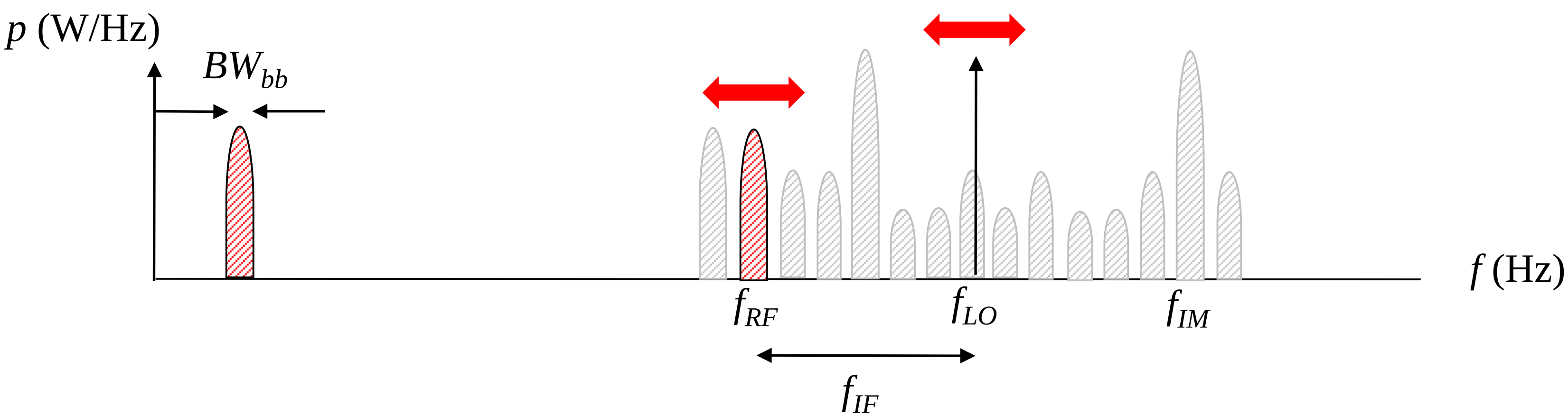
The Pigeonhole Principle

- If n discrete objects are to be allocated to m containers, then at least one container must hold no fewer than $\lceil n/m \rceil$ objects, where $\lceil \; \rceil$ is the ceiling function: the smallest integer $\geq x$.
- Similarly, at least one container must hold no more than $\lfloor n/m \rfloor$ objects, where $\lfloor \; \rfloor$ is the floor function: (the largest integer $\leq x$.
- For random and uniform probability, then the probability of at least one hole will hold more than one pigeon is:

$$1 - \frac{m(m-1)\cdots(m-n+1)}{m^n}$$

Spread Spectrum (SS)

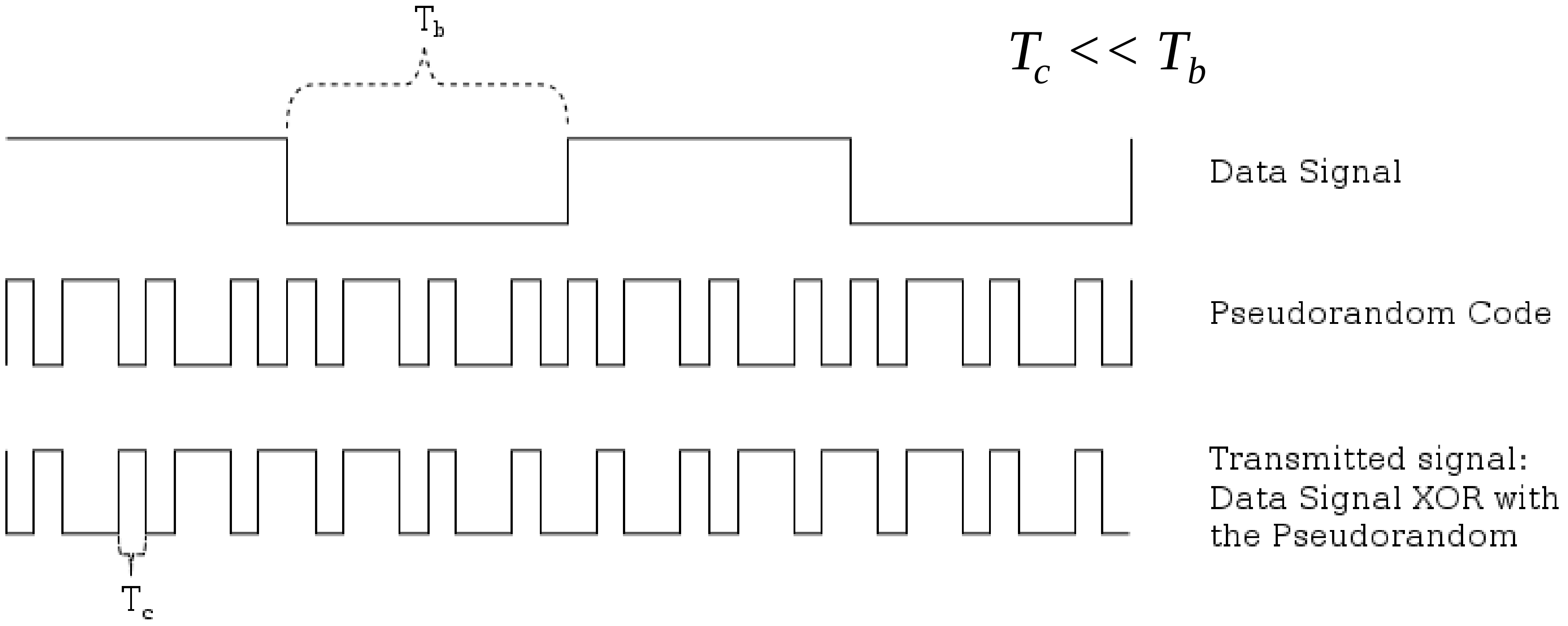
- **Channel hopping**: Signals hopped among pre-determined order of channels (by LO), such as in Bluetooth. In a given time period say 1 second, the TX spectrum is spread over the entire allowable band.
- Broaden the effective spectrum of transmission
  - For security: prevent eavesdropping on a specific channel
  - For reliability: more immune to narrow-band interference



CDMA (Code Division Multiple Access)

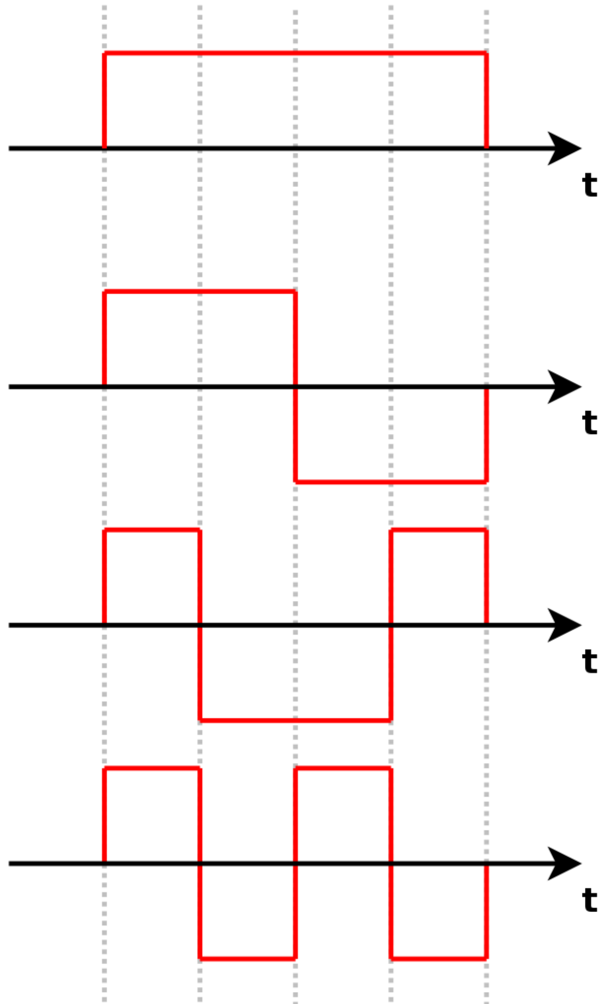
- Inject a "chip" (pseudo-noise or PN code sequence) into the baseband to spread the spectrum, as in a direct sequence spread spectrum (DSSS).

$$T_c << T_b$$



Baseband and PN code need to be synchronized.

Example of Orthogonal Digital Signals



$$\int_0^T c_i(t)c_j(t)dt = \delta_{ij} \qquad \forall i, j$$

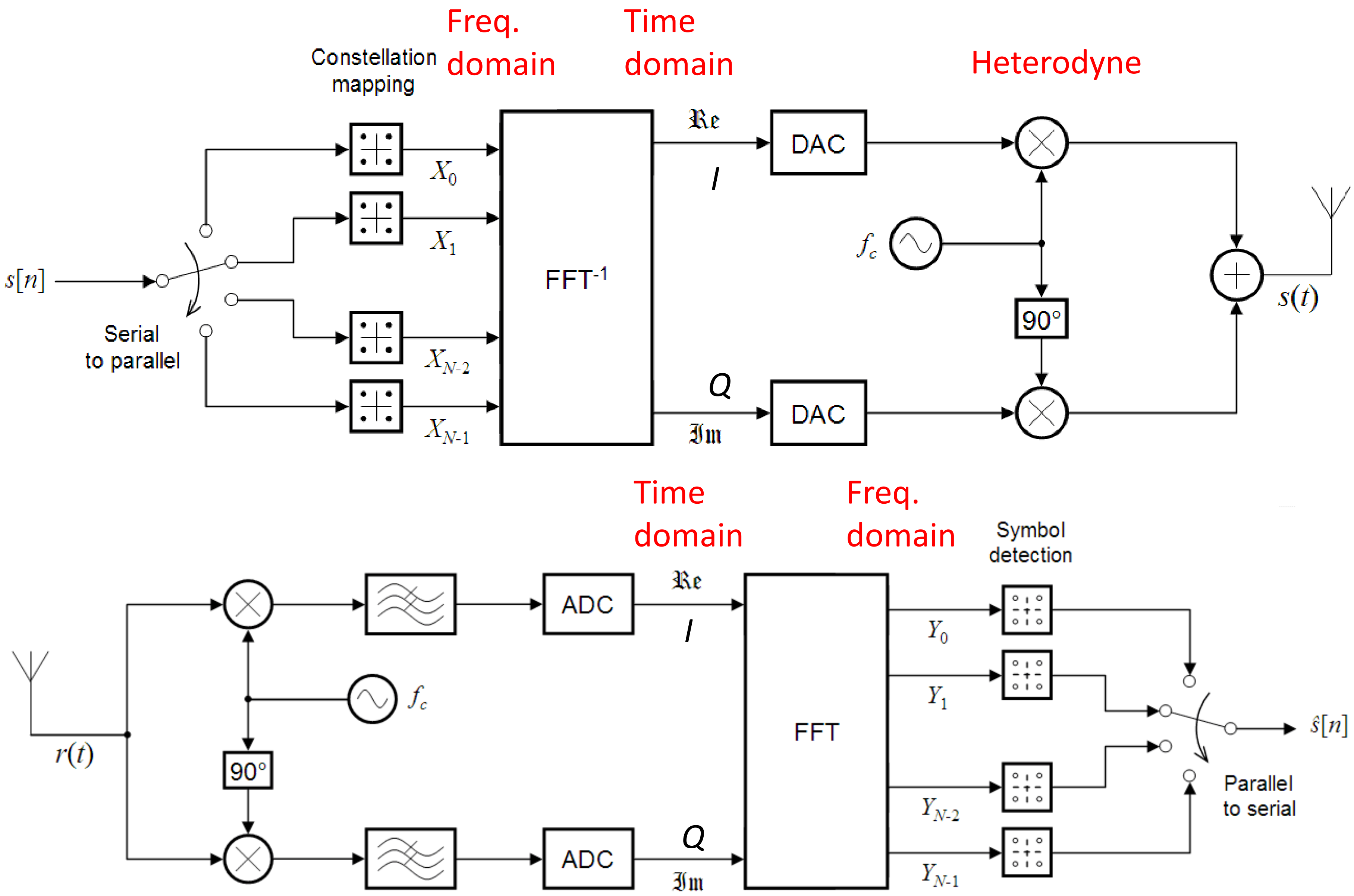
T: Symbol duration

c_i: i-th PN code

Orthogonal Frequency Division Multiplexing (OFDM)

- Orthogonal subcarriers in the baseband, similar to those used in FM for stereo and color for broadcasting TV.
- Sub-carrier frequencies are orthogonal with spacing $\Delta f = K/T$, where T is the symbol duration and K a chosen integer.
- Require very accurate synchronization between TX and RX (deviation will cause loss of orthogonality)
  - AWGN (additive white Gaussian noise) channel description
  - Multi-path interference as noise into the inter-symbol interference (ISI) for indoor wireless link
  - Doppler effect correction for moving TX/RX (change of carrier frequency)
- Easier implementation with DSP: no subcarrier filter or pilot.
- High spectral efficiency with symbol rate close to the Nyquist rate: lower symbol rate in each subcarrier lowers required SNR

OFDM Radio Transceiver



OFDM with *N* Subcarriers

Baseband: $$v(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T}; \qquad 0 \le t < T$$

Orthogonality: $$\frac{1}{T}\int_0^T e^{-j2\pi k_1 t/T} e^{j2\pi k_2 t/T} dt = \delta_{k_1 k_2}$$

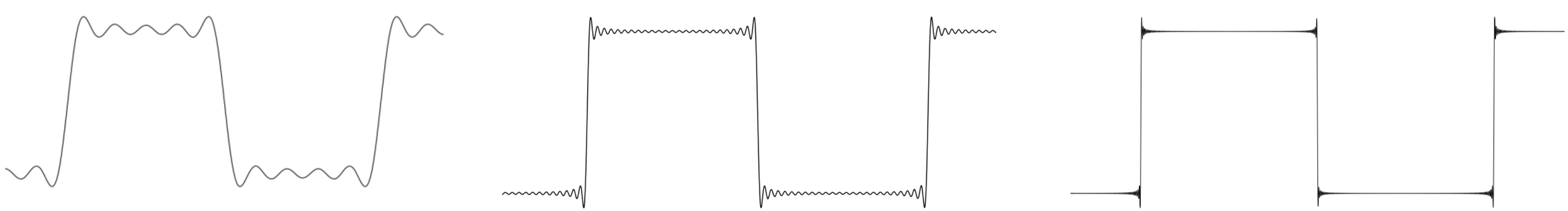
Further Observation in OFDM

- Symbol rate in each subcarrier is very low: immune to multi-path inter-symbol interference (ISI), especially for indoors.
- Symbol detection has much longer time to ease the ADC requirement on jitter and noise
- Within the symbol period, each subcarrier does NOT interfere each other.
- Can use one or all subcarriers: flexibility in data rate
- Replacing IF with the Fourier block: resolving ma
- We have very good and efficient algorithms on FFT and IFFT.

A Word on Gibbs Oscillation

- Abrupt transition such as that in digital switching can cause oscillation when time signal is reconstructed from limited bandwidth
- Need to use Haar wavelet or ENO functions to converge faster

$$\sin\left(x\right)+\frac{1}{3}\sin\left(3x\right)+\frac{1}{5}\sin\left(5x\right)+\ldots$$



5 harmonics 25 harmonics 125 harmonics

Errors in the Digital Codes

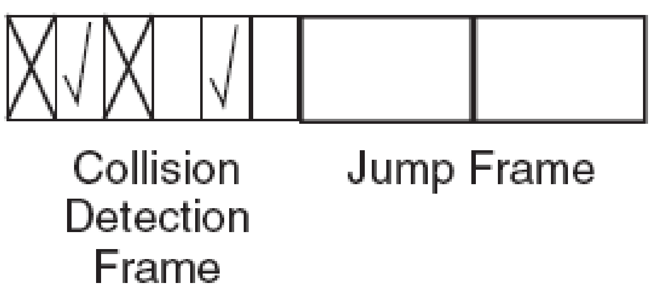
- **Random errors**: the bit error probabilities are independent or nearly independent of each other. Example: thermal noise; interferences.
- **Burst errors:** the bit error occurs sequentially in time or as groups of “stuck-at”. Example: weak signal when the antenna is detuned or scratch in DVD
- **Impulse errors**: large blocks of the data are full of random errors. Example: transmission collision; reader interference.

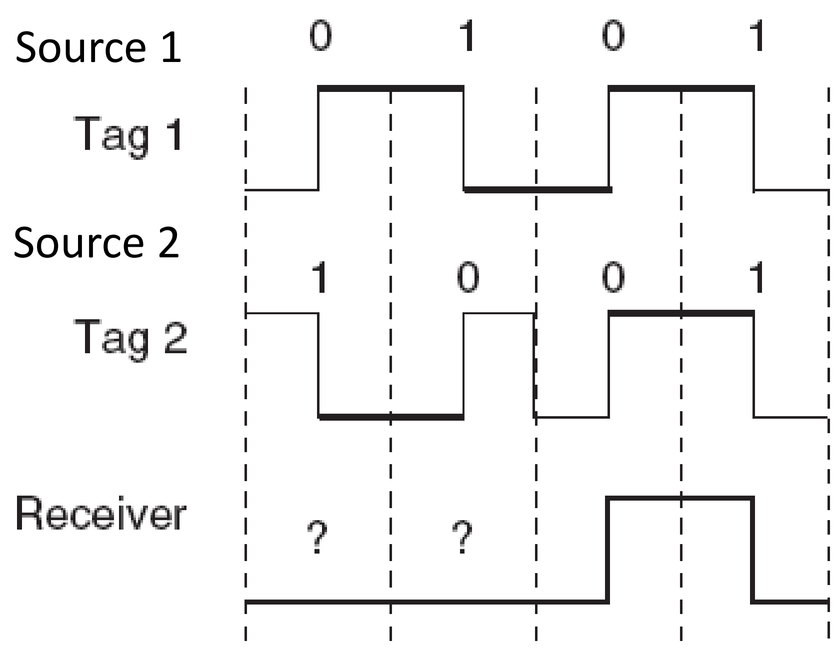
Error correction $\Rightarrow$ Data Redundancy!!!

Collision Detection in Fixed Time Slots

- Dedicated the initial frames for pooling, and then decide the jump frame sizes.
- Collision detection from Manchester coding (as one possibility)

Require exactly one transition in the detection frame





Collision Detection by Cyclic Redundancy Check

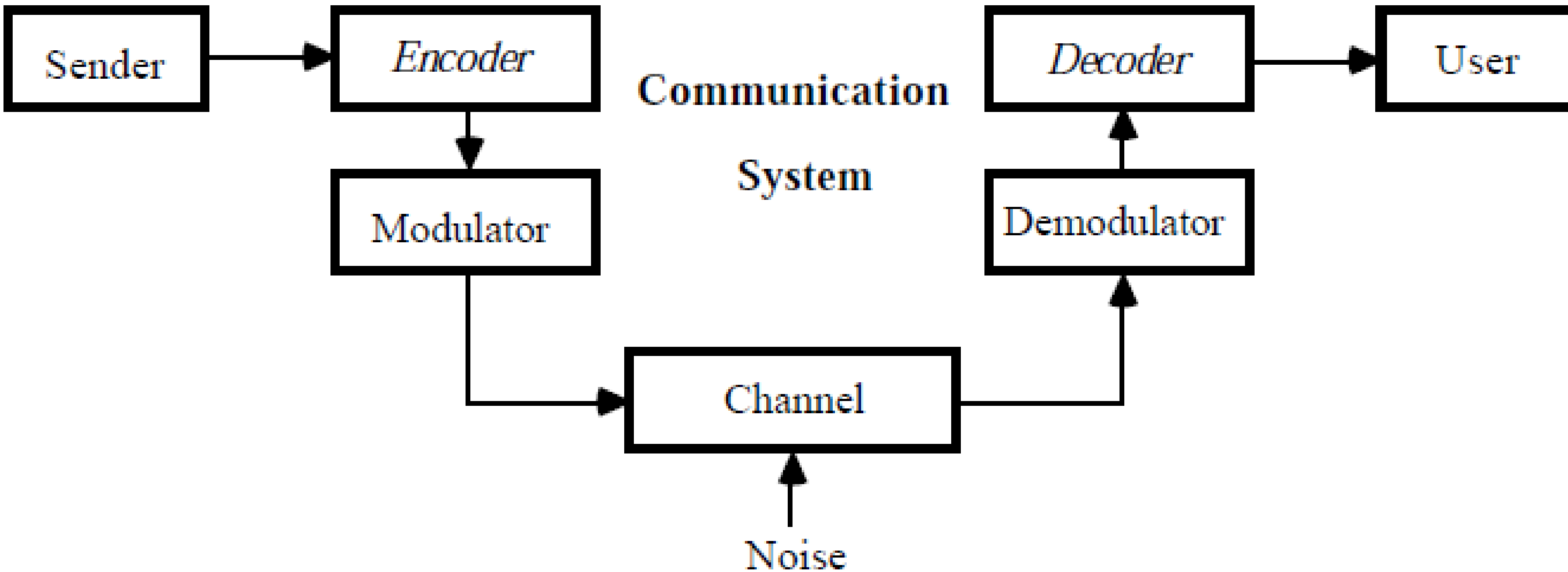
```
11010011101100 000 <--- input right padded by 3 bits
1011               <--- divisor
01100011101100 000 <--- result
 1011              <--- divisor ...
00111011101100 000
  1011
00010111101100 000
   1011
00000001101100 000
       1011
00000000110100 000
        1011
00000000011000 000
         1011
00000000001110 000
          1011
00000000000101 000
           101 1 -----------------
00000000000000 100 <--- remainder (3 bits)
```

Cyclic Redundancy Check (CRC): Very good in detecting errors; but less efficient in error correction.

Levels of Error Correction Code (ECC)

- Repetition code: based on majority vote
  - Very inefficient in code rate
  - Fast recovery
  - No assumption on the position of bits in each packet
- Forward correction code
  - Bit-level: Hamming code: popular in memory
  - Block code: Reed-Solomon code: popular in serial storage and communication channels
- Automatic repeat request (ARQ)
  - Stop and wait
  - Continuous duplex: popular in multi-level circuits (MLC)

Error Correction System



- Probability of error:
  - probability of uncorrectable errors: P_{UE}
  - probability that the channel will change a symbol during the processing or transmission: P_{SE}.
  - $P_{UE} = P_{SE}$ if there is no error correction system.

Bit-Level Hamming Code Example

	Data Bits				Check Bits		
	A	B	C	D	E	F	G
0	0	0	0	0	0	0	0
1	0	0	0	1	0	1	1
2	0	0	1	0	1	0	1
3	0	0	1	1	1	1	0
4	0	1	0	0	1	1	0
5	0	1	0	1	1	0	1
6	0	1	1	0	0	1	1
7	0	1	1	1	0	0	0
8	1	0	0	0	1	1	1
9	1	0	0	1	1	0	0
10	1	0	1	0	0	1	0
11	1	0	1	1	0	0	1
12	1	1	0	0	0	0	1
13	1	1	0	1	0	1	0
14	1	1	1	0	1	0	0
15	1	1	1	1	1	1	1
	b_7	b_6	b_5	b_4	b_3	b_2	b_1

Check-Bit Generation Before and After

- Bit A, B, C, and D: original bits: $2^4 = 16$ possible combinations.
- Bit E, F and G: parity bits: total $2^7 = 128$ possible combinations.

$$E = A \oplus B \oplus C \qquad Eq.(1)$$

$$F = A \oplus B \oplus D \qquad Eq.(2)$$

$$G = A \oplus C \oplus D \qquad Eq.(3)$$

- (7, 4) Hamming code:
- k = 4: the uncoded bits in a word
- n = 7: total number of bits in a codeword
- (n – k): the parity check bits
- t: the number of bits correctable ~ (n – k)/2

Finding the Error-Bit Address

Bit in Error	**Eq. 1** $E' = A \oplus B \oplus C$	**Eq. 2** $F' = A \oplus B \oplus D$	**Eq. 3** $G' = A \oplus C \oplus D$
None	True	True	True
A	False	False	False
B	False	False	True
C	False	True	False
D	True	False	False
E	False	True	True
F	True	False	True
G	True	True	False

The position of error always corresponds to a unique combination in the truth table!!

The error bit address can be uniquely determined and then toggle to correct!!

Criteria to Generate the Check Bits

"Distance" between legal codes can be increased by check bits!!

	Data Bits				Parity Bit $A \oplus B \oplus C \oplus D$
	A	B	C	D	E
0	0	0	0	0	0
1	0	0	0	1	1
2	0	0	1	0	1
3	0	0	1	1	0
4	0	1	0	0	1
5	0	1	0	1	0
6	0	1	1	0	0
7	0	1	1	1	1
8	1	0	0	0	1
9	1	0	0	1	0
10	1	0	1	0	0
11	1	0	1	1	1
12	1	1	0	0	0
13	1	1	0	1	1
14	1	1	1	0	1
15	1	1	1	1	0

- Original Word ABCD: each word can be differed by only one bit: if one bit is wrong, it will still be legal.
- If we add just a parity bit, then each word is differed by at least 2 bits! If only one bit is wrong, then it will become an illegal word.
- However, two words with one parity bit can go to the same illegal word, so when we have the wrong word, we cannot distinguish where it is from.

Original Word 1: 00101
Original Word 2: 00110
Received Word: 00100

Bit “Distance” in Legal Words

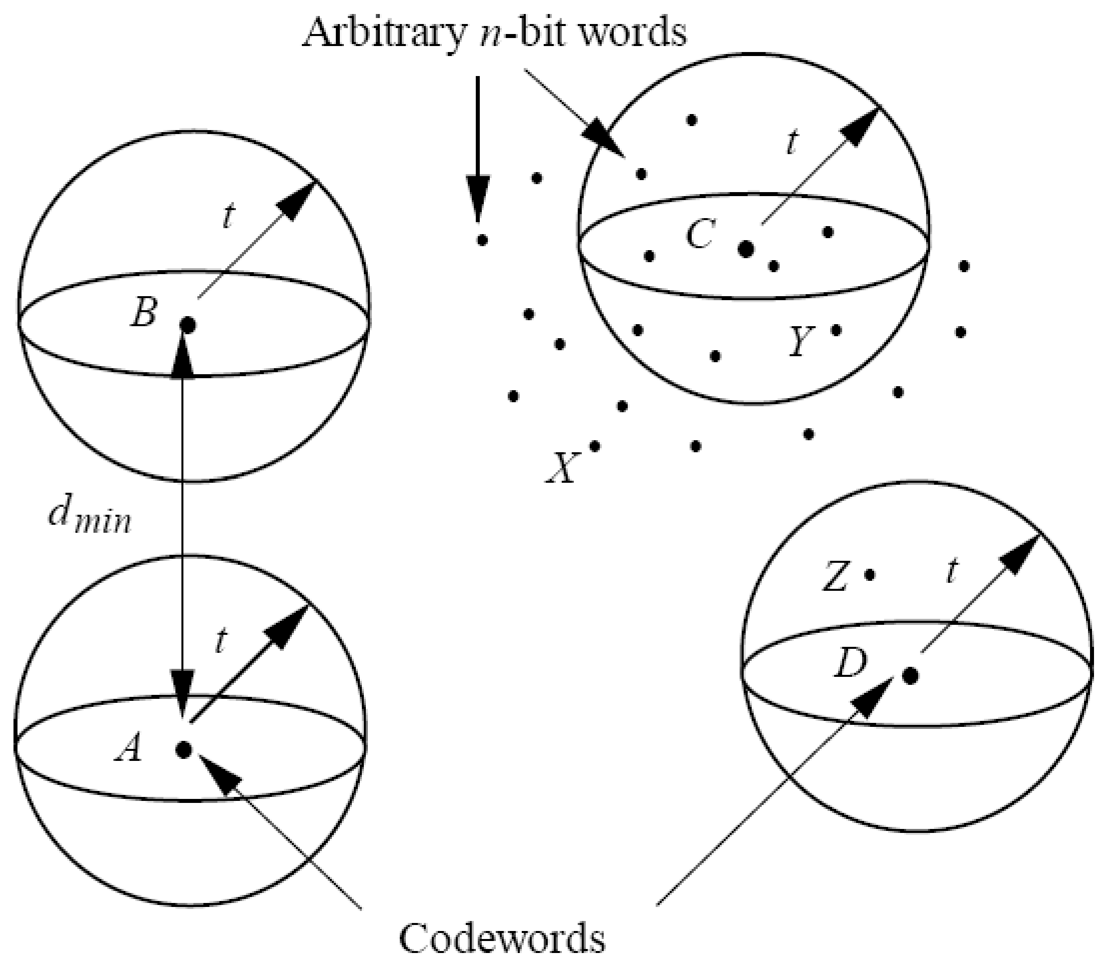
Intuitively, if we are expecting **m** bits can be in error, then the original legal words (plus whatever check bits added):

- Need to have at least distance **m+1** for the error to be detectable!
- Need to have at least distance **2m+1** for the error to be correctable!

- This does not prescribe how efficient is the detection or correction, but just whether there is no ambiguity when we receive a word containing at most m-bit errors!

Hamming Distance of Legal Words

- The minimum "Hamming" distance is defined as the smallest number of places that any two codewords (block words) in the codebook differ.
- Error correction code is to add check bits to enlarge that distance!



Further Reading on Hamming Distance and Quad Logic

- *R. W. Hamming, Coding and information theory; 2nd ed.* Richard W. Hamming , Prentice Hall, 1986
- Z. Kohavi, *Switching and finite automata theory,* McGraw-Hill, 1970, 1987 (Coding and quad logic)

Richard Hamming
(1915 – 1998)

Detectability and Correctability

For a (n,k) coding scheme (2^n codewords to represent 2^k data)

- Assume $t = \left\lfloor \frac{n-k-1}{2} \right\rfloor$ is the minimal distance between codewords
- n – k – 1 of error bits will be detectable (or at least 2t number of error bits will be detectable)
- t number of error bits will be correctable

Exercise: How many bits are less than Hamming distance 2 from (7,4) coding scheme?

Exercise: How many bits are less than Hamming distance 4 from (n,k) coding scheme?

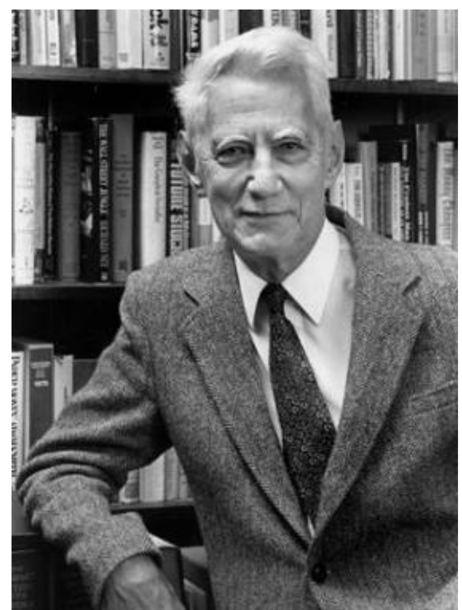
Shannon Coding Limits

The Shannon limit was posted in 1948, but only until Reed-Solomon coding is published in 1960, practical, efficient coding is available.

- C: Upper limit to the number of bits per second that can be reliably transmitted across a channel
- W: channel bandwidth in Hz; R: transmitted bit rate (bits/s)
- S: received signal power
- N: additive noise power
- E_b: signal energy per bit
- N_0: noise power level in W/Hz

$$C = W \log_2\left(1 + \frac{S}{N}\right)$$

$$C = W \log_2\left(1 + \frac{E_b}{N_0}\frac{R}{W}\right)$$



Claude Shannon (1916 -2001):

"I just wondered how things were put together."

Transmission Rate

- For the accomplished transmission rate R (bits/sec), if
  - R < C: Arbitrarily small error rate can be achieved
  - R > C: Not possible to achieve reliable error rate no matter what code is used.

$$C = W \log_2 \left(1 + \frac{E_b}{N_0} \frac{R}{W} \right)$$

Probability of Random Error

- Probability of uncorrectable errors: P_{UE}
- Probability that the channel will change a symbol during the processing or transmission: P_{SE}
- Assume random errors are uncorrelated (no burst)

$$P_{UE} = 1 - \sum_{i=0}^{t} C_i^n P_{SE}^i \left(1 - P_{SE}\right)^{n-i}$$

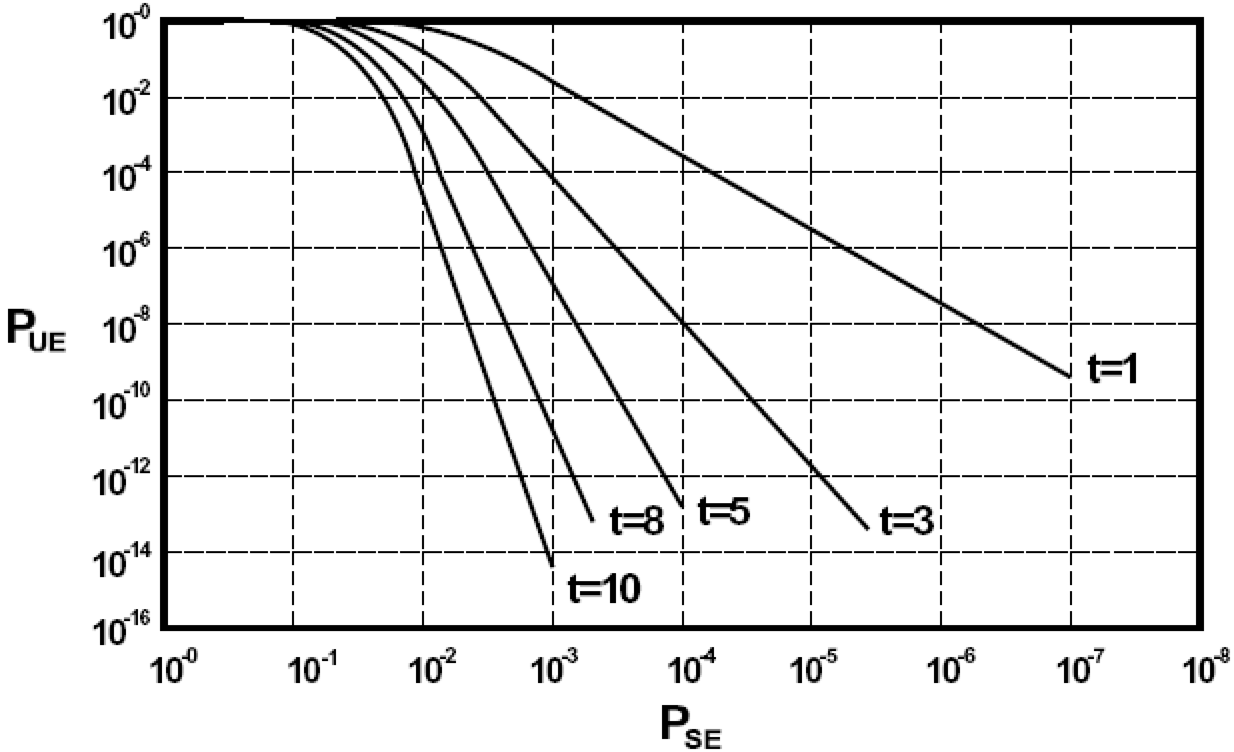
- Another way to measure error probability: corrected bit error rate
  — CBER = the reciprocal of the expected number of correct bits between uncorrectable errors

RS Code Performance Curves

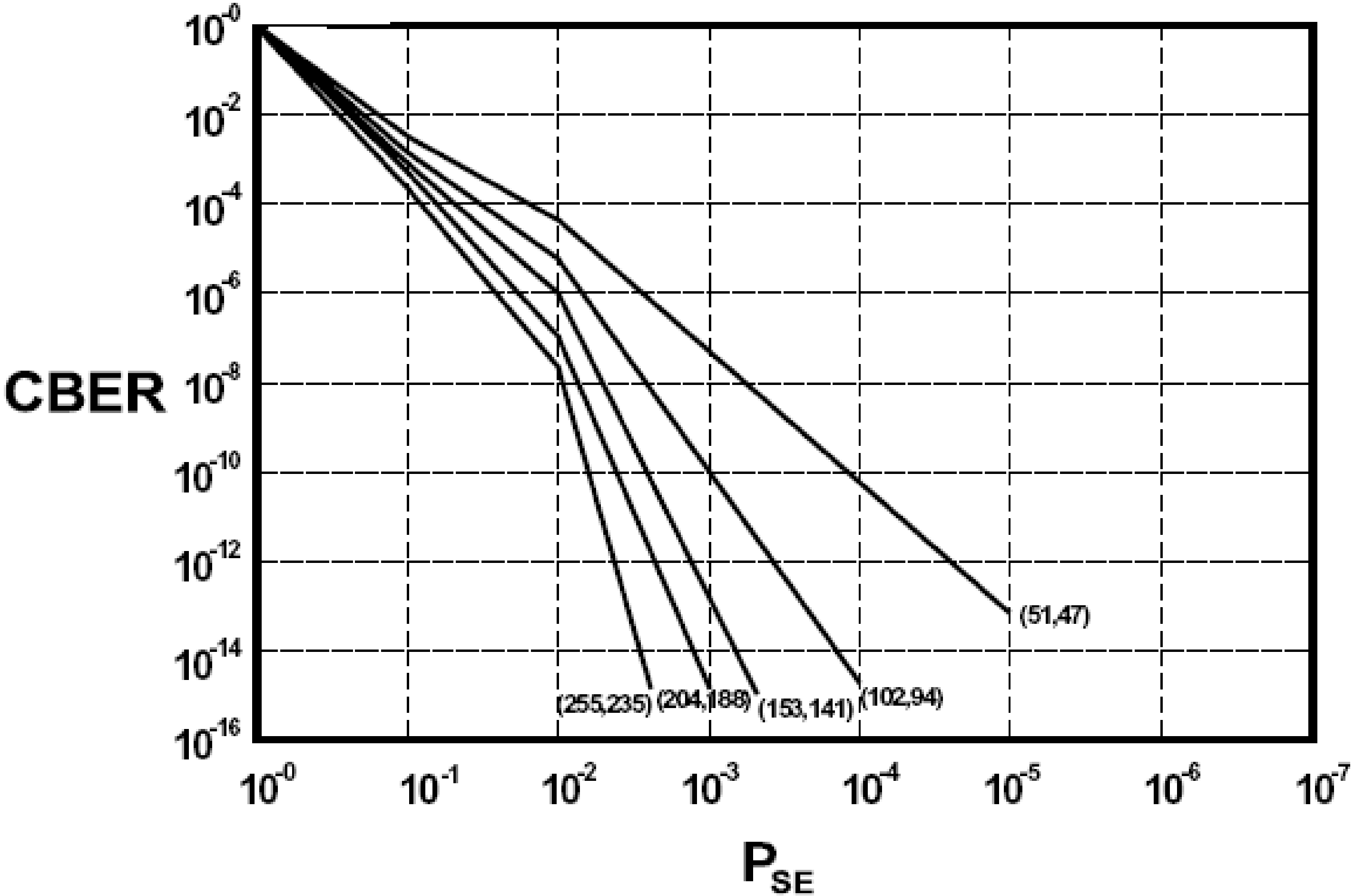
System performance of Reed-Solomon (RS) Block error correction code

- RS(255, k) code
  - k = 244; t =10
  - k = 253; t = 1

Notice that within reasonably small number of check bits (< 10 check bits for 244 data bits), if P_{SE} is larger than 0.1, ECC does not perform well at all!!!



Bit-Error-Rate Curves



Example: For RS(255, 235) code with $P_{SE} = 10^{-3}$, CBER = 10^{-17}. That is, on average 1 error will happen after 10^{17} bits read. For a 1Gbit/s channel, this takes about 3 years!

Hamming Codes

- To detect 2-bit errors and correct 1-bit error by parity bit locations, the block length $n = 2^r - 1$ and message length $k = 2^r - r - 1$ forms (n, k) Hamming code.
- Coding efficiency $\xi = k/n$

Total bit n	Data bit k	Redundant bit n - k	Hamming code	Efficiency ξ
3	1	2	(3, 1) triple repetition code	0.333
7	4	3	(7, 4)	0.571
15	11	4	(15, 11)	0.733
31	26	5	(31, 26)	0.839
255	248	8	(255, 248)	0.972

What Do You Learn

- Multiple access methods from the transceiver point of view
- TDMA, FDMA and CDMA
- The power combining digital communication with RF frontend!