Technische Universität Darmstadt

Telecooperation

# Ubiquitous & Mobile Computing

## Connectivity: Mobile Networks 1

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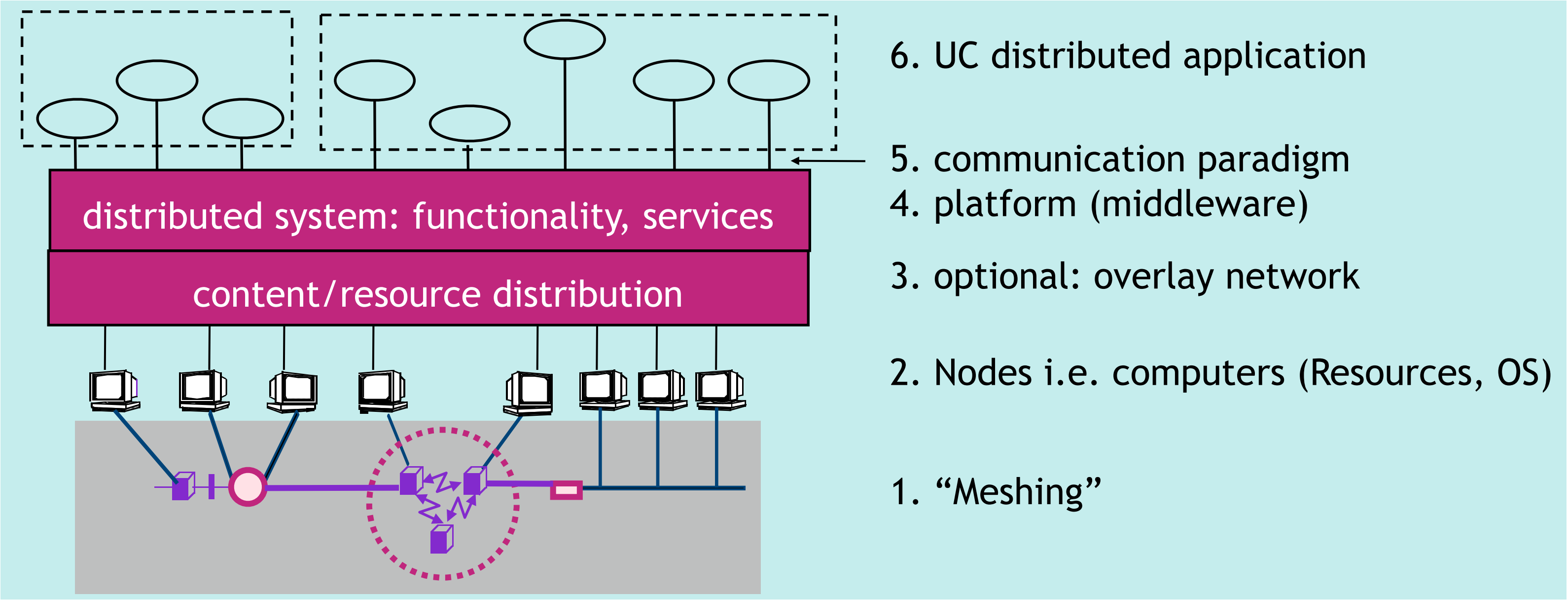
# General Introduction – Connectivity

- Background: Elaborate Disciplines of
  - Computer Networks: connect computers around the world
  - Distributed Systems: software infrastructure atop Comp.Nets
  - what's the distinction? well… not *precisely* defined, but:
    - Dist. Systems establish a level of transparency atop Comp.Nets
    - … of locations, distribution, concurrency, performance…
- A very rough layering may look like this:



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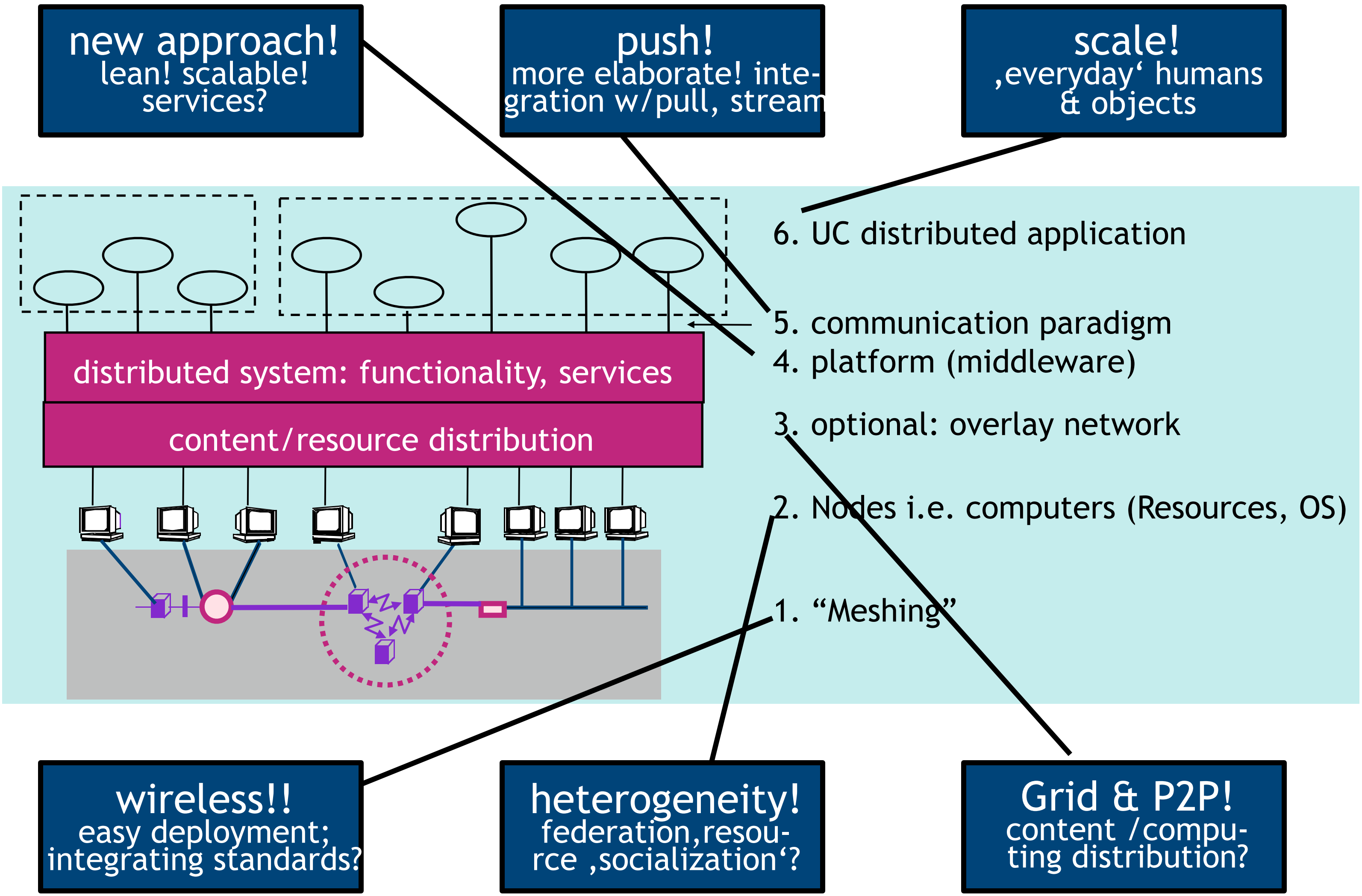
# General Introduction – Connectivity

Notes about the “layers” shown on slide before:

1. Meshing: how to interconnect adjacent computers
   - today: mostly wired; since ~1990: shared → switched media
   - UbiComp: wireless networks crucial
2. Nodes: apart from the mesh, computers are the *resources* added to system
   - today: mostly considered homogeneous (except: clients & servers for non-P2P)
   - today: resources mostly under control of computer owner
   - UbiComp: very heterogeneous nodes, resources partly ‘socialized’
3. Overlay Network
   - new: ‘socializes’ (some) resources from layer 2 → ubiquitous distributed system
   - today: only used for special purposes (music exchange etc.)
   - UbiComp: increasing importance, towards general use
4. Platform: everything beyond 3 providing developers with ‘powerful, easy-to-use’ distr. sys.
   - note: layers 3 & 4 use/contain the classical Internet layers TCP/IP etc.
   - today: 2 major purposes (same for UbiComp, but different (5), different services):
     - providing basic services deemed useful for many applications/developers
     - implementing (5) via special protocols & bookkeeping instances
5. Communication abstraction: crucial for programmers!
   - today: mainly information pull, client/server paradigm
   - UbiComp: “push” dominates, but must embrace “pull”, too (see end of chapter)
6. Distributed applications themselves
   - today: rather ‘closed’ i.e. developed top-down by a team

# Major Connectivity Trends in UC



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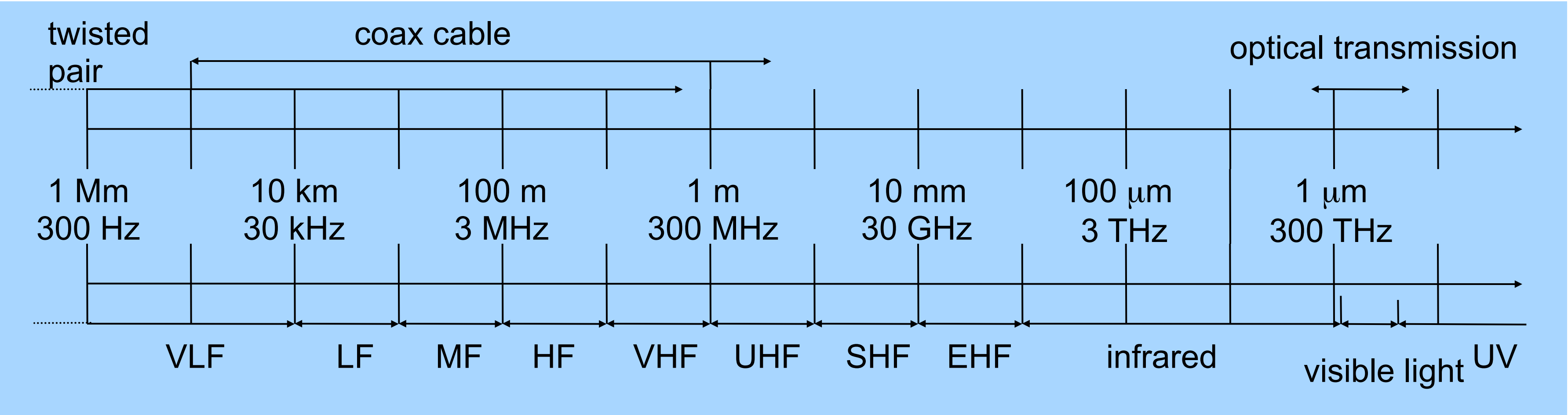
# Electromagnetic Spectrum




- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency
- UHF = Ultra High Frequency
- SHF = Super High Frequency
- EHF = Extra High Frequency
- UV = Ultraviolet Light

**$f * \lambda = c$**
**(c: speed of light, $3 * 10^8$ m/s)**

note: above figure shows orders-of-magnitude (log)

rules-of-thumb (remember!):
**1 MHz : 300 m**
**100 MHz : 3 m**
**10 GHz : 3 cm**

# Basics: 8* „Physics“ Laws & Observations

*0. Beginner‘s Confusion*

don‘t mess up: carrier frequency ⇔ bandwidth

*1. Playground: electromagnetic spectrum*

- above FM (e.g. FM-Radio, ~ **$10^8$** Hz)
- below visible light (~ **$10^{15}$** Hz)

  in other words, mobComm uses
- ~ microwaves 0.5 - 100 GHz or
- ~ infrared > 100 THz

*2. Rules-of-Thumb*

- **signal energy ⇔ data rate × reach** (plus: observe rule 3.1 (-))
  related to: electrosmog, advancements in EE, cost
- **the higher the frequency, the more behavior resembles that of light**
  - very low frequencies: „surface waves“
  - medium freq: e.g., reflection at ionosphere ...
  - very high freq.: „line-of-sight“ (cf. shadowing, distortion... below)

# Basics: 8* „Physics“ Laws & Observations

*3. Carrier frequencies move up as R&D continues:*

higher carrier frequencies mean ⇒

1. (-) needs higher energy, more difficult (expensive) electronics
2. (+) fewer competing „networks“ (a mess up to 2 GHz, difficult up to 10)
3. (+) larger bandwidths and/or # of channels

   ® higher data rates or more subscribers

examples:

| | | |
|---|---|---|
| 890 - 915 MHz | (1990- today: | GSM “uplinks”): |
| 5,1 – 5,8 GHz | (2000 ff: | Wlan 802.11a): |
| 59 - 62 GHz | (20xx: | future WLAN [“MBS”?], WiMax direct links in 50+ GHz) |

(notes:

1. WLAN bandwidth still scattered: US 5,15-5,35 / 5,725-5,825,
   EU 5,15-5,35 / 5,47-5,725; various [US/EU incompatible] energy leves
2. “MBS” has 3GHz of „space“, GSM uplink just 25 MHz)

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# Basics: 8* „Physics“ Laws & Observations

*4. Signal attenuation A („path loss“) is crucial*

- function of distance d, landscape, obstacles (buildings)
- single most important difference to wired communications (most substantial effect on protocol design etc.)!
- A simple model for path loss (A: mean received signal power, related to transmitted power):
  - decreases w/ square of frequency
  - decreases w/ power-of-$\alpha$ of distance ($\alpha$ = 2 in free space, up to 5 in urban environment)

$$A = \frac{P_r}{P_s} = g \frac{1}{f^2 d^\alpha}$$ (g: constant)

*5. Signal path is crucial*

- highest attenuation: walls (steel?), signal „shadow“ (urban street?)
- buildings → reflection → multipath → distortion, interference !!
- line-of-sight ⇔ multipath: even different network designs!

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# Basics: 8* „Physics“ Laws & Observations

*6. Doppler effect matters*

mobile sender stretches/quenches waves ® different nets for different mobility speeds?

- slow (walk): WLAN (Laptop), cordless phone
- medium (drive): cell phone < 250 km/h (→ high-speed trains? need extension!)
- fast (fly): airplane phone system...

*7. Signal latency often non-issue*

- in speed-of-light range: 2/3 c (air) ... 1/1 c (in space)
- depends (in range above) on altitude (air), frequency, ...
- example: GSM 9.6 kbps data, 120B (SMS?) msg. over 3km:
    - $10^{-5}$ sec latency, 0.1 sec transmission time!

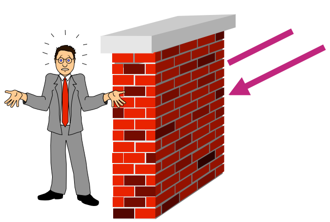
*8. Signal latency often crucial (oooops!)*

- multipath → interference (see above)
- timing, synchronization of stations, etc. (see later)
- GPS etc.: calculation of distance, position
- High tier antennas, in particular geostationary satellites:
    - 35.800 km orbit → up + down: some $7*10^7$ m, speed some $3*10^8$ m/s → ~ ¼ s delay
    - 1Mbps link: 120B „put on ether“ in only ~ $10^{-3}$ s

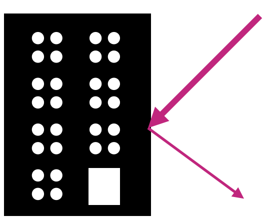
# Basics: „Physics“, Observations (6)

- recall attenuation: due to path loss
- recall distortion: mainly due to multipath reflection
- Further effects:
  - shadowing (HiFreq: approaching 100%)
  - scattering (HiFreq: everyday objects [e.g., 30cm size])
  - diffraction: adds to attenuation, distortion

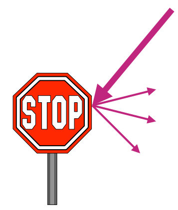
Summary of the four „obstacle“ effects



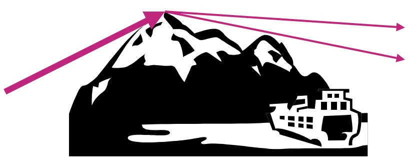
shadowing



reflection




scattering



diffraction

# Basics: SNR, Decibel

„design center“ of all networks (layer 1):

Signal-2-Noise-Ratio SNR (or, S/R)

i.e. power of ‚signal of interest‘ related to power of ‚what disturbs‘

Decibel: unit used to express relative differences in signal strengths.

- given: two signals with powers P1, P2
- → compute $10 * \log_{10} (P1/P2)$
- e.g.: P1 is 100 times P2:
  - $P1/P2 = 100$, $\log_{10} (100) = 2$, ‚relation P1 : P2‘ is 20 dB
- ‚„relation‘ may be: SNR; power sent vs. received (attenuation); ...
- e.g.: signal over 2 hops, no amplifier
  - attenuation is 20:1, then 7:1 → overall attenuation. is 140:1
  - or: 13.01 dB + 8.45 dB = 21.46 dB ($10*\log_{10}20 + 10*\log_{10}7 = 10*\log_{10}140$)

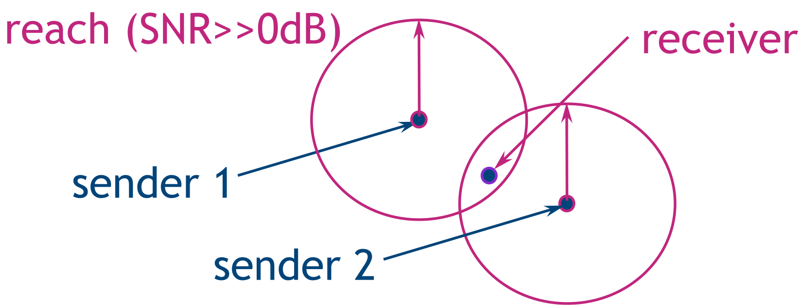
(note: power is f(amplitude$^2$) → $20*\log_{10} (A1/A2)$ yields same result

# Basics: ISI Peculiarities (1)

*ISI (InterSymbol Interference) much different from wired networks*

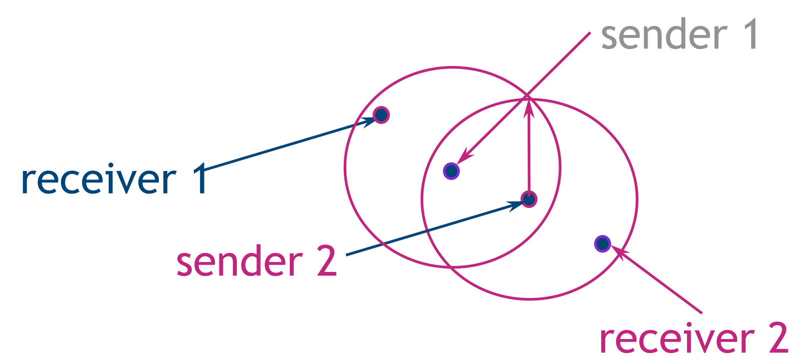
1. *Hidden-Terminal Problem → restricted listen-before-talk (LBT)*

- given goal: uncoordinated access of N senders to 1 medium
- has risk of collision → avoid by checking first if medium free
- In example:
  - S1 & S2 check: LBT o.k.
  - BUT: R experiences collision (S2 may also be in „shadow“ of S1)




2. *Exposed-Terminal Problem → LBT may be too pessimistic*

- In example:
  - Both S1 and S2 could send
  - But S2 senses S1 during LBT



# Basics: ISI Peculiarities (2)

*ISI (InterSymbol Interference) much different from wired networks*

*3. Path Loss → no listen-while-talk (LWT)*

- again goal: uncoordinated access of N senders to 1 medium
- again: problem collisions → detect, resolve
- wire (Ethernet): LWT possible
  - during Xmit: if signal-on-wire ≠ signal-sent: → collision
- wireless: LWT impossible (received signal much too low-energy)

*4. Path Loss → no full duplex traffic*

- wire (twisted pair): full duplex possible (2 peers use same wire)
- wireless: needs two channels (= two carrier frequencies)
  - mobile station MS → base (transceiver) station BTS: „uplink“
  - base station → mobile station: „downlink“
  - (satellite jargon)

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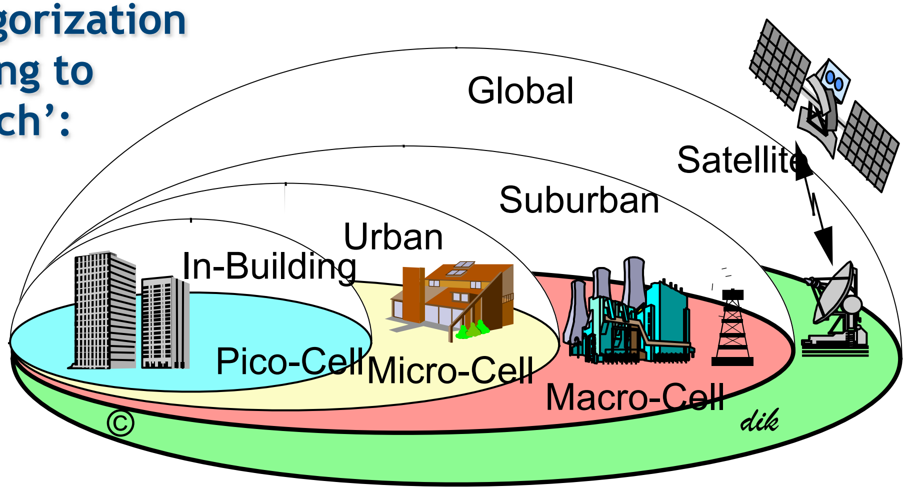
# Basics: Cellular Networks

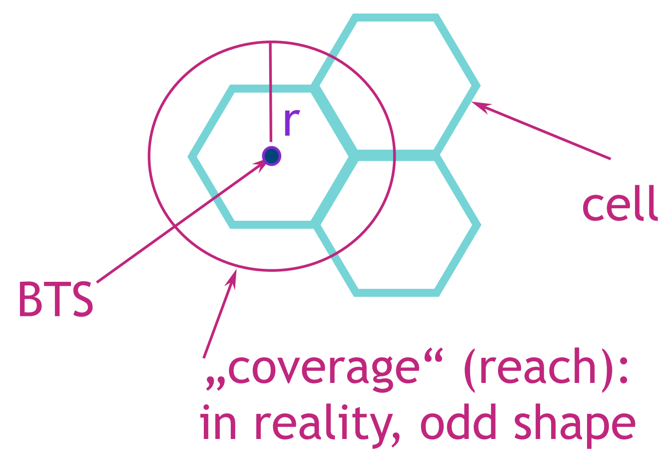
many categorizations of “cell sizes” exist!

For our lecture: a) cell sizes (roughly) categorized according to radius, e.g.:

| | | | | |
|---|---|---|---|---|
| - | pico: | r = 50 m | private (home, office) | PicoNet |
| - | micro | r = 500 m | inner city (many users) | wLAN, PLMN |
| - | macro | r = 10 km | ‚standard GSM‘; city, road | PLMN |
| - | hyper | r = 30 km | rural area | PLMN, HALO |
| - | overlay | r = 200 km | high tier antenna coverage | HALO, LEO |

**b) categorization according to ‘outreach’:**



# Basics: Cellular Networks

Roaming (option in cellular networks, some degree always supported):

- MS may move freely between cells, even (!) switched-off
- MS are "found", identified upon switch-on (cf. incoming calls)

Handover (option in cellular networks):

- equals "roaming" during existing connection (active phone call)
- connection „hand off" to new cell
- w/o interruption & noticeable effect to user(s)

Home location register HLR:

- admin. data in „home" cell of subscriber
- holds all permanent data of system-wide concern
- may point at „current-VLR", see below

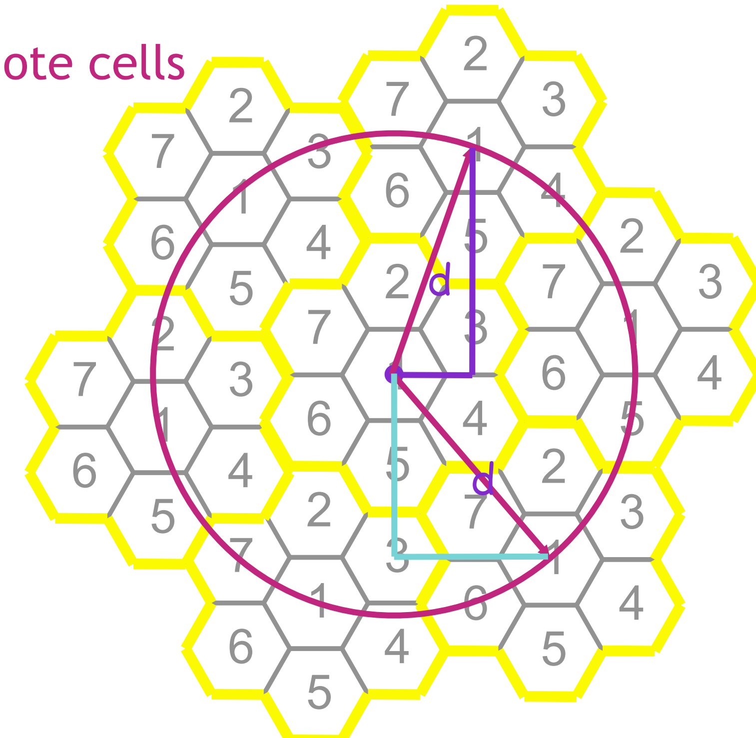
Visitor location register VLR:

- holds all admin. data relevant for the cell in which user „roams"

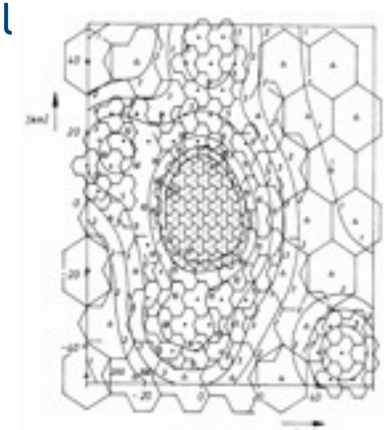
# Multiple Access: Introduction (2)

- What is divided? ≥ four options (order ≈ tech. complexity):
  1. Space (SDMA):
     - „bands“ are re-used at a certain distance (remote cell)
     - attenuation → remote re-use won‘t interfere (much) with local cell
  2. Frequency (FDMA):
     - different MS use different carrier frequencies
     - allocated frequency band divided into subbands
     - GSM900: 124*200kHz, GSM1800: 374*200kHz
  3. Time (TDMA):
     - different MS use different time-slots
     - often: revolving frames, MS knows „its“ pos. (slot) in frame
  4. Code (CDMA):
     - different MS use different „characteristic“ codes
     - receiver tunes to this code

# Multiple Access: SDMA-1




- SDMA (SDM): frequency bands re-used in remote cells
- different re-use patterns possible:
  (repeated) clusters of cells
  - N = 3, 4, 7 (shown), 12, ... cells per cluster
  - each band used only once per cluster
- design parameters:
  - reuse distance d=f(r,pattern)
  - cell radius r (coverage)
- for different N (cluster sizes, patterns):
  - different d/r ratios → different SNR induced by remote cells of same band
  - tradeoff: 1/N of all bands usable per cell
- realistic example (from Book by B. Walke):

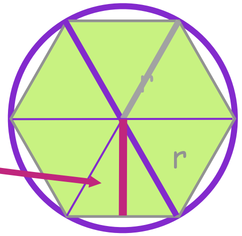


# Multiple Access: SDMA-2

1. channel assignment:
   - fixed: each cell has pre-assigned f's, for new calls & handover
   - reservation: some f's reserved for handover
   - ‚borrowing' (from neighbors) ... totally dynamic
2. „Re-use related SNR" (abstract from other noise)? E.g., N=7:
   - ...is called C/I ratio (C: carrier signal, I: interference sig.)
   - remember path loss $L = g \cdot f^{-2} \cdot d^{-\alpha}$ (for fixed f: $L = h \cdot d^{-\alpha}$ )
   - 6 neighbor BTSs w/ distance d (neglect others), max (BTS→MS) = r
   - see (figures, Pythagoras): $d^2 = (5 \cdot (\frac{1}{2}\sqrt{3}\, r))^2 + (r+\frac{1}{2}r)^2 = 84/4\, r^2 = 21r^2$
   - note: i) for carrier signal C: d=r; ii) let $\alpha=4$; iii) 6 neighbors!
   - → $C/I = (h \cdot r^{-4}) \,/\, (6 \cdot h \cdot d^{-4}) = d^4/6r^4 = 21^2 r^4/6r^4 = 147/2 = 73{,}5$ (18,66dB)

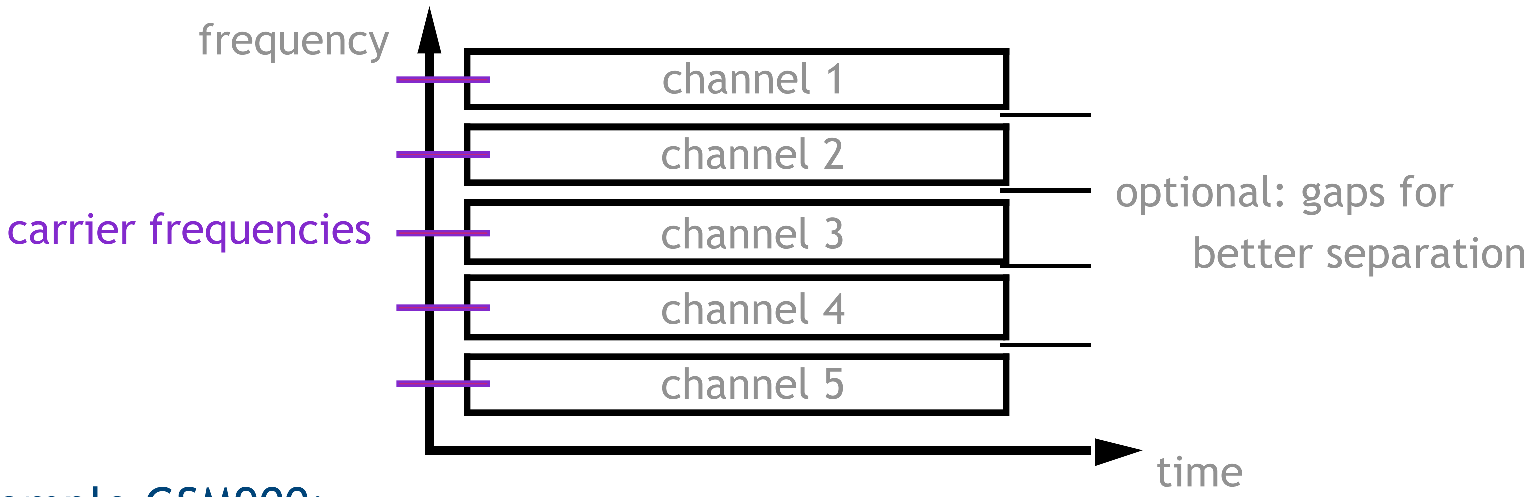
   N=3: C/I=13.5=11.3dB (N=4: 16=12dB), but twice as many users possible

$\sqrt{r^2 - \frac{1}{4}r^2} = \frac{1}{2}\sqrt{3}\, r$



# Multiple Access: FDMA

Channels = subbands, distributed over available bandwidth




Example GSM900:

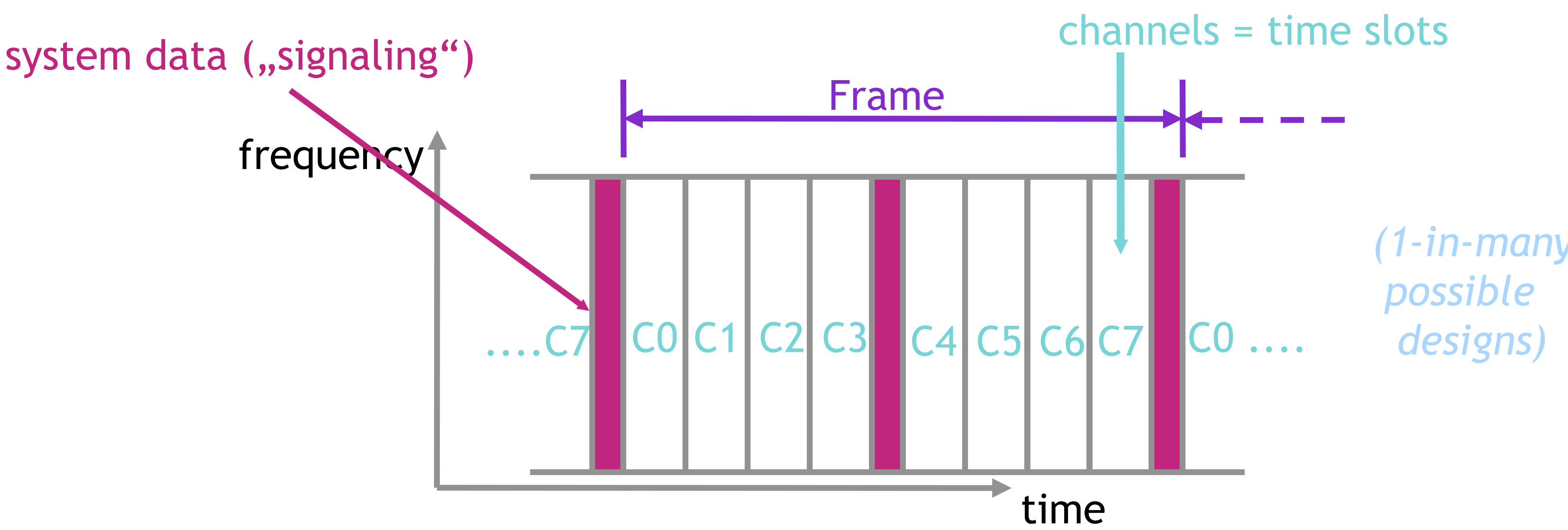
- carrier frequency of uplink/downlink $F_u/F_d$:
  - $F_u(n) = 890.2\text{ MHz} + (n-1) * 0.2\text{ MHz}$, n=1 … 124
  - $F_d(n) = F_u(n) + 45\text{ MHz}$

note: high-speed (wLAN, wATM etc.) → increasing use of OFDM:

overlapping bands, orthogonal frequencies (harmonic distances of subcarriers, equals carrier distance) dyn. bandwidth assignment ...

# Multiple Access: TDMA

- Entire frequency dedicated to single sender-receiver pair, but only for a short period of time (time slot, slice)
- not applicable in analog transmission systems (old telephone net)
- e.g., 9.6 kbps per channel → > 80 kbps on ether for 8 channels
- GSM: 8 slots (TDMA+FDMA!)
- practical systems: TDMA always w/ FDMA



# Multiple Access: CDMA

CDMA, also called „spread spectrum“ SS

- versions: FH (FHSS), DS (DSSS) (chaotic crosstalk, but not ‚concurrent‘!)
- each sender uses “entire” bandwidth & time, „spreads“ code
- Wideband (W-CDMA): plus FDMA, but huge subbands (~5MHz)
  - Narrow (N-CDMA): smaller (~1MHz), but still >> FDMA+TDMA-subbands
- receiver knows coding rules of sender:
  - autocorrelations → transforms signal back (to lo-bandwidth/hi-power)
  - all other signals appear as noise (→ # of senders limited, cf. TDM,FDM)
- no channel assignment → simpler plus better spectrum utilization → used in wireless LANs, increasingly in PLMN
- no synchronization needed (each code is self-synchronizing)
- Problem: needs fine-grained transmission power control
  - e.g., MSes must adjust such that all signals reach BTS w/ ~same power
  - but: signal loss may change very fast (as MS moves)
  - IS-95 (USA Qualcomm): 1kbps „adjustment channel“ per MS

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# Multiple Access: CDMA (FH)

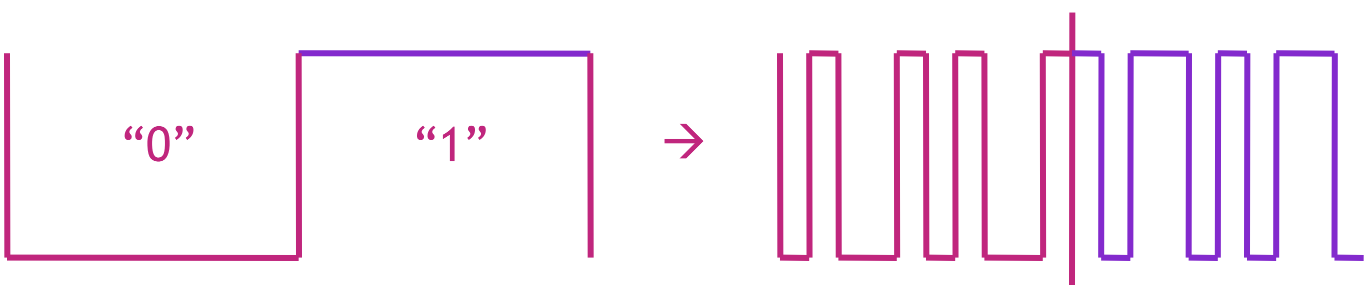
## Frequency-Hopping FH:

- Sender + receiver constantly change (hop-2-new) frequency
  - basis: pseudo-random sequence, initial value agreed
  - origin: military networks (sequence unknown → secret comm.)
- „Hope“: few collisions → high probability of correction
- Fast-FH: several / many hops per bit
  - „a few“ collisions per bit don‘t harm
- Slow-FH: several bits per hop
  - GSM: optional (deterministic) slow-FH
    - reason: distribute errors in „noisy“ bands over all channels
    - hope: corrected by forward-error-correction FEC

# Multiple Access: CDMA (DS)

Direct Sequence (by far most commonly used):

- each bit mapped onto sequence of mini-bits (“chips”)
- 10 chips / needs 10 times higher data rate (reality: up to ~1000)
- Bit „1“ → chip-sequence, Bit „0“ → inverse sequence
- receiver autocorrelates → reconstructs original signal
  - again: secrecy is by-product (IFF chip-seq. per station is random) SNR near 0 → not even existence of communication detectable
  - again: much more dynamic than FDM, TDM
  - plus: no (‚expensive‘) synchronous frequency-hopping needed!



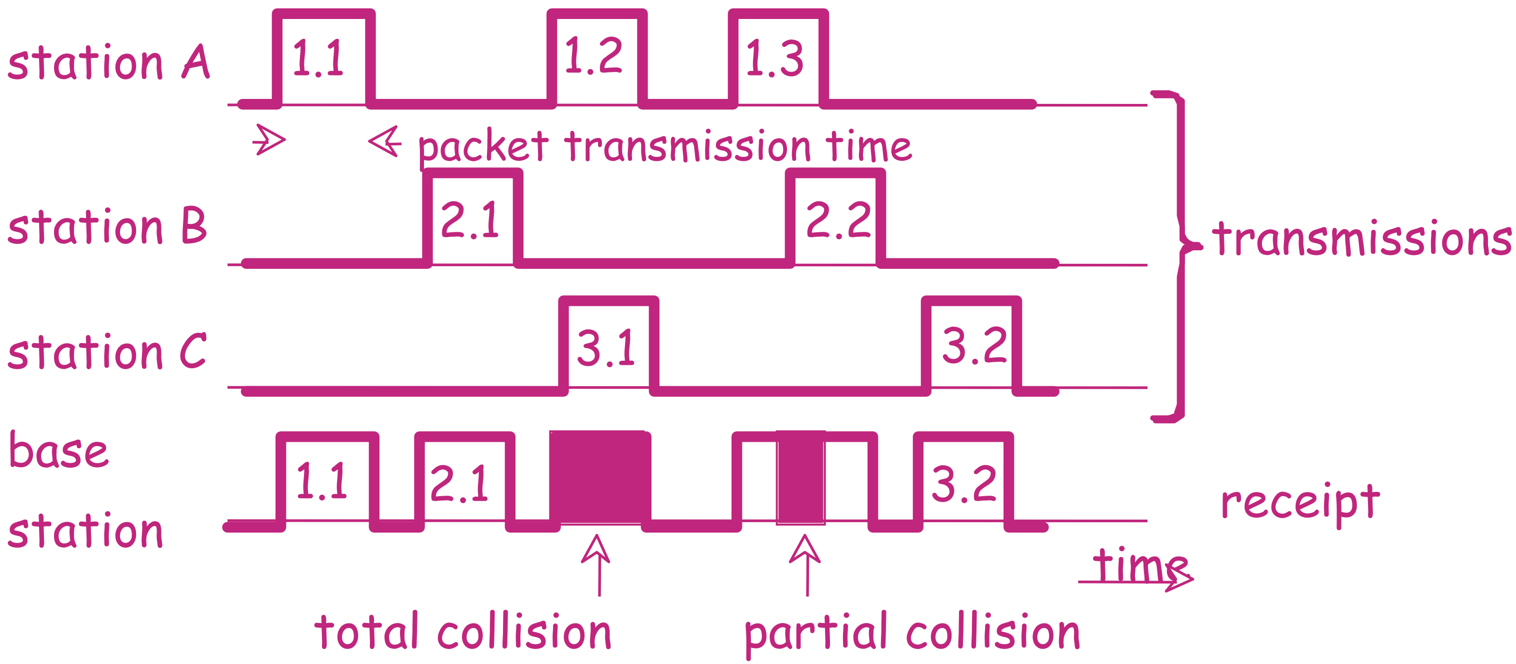

Note:
in reality,
Chip-seq.
changes
over time

# Concurrent Access: ALOHA

- developed at U Hawaii (islands, hills!) since 1970:
  - wireless net connects terminals(/hubs) ⇔ host system
  - compares well to: MS ⇔ BTS
  - ‚grand father' of concurrent access schemes (wireless *and* Ethernet)
- channels: 407,350 MHz uplink, 413,475 downlink
  - concurrent access (ALOHA) on uplink only
  - downlink: packets + acknowledgements (ACK) for uplink packets
- MS send whenever packet ready
- BTS sends corresponding ACK on downlink
- if 2-or-more MS send with time overlap –> collision
  –> BTS ignores „jam" received –> no ACK
- MSes: timeout (no ACK received) –> send again
  –> collision repeated?
  no: since random „backoff" (waiting time)

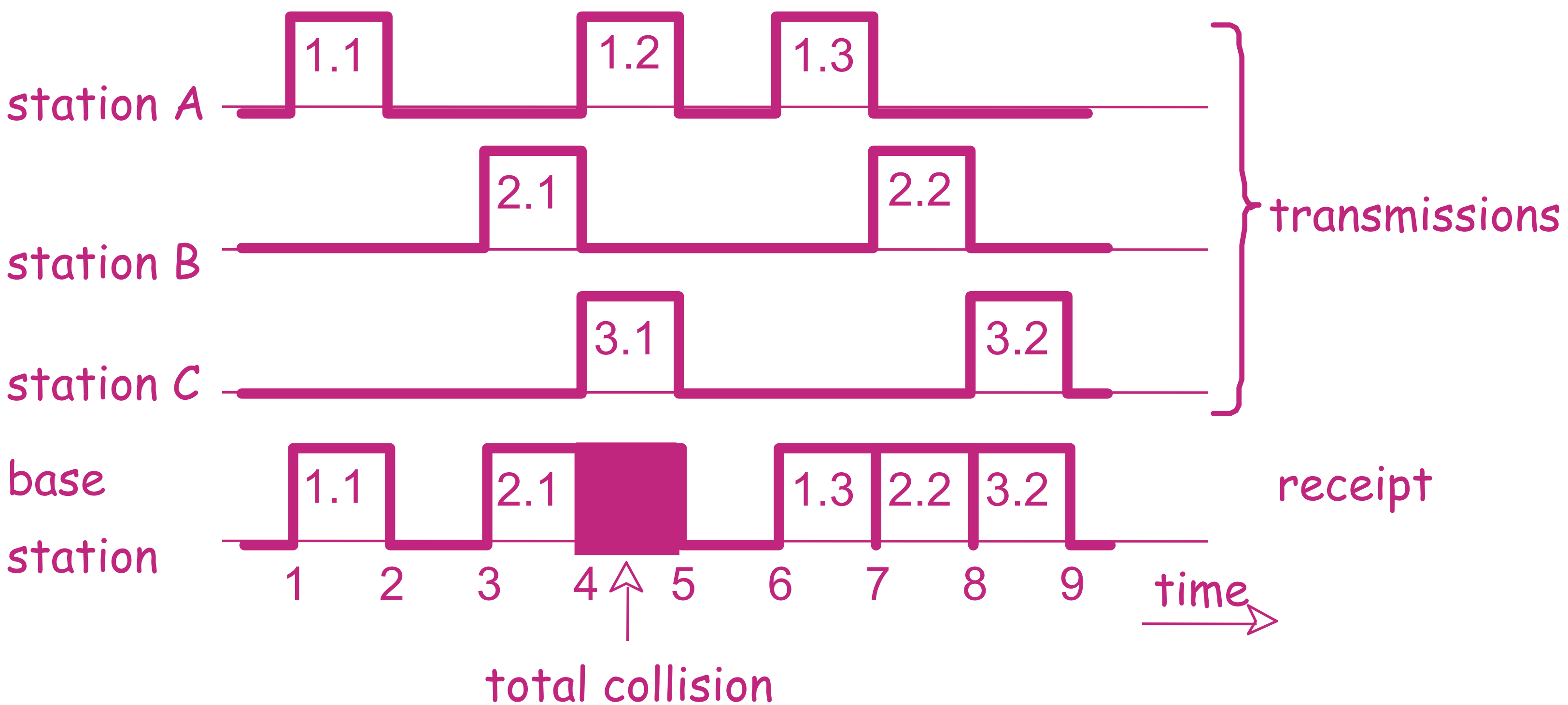
# Concurrent Access: Pure ALOHA

- packets 1.1 (station A), 2.1 (B), 3.2 (C) transmitted ok
- packets 1.2/3.1 collide, 1.3/2.2 too (partial as bad as total!)



# Concurrent Access: Slotted ALOHA

- Fixed (maximum) packet size, equals time slots
- common clock for slots (xmitted at downlink → latency was rel. low)
- start xmit w/ slot only (end ≤ slot end) → all collisions are total
- ‚surprise': mean throughput increased by factor of 2!
  - why? xmission slightly later, but ‚just hit'-overlaps avoided



# Concurrent Access: CSMA

Idea: stations ‚sense' channel before sending

- CS = carrier sense („cs = on" means: channel busy)
- CS also called LBT = listen-before-talk

- advantage: channel busy -> somebody sends -> don't disturb
- total avoidance of collisions? NO
  - $MS_1$ ready2send, $MS_2$ *just* started (signal has not arrived yet)

    -> $MS_1$: CS=off (no ‚busy' sensed) -> collision
- collision probability high at end of a transmission:
  - several MS want to send, sense channel during CS=on
    - all MS realize CS=off → immediate xmit
  - CSMA variants therefore wrt. „when/how to start xmit"

# Concurrent Access: CSMA variants

Major distinction: procedure applied when station is ready2send

1. non-persistent:

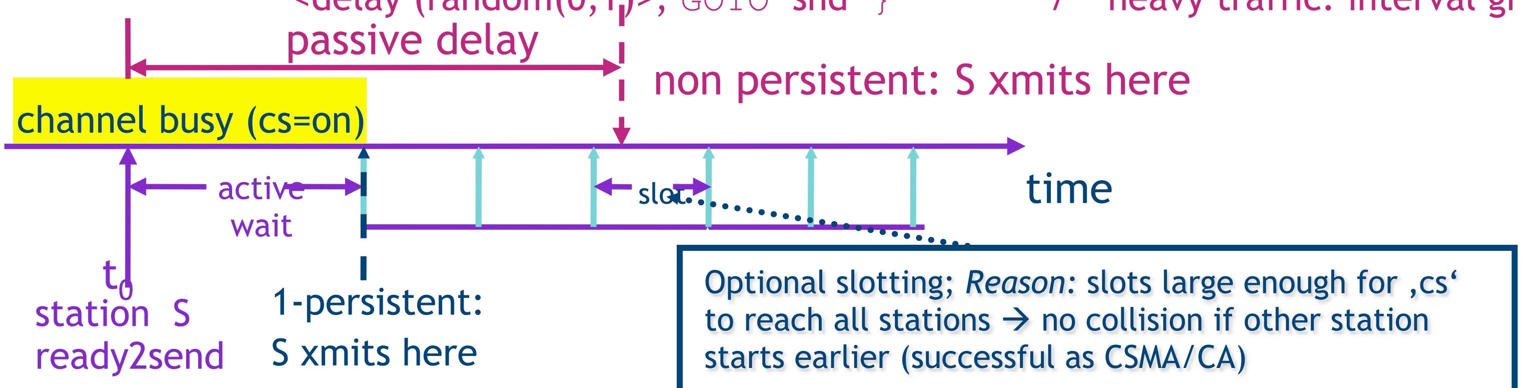
```
snd:  while <cs=on> DO < delay (t)> ;        /** t constant or random
      <send>;                                /** no polling, no danger after end of Xmit
```

2. p-persistent:

```
snd:  WHILE <cs=on> DO <active wait>;        /** usually: cs=off→ interrupt
      IF <random-bool(p)> THEN <send>        /** true with probability p < 1
      ELSE{ <delay t>; GOTO  snd }           /** t may be random # of ‚slots‘
 /** lower p reduces probability of ‚competition‘ after end of xmission
```

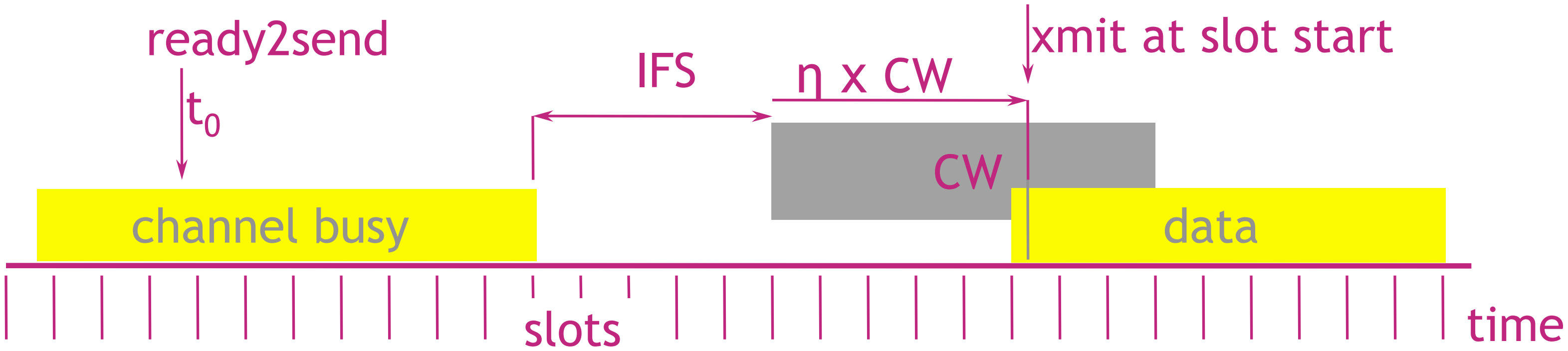
3. 1-persistent: (the one used for ‘wired’ Ethernet = CSMA/CD – LWT is possible there!)

```
snd:  WHILE <cs=on> DO <active wait>;        /** as above
      <send>;                                /** high competition → backoff algo.
IF <collision> THEN {                        /** here: binary exponential backoff
      IF <subsequent-collision> THEN T:=T*T ELSE T:=Tstart;
      <delay (random(0,T))>; GOTO  snd  }    /** heavy traffic: interval grows exp
```



# Concurrent Access: CSMA/CA

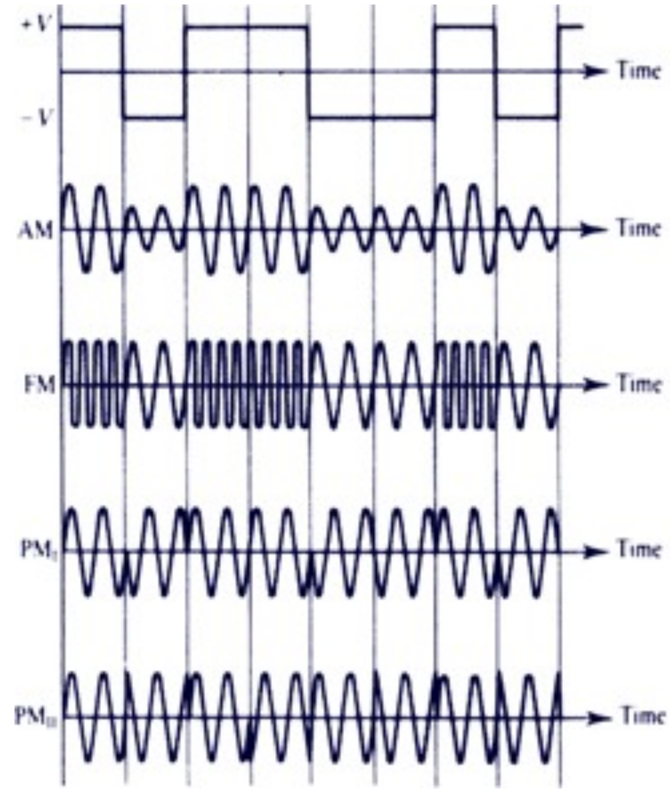
- CA = collision avoidance; several minor variants
  as described here: ≈ slotted variant of p-persistent CSMA with p=0
- contention window CW = time interval considered collision intensive
- after active wait; cs=off → delay during IFS (interframe spacing)
  - minimum IFS determined by wireless signal latency
  - 3 different IFSs (signal/priority/data: SIFS, PIFS, DIFS): priorities
- then:
  - draw random $\eta \in [0,1)$
  - wait for slot that ‚contains' time $\eta \times$ CW (active wait: maybe cs→on)
    $\eta$ –> risk of collision ‚spread' over CW
  - if still collision –> increase CW exponentially (up to maximum)
- fairness: if preceded by other station, # of slots waited count next time



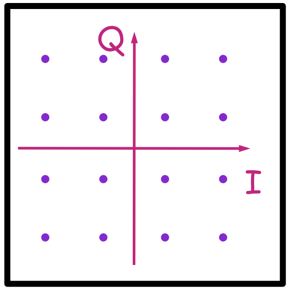
# Modulation (1)

Low bandwidth → needs highly efficient modulation

- known: carrier frequency:
  - $s(t) = A \cdot \sin(2\pi f \cdot t + \varphi)$
  - bits modulate amplitude A, frequency F, phase $\varphi$ (P)
  - A/F/P-„modulation“ AM, FM ...
  - also: shift keying ASK, FSK, PSK
  - A→F→P: better, more complex




- QAM: quadrature amplitude modulation = PSK + ASK
  - e.g., 16 values, 4 bits: I/Q-diagram for 4-QAM (‚optimal‘ I/Q-diag on 2 amplitude ‚rings‘? or else?)
  - 16QAM exists (needs good SNR) (16-PSK would have phases < $2^{\circ}$ apart)
  - wired-modem 4-QAM example (9600 baud): 12 phases, 4 phases w/ 2 amplitudes:



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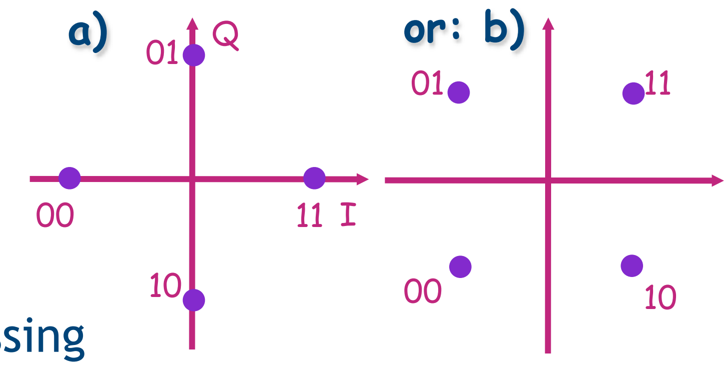
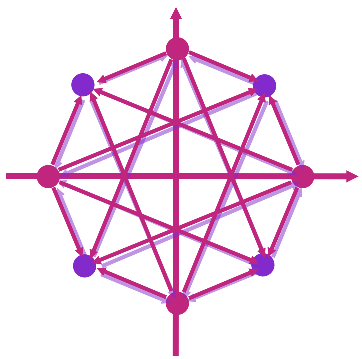
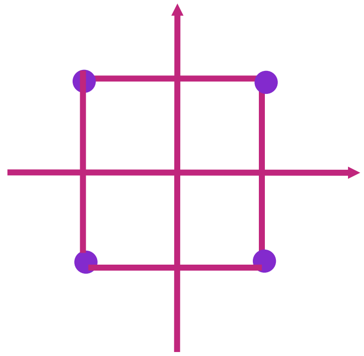
# Modulation (2)




- **QPSK** (Q=quadrature):
  - 4 phases: 0, 90, 180, 270 (a)
  - only phase changes, same amplitude
  - 2 bits per symbol (dibit)
  - Problem: 180° phase change -> zero crossing -> decoding at receiver problematic, because temporarily no carrier



- **π/4-QPSK**
  - add 45° phase jump after each symbol, independent of data
  - carrier signal always present



- **OQPSK**: Offset-QPSK
  - change of real part/imaginary part delayed by half symbol time
  - max. phase change reduced to 90°

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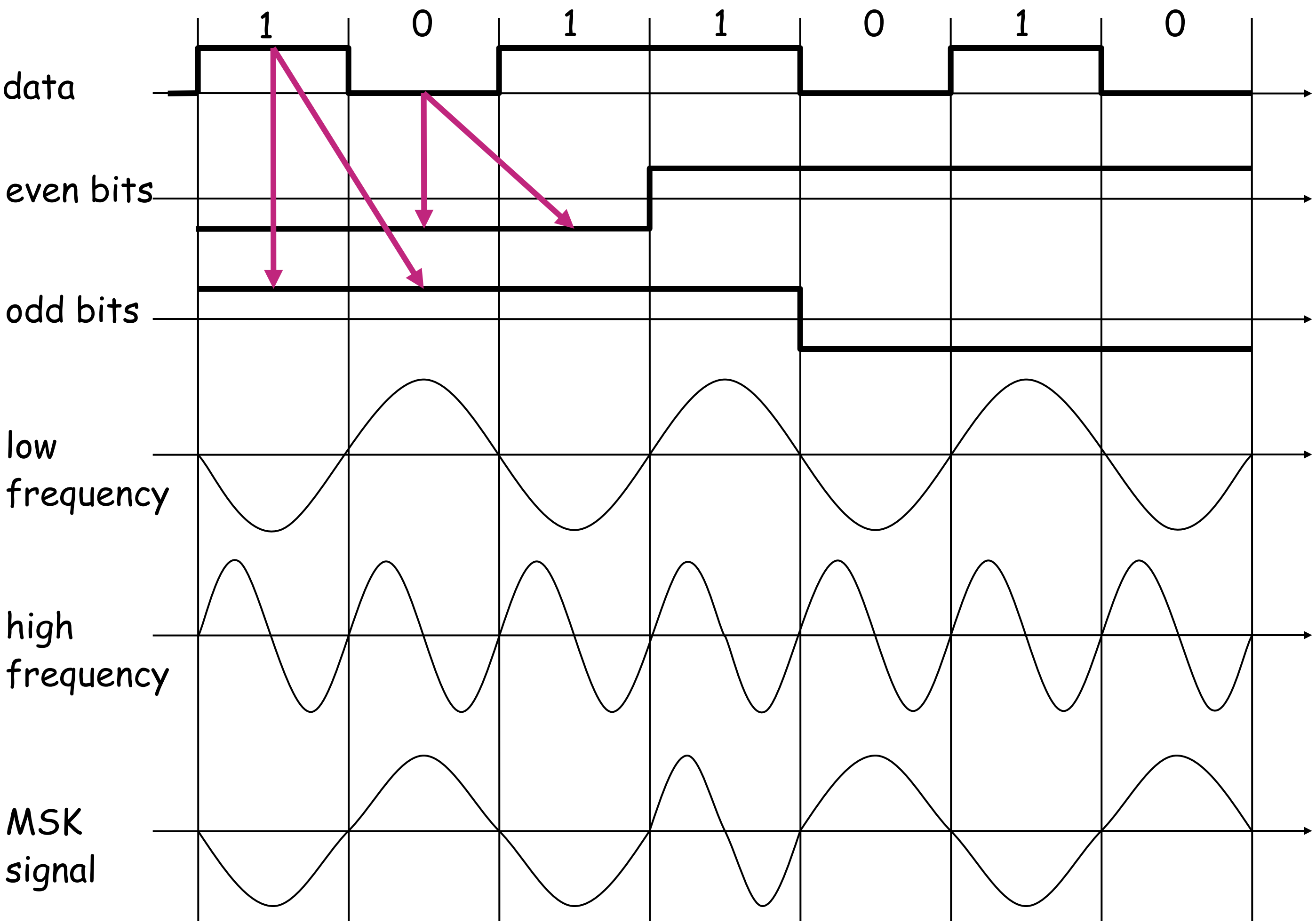
# Modulation (3)

- Advanced FSK: ambiguously called MSK, GMSK (GFSK unambiguous)
- Example for M(F)SK below, gaussian filter would make it GFSK




| bit | |
|---|---|
| even | 0 1 0 1 |
| odd | 0 0 1 1 |
| signal | h l l h |
| value | - - + + |

h: high frequency
l: low frequency
+: original signal
-: inverted signal