The GSM Air Interface
Fundamentals and Protocols

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May 20, 2003

Resources

- Most of the materials in the following slides is from:
  - The books of Bernhard Walke [3]
  - The book of Rappaport [1]
  - The book of Stallings [2]

Overview

- *Fundamentals of Cellular Systems and GSM*
- Fundamentals of Wireless Channels and Error Control
- GSM Channel Access Procedure
- GSM Speech Transmission
- Summary

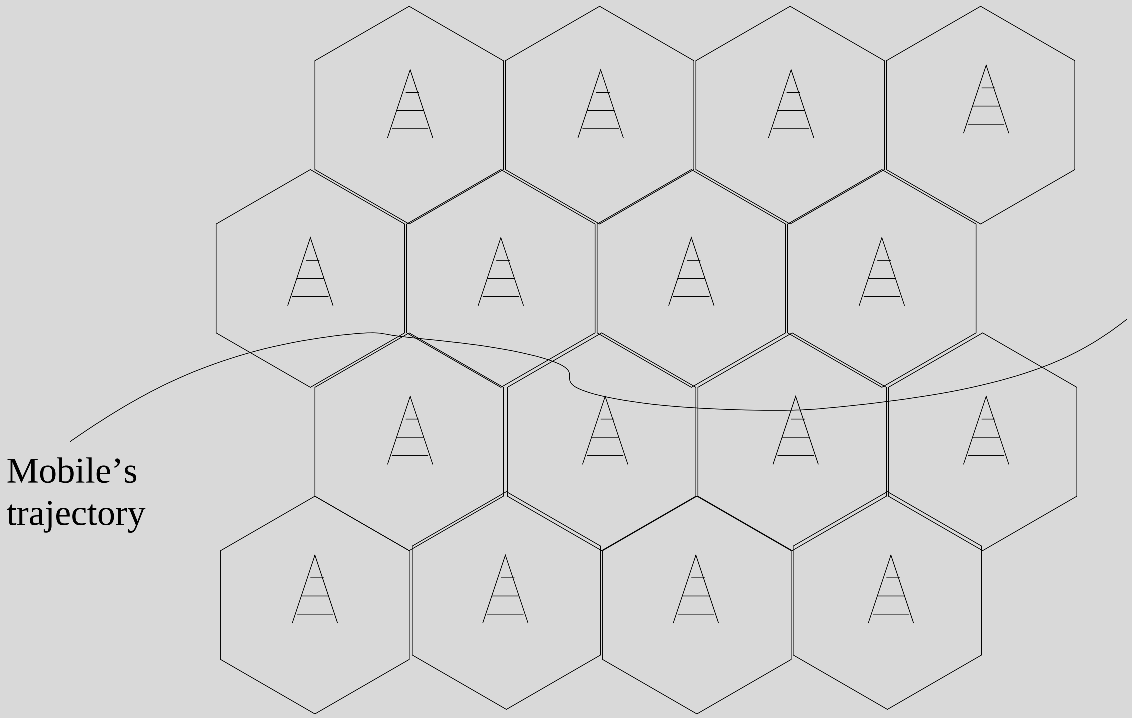
Fundamentals of Cellular Systems and GSM

- Cellular systems offer location-independent voice communications:
  - users can move freely while talking
  - they can place calls at any time and any place
  - they can be called everywhere
- GSM (Global System for Mobile Communications):
  - CEPT initiated work in 1982, ETSI issued the standards in 1990
  - digital system, primarily for voice, data services on top (GPRS)
- There are other (old and new) cellular systems: AMPS, IS-136, IS-95, UMTS (upcoming), TFTS, PDC (Japan), . . .

Fundamentals of Cellular Systems

- A BS constitutes a *cell* by its transmission radius
- A mobile equipment (e.g. a *cellphone*) always communicate with the closest *base station* (BS)
- The BS's are spreaded over the area to provide full coverage
- Multiple BS are aggregated in a *mobile switching center* (MSC)
- The MSC's are interconnected by a *backbone*

Fundamentals of Cellular Systems II



Fundamentals of Cellular Systems III

- The overall cellular system is granted some part of the spectrum, which is subdivided into *channels*
- Each BS is assigned a (sub-)set of channels to serve mobiles
- Neighboring BS's are assigned different sets of channels to avoid interference
- The same channel could be re-used by another base station having sufficient distance to avoid interference ($\Longrightarrow$ *frequency reuse*)
- Moving mobiles will occasionally leave the transmission range of one BS to enter the range of another $\Longrightarrow$ *handover*

Fundamentals of Cellular Systems IV

- During a call a BS assigns a fixed portion of a slot to a mobile:
  - mobiles arriving to a “full” BS will get no service
  - Reducing cell size / transmission power while increasing the number of BS:
    - increases the *system capacity*
    - increases the number of *handovers*
- Handover is initiated by the mobile, which has to constantly check the signal levels of surrounding BS

Fundamentals of Cellular Systems V

- There are different channel assignment strategies:
  - fixed assignment: each BS is allocated a fixed set of frequencies and allocation does not change over time
  - fixed assignment with borrowing: before a call is blocked, a BS might try to “borrow” a channel from a neighboring BS
  - dynamic assignment: MSC keeps all channels and allocates them on request to a BS

Fundamentals of Cellular Systems VI

- How to cope with handovers?
  - treat a handover as a new call $\Longrightarrow$ blocking $\Longrightarrow$ connection drop $\Longrightarrow$ angry users
  - guard channel concept: set aside some channels for handover calls $\Longrightarrow$ wasted capacity
  - queueing off handovers: between initiation of handover and the actual event some time passes (in GSM: 1-2 seconds), this time can be used to wait for ending / leaving calls, the waiting call is then treated next
  - Umbrella cells for highly mobile users

GSM as a Cellular System

- In GSM the structure and terminology is a bit different:
  - mobile stations (MS)
  - *base transceiver station* (BTS): has transmit / receive circuitry and does transcoding / rate-adaptation
  - several BTS are managed by a *base station controller* (BSC): BSC allocates channels to BTS, handover management, paging
  - several BSC's are under control of a *mobile services switching centre* (MSC): gateway to PSTN, handover,
- These are only the "close-to-radio" elements

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Fundamentals of Wireless Channels and Error Control

- Information is transmitted *wire-less* between transmitter (Tx) and receiver (Rx), using electromagnetic waves propagating in free space
- Both Rx and Tx have an *antenna*
- Frequency bands:
  - radio frequencies up to millimeter waves, typically ≤ 5 GHz, but 60 GHz systems under development
  - infrared
- In radio and millimeter range frequencies are shared resources, allocation by regulation bodies, e.g. FCC, CEPT

Propagation Phenomena

- Path loss and attenuation on obstacles
- reflection, diffraction, scattering
- interference (adjacent or co-channel)
- thermal or man-made noise
- Imperfections of transmit / receive circuitry

Path Loss

The path loss can be modeled approximately as ([3, Eq. 2.8])

$$P_R \sim P_T \cdot C \cdot \left(\frac{d_0}{d}\right)^{\gamma} \qquad (d \geq d_0)$$

- P_R and P_T are the power levels at Rx and Tx
- C is a constant involving wave length, antenna gains, further technological parameters
- d_0 is the *far field distance* of the transmit antenna, d is the distance between Tx and Rx
- γ varies between 2 (free space propagation) and 5 (strong attenuation, e.g. due to obstacles)

Path Loss – Consequences

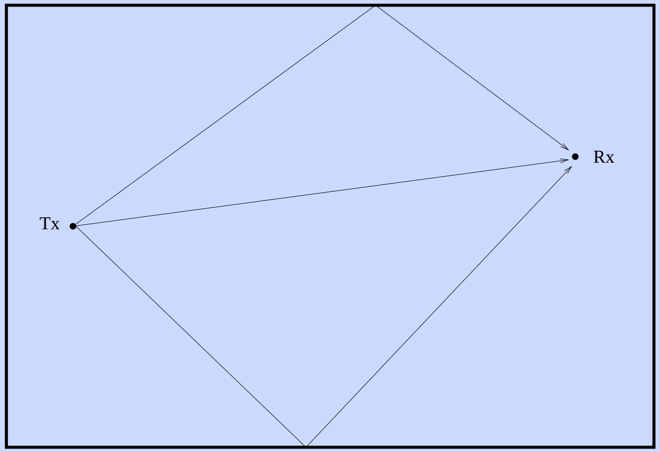
- A receiver needs a minimum signal power (*receive threshold*) $\Longrightarrow$ for fixed P_T the communication distance between Tx and Rx is bounded
- Conversely, if two stations A and B have a large distance, they need high transmit powers to communicate successfully
- If stations A and B both transmit to C and $dist(A, C) \neq dist(B, C)$ then A's and B's signals have different levels at C

Path Loss – Consequences Cont'd

- In addition to "normal" path loss, signals can be attenuated on obstacles
- If a receiver moves, passing obstacles leads to variation in the mean received signal power
- Signal power variation happens on timescales related to human activity $\Longrightarrow$ *slow fading*

Multipath Fading

- A signal can be transmitted on multiple paths from Tx to Rx due to
  - reflection
  - diffraction
  - scattering



Multipath Fading – First Consequences

- Result: a signal arrives on several paths, each having a different delay and attenuation $\Longrightarrow$ delay spread
- Interference (destructive or constructive)
- Inter-Symbol Interference: if channel symbols are transmitted without guard time, waveforms belonging to different symbols may overlap (due to delay spread)

Multipath Fading – Delay Spread

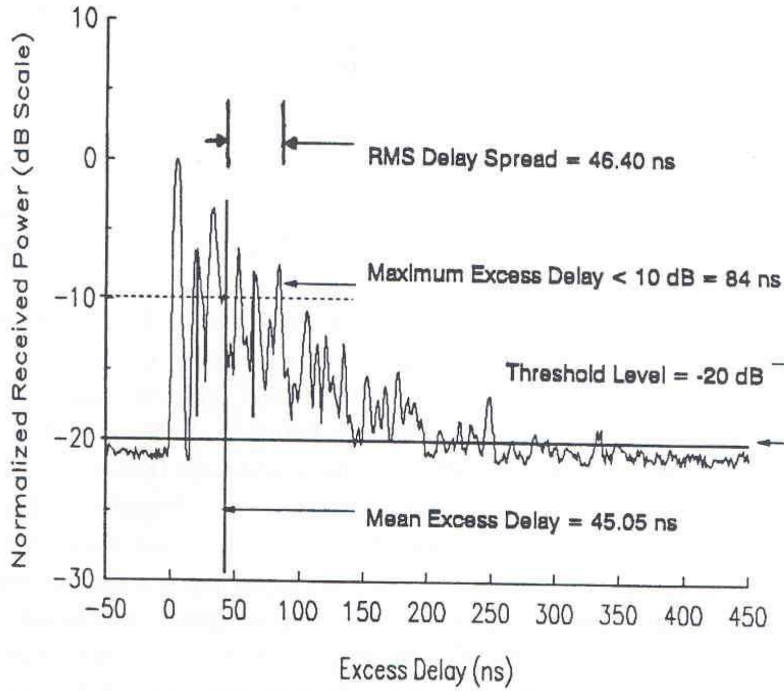


Figure 5.10 Example of an indoor power delay profile; rms delay spread, mean excess delay, maximum excess delay (10 dB), and threshold level are shown.

Figure 1: (From: [1, Chapter 5])

Multipath Fading – Mobility

- Mobility of Rx introduces some problems:
  - Doppler shift
  - varying propagation environment (number of paths, their delay and relative attenuation)
- We get a rapidly fluctuating received power level $\Longrightarrow$ *fast fading* or *multipath fading*
- If the signal power level sinks below a certain threshold, the receiver cannot decode the signal

Multipath Fading – Example

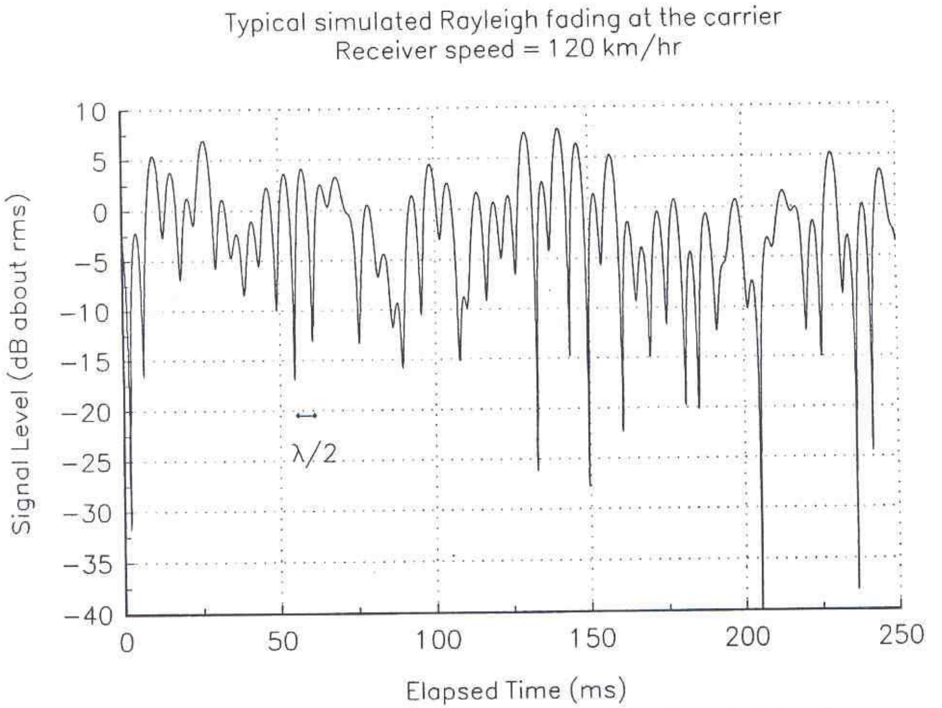


Figure 5.15 A typical Rayleigh fading envelope at 900 MHz [from [Fun93] © IEEE].

Figure 2: (From: [1, Chapter 5])

Noise and Interference

- Interference sources:
  - co-channel interference: other stations sending on the same channel
  - adjacent-channel interference: other stations sending on neighbored channels (leakage due to imperfect filters)
  - other devices: microwave ovens, city train power electronics, . . .
- Thermal noise is introduced in transmitter and receiver electronics, and background radiation

All this Translates into Channel Errors ...

- The "error rate" depends on:
  - transmitted energy per bit (lower for "faster" modulation schemes)
  - received signal power (influenced by distance/path loss, multipath fading)
  - interference + noise
- rules of thumb about errors on wireless channels:
  - higher / faster modulation schemes have higher error rates
  - errors tend to occur in *bursts*
  - overall error rates can be quite high: $10^{-2} \ldots 10^{-3}$

Some Countermeasures / Error Control

- *open-loop* vs. *closed-loop* error control:
  - In open loop schemes the transmitter adds some amount of redundancy to the data but gets no feedback from the receiver about the transmission outcome
    - equalization
    - forward error correction / Interleaving
    - multiple packets
  - in closed loop approaches the transmitter may also use redundancy, but receives feedback (*acknowledgements*) and performs *retransmissions* (maybe adapting the amount of redundancy) – ARQ protocols
- For delay-critical speech data open loop schemes are preferred

Some Countermeasures / Error Control II

- Equalization: send some "well-known" training sequence, let the receiver figure out the specific pattern of distortion ("learn about the channel") and use this to infer proper corrections which are applied to the remaining user data

- error-correcting codes (forward error correction, FEC): for k bits of user data add $n - k$ redundancy bits and transmit n bits (the fraction k/n is called *code rate*), such that:
  - bit errors can be detected
  - a limited amount of bit errors can be *corrected*

  Most FEC schemes work best when bit errors occur independently

Some Countermeasures / Error Control III

- Interleaving: user data blocks are “shuffled” before transmission and “deshuffled” after reception and before FEC decoding. Hopefully bursty error patterns are translated into “independently looking” ones

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GSM Channel Access Procedure

- Basic problem of *multiple access schemes*:

  To let a number of stations share a common resource (namely, the transmission medium / channels) in an efficient manner and such that some desired performance objectives are met.

  Analogy: how to distribute speech rights among 100 people in a room?

- Example performance objectives:
  - fairness
  - low delay in case of low load
  - high throughput in case of high load
  - reasonable overhead
  - stability

Basic Multiple Access Schemes

- More than 30 years research in multiple access control (MAC) protocols
- One possible classification is the following:
  - random access protocols: (slotted) ALOHA, CSMA, CSMA/CD, CSMA/CA, . . .
  - fixed assignment protocols: TDMA, FDMA, CDMA, SDMA
  - demand assignment protocols:
    - centralized: polling protocols, reservation protocols
    - decentralized: token passing protocols
- GSM uses a combination of TDMA, FDMA and random access

FDMA - Frequency Division Multiple Access

- Basic idea: the overall frequency band is subdivided into equal-sized *channels*, which can be used simultaneously
- Channels are separated by some *guard bands* to reduce adjacent-channel interference
- A channel is assigned exclusively to two stations / a set of stations; in the GSM context: to a BTS

GSM FDMA Structure

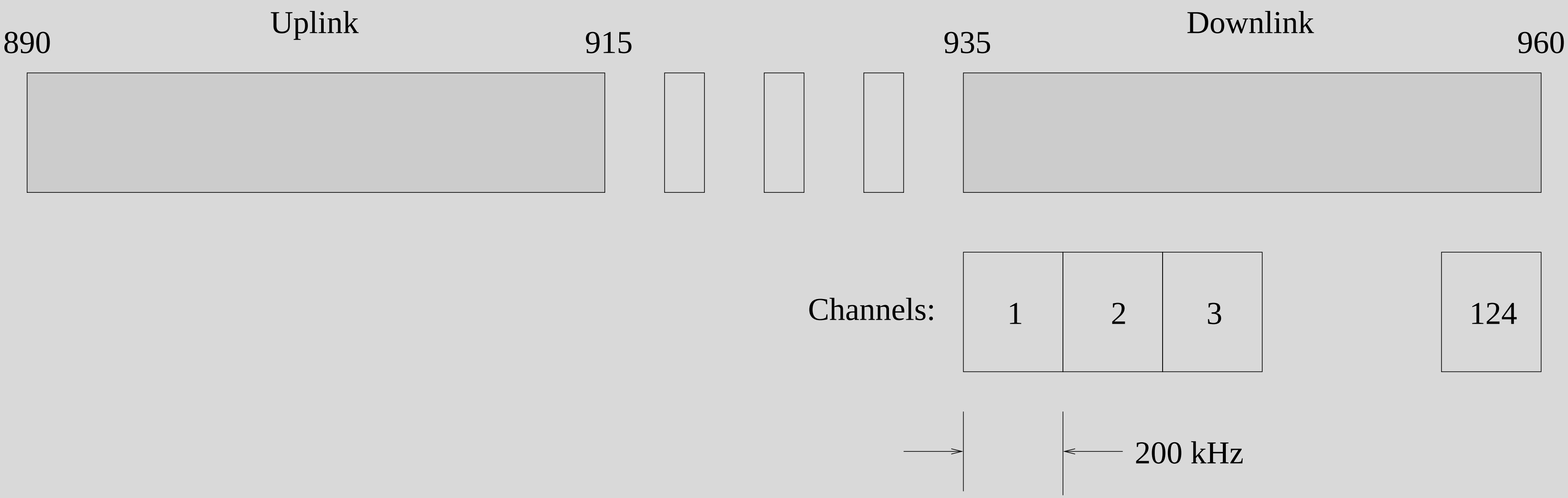

Figure 3: (from: [3, p.138])

GSM FDMA Structure

- Two 25 MHz wide frequency bands are assigned for GSM in Europe, used in *frequency division duplex* (FDD) mode:
  - 890 to 915 MHz: uplink (mobile to BTS)
  - 935 to 960 MHz: downlink (BTS to mobile)

  Extension bands are planned
- Channels 1 and 124 should not be used to protect neighboring bands
-

TDMA - Time Division Multiple Access

- Operates on a single channel
- All stations have to be synchronized
- time is divided into *superframes* of fixed length, a superframe is divided into a number of *slots*
- *guard bands* are needed to compensate for different propagation delays
- In GSM the TDMA approach is applied to uplink and downlink channels

GSM TDMA Frame Structure

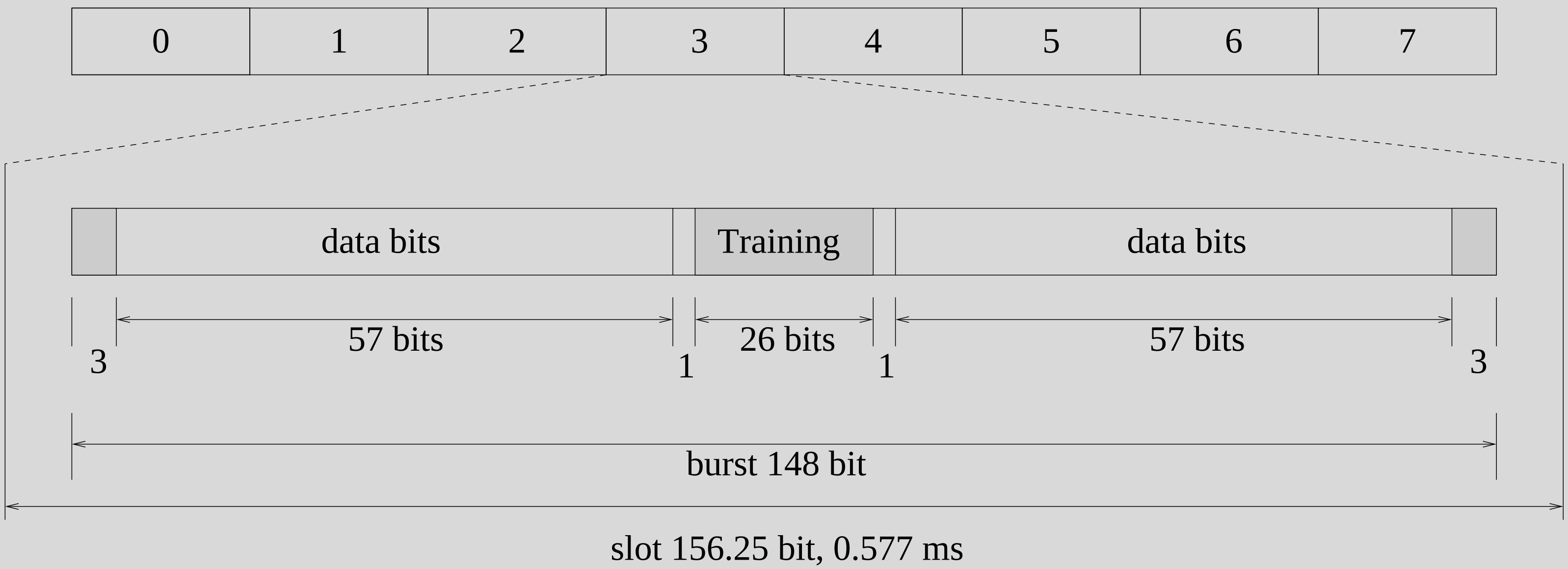

Figure 4: Structure of Normal Bursts (from: [3, p.139])

GSM TDMA Frame Structure II

- the modulation scheme used in a slot (GMSK – Gaussian Minimum Shift Keying) has a raw bit rate of $\approx$ 270 kBit/s
- The training bits are used for equalization
- the data in a slot is called a *burst* of 148 bits length, not all bursts have the structure shown in the Figure; The remaining 8.25 bits are *guard time*
- The tail bits / start-stop bits are constant
- If a user owns one slot, he gets a maximum bit rate of 24.7 kBit/s (without any error correction)

GSM Physical and Logical Channels

- A *physical channel* is specified by a specific time slot in a specific channel / carrier frequency
- logical channels:
  - run over a physical channel, but not necessarily in all its time slots
  - are classified into *traffic channels* and *control channels*
  - have to be *managed*: set up, maintenance, tear down
- control channels are interspersed with traffic channels in well-specified ways (e.g. every 26 TDMA frames a logical channel gets bandwidth in a physical channel)

Traffic Channels

- B_m channel or *full rate* channels offer a data rate of 22.8 kBit/s:
  - speech data: used as 13 kBit/s voice data plus FEC data
  - packet data: used as 12, 6, or 3.6 kBit/s plus FEC data
- L_m channel or *half rate* channels offer 11.4 kBit/s:
  - speech data: improved codecs have rates of $\approx$ 6.5 kBit/s, plus FEC
  - packet data: can be transmitted at 3 or 6 kBit/s
- Two half rate channels can share one physical channel
- Consequence: to achieve higher packet data rates, multiple logical channels have to be allocated $\Longrightarrow$ this is what GPRS does

Control Channels

- Broadcast logical channel:
  - is subdivided into several subchannels
  - BTS announces network specific data like:
    * network identification / operator
    * availability of options like voice activity detection etc.
    * frequencies used by the BTS and neighbors
    * frequency correction / synchronization information
- Paging channel: used only in downlink for handling an incoming call

Control Channels II

- Random access channel: used only in uplink for requesting a connection establishment (a slotted ALOHA random access protocol is used on this channel)
- Access grant channel: the BTS informs a mobile about the outcome of a connection setup request
- There are further control channels, e.g. supporting authentication, handover

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GSM Speech Transmission

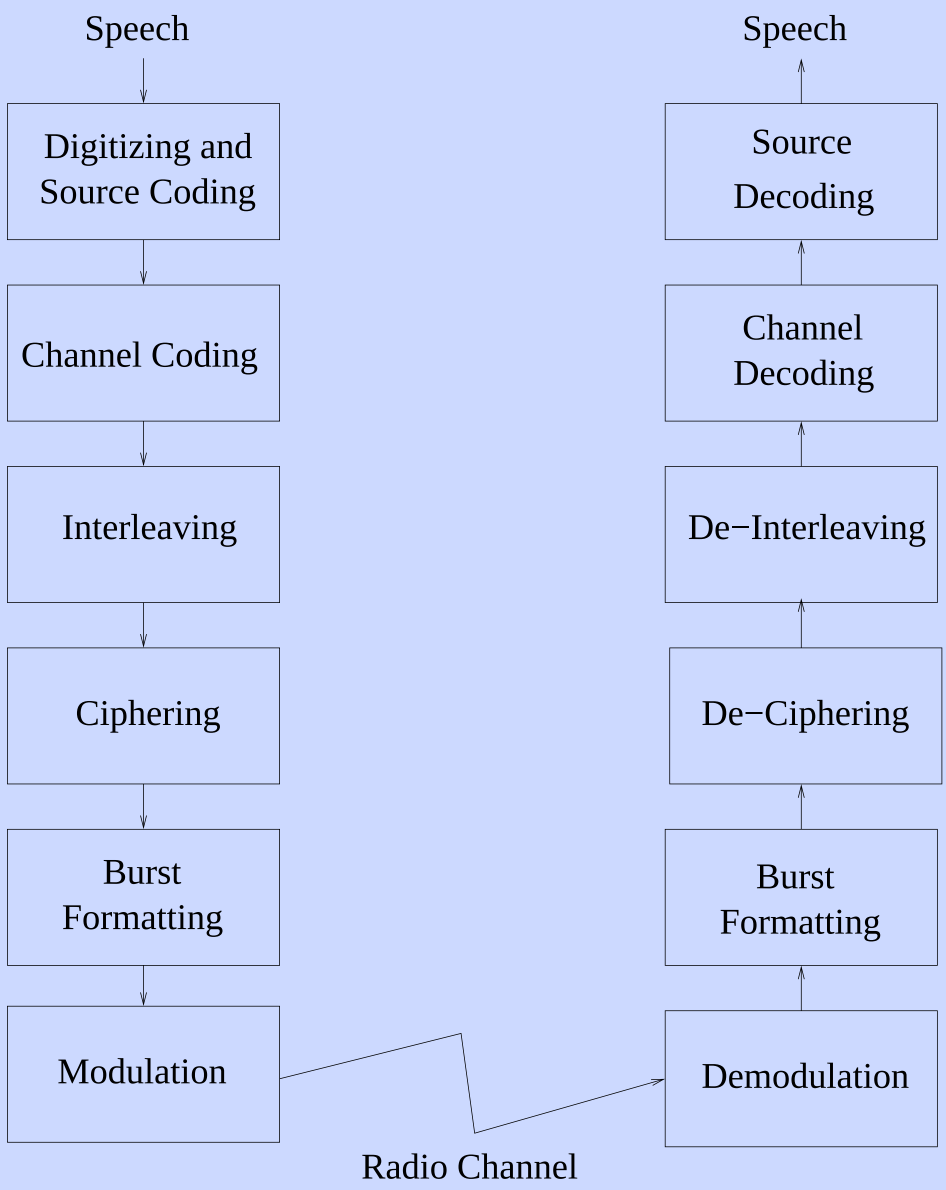

Figure 5: Speech Transmission (from: [1, p.564])

GSM Speech Transmission

- Source coding:
  - "Residually Excited Linear Predictive Coder" (RELP)
  - Coder produces 260 bits every 20 msec (13 kBit/s)
  - voice activity detection: no output during silence periods (improves battery lifetime, reduces interference), comfort noise is generated at receiver

GSM Speech Transmission II

- Channel coding:
  - output bits of channel coder is sorted into groups according to their relevance for speech quality
  - 3 parity bits are added to the most important 50 bits
  - A block of 189 bits is formed from:
    * the 53 bits from the previous stage
    * further 132 bits from the speech data (second-highest importance)
    * four trailing zero bits
  - This block is FEC-encoded with a rate 1/2 convolutional coder
  - The remaining 78 bits of the 260 bits speech data block enjoy no error detection / protection
  - The overall resulting block has 456 bits
  - different coding rules for packet data frames and control frames

GSM Speech Transmission III

- Interleaving:
  - The 456 bits are fragmented into eight blocks of 57 bits size
  - These eight blocks are "shuffled" to form eight new blocks
  - One shuffled block of the current speech packet and another from the previous speech packet are written into a normal burst
- Ciphering:
  - A shared secret between mobile and BTS is applied to each of the eight interleaved blocks of a speech packet
  - Two different encryption algorithms, changed from call to call
- After interleaving and ciphering the final burst is formatted (adding headers and trailers)

GSM Speech Transmission IV

- Modulation: each bit of a formatted burst is translated into a *waveform* (specified by the GMSK modulation) and transmitted over the antenna
- On the receiver side all steps are "inverted", most interesting is the de-interleaving and channel-decoding step:
  - the decoder tolerates one missing 57 bit block
  - the least important bits are taken as they are
  - after decoding the more important bits an additional check of the 3-bit checksum is made; if this fails, the whole speech packet is discarded

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Summary

- GSM allows users wire-less service and true mobility
- Mobility is supported by a (hierarchical) cellular concept and handovers
- Bandwidth is a scarce resource
- Capacity is an important issue, interference-limited
- Significant effort is made in GSM to protect speech transmission against channel errors and eavesdropping

References

[1] Theodore S. Rappaport. *Wireless Communications – Principles and Practice*. Prentice Hall, Upper Saddle River, NJ, USA, 2002.

[2] William Stallings. *Wireless Communications and Networks*. Prentice Hall, Upper Saddle River, New Jersey, 2001.

[3] Bernhard Walke. *Mobile Radio Networks – Networking, Protocols and Traffic Performance*. John Wiley and Sons, Chichester, 2002.