Radio Access and Link Control in Cellular Networks

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Outlines

- Access procedures
- Error control
- ARQ
- HARQ
- Radio Resource Management

Access procedures : broadcast common channel I

- Every cellular network needs a reference signal
- Functions : system detection, choice of the best BS (best server), synchronization (time, frequency, code), system information (or context) acquisition
- Also essential for handovers and roaming
- This signal is broadcast, it's a **control** channel, i.e., it does not broadcast any user information

Access procedures : broadcast common channel II

Examples of system informations (organized in System Information Blocks) :

- network identity (PLMN), location area, cell identity, frame number
- cell selection and re-selection, handover parameters (based on radio quality)
- resource organization (common control channels parameters)
- access rules (power control, access codes, etc)
- neighborhood informations (neighbors cells or technologies)

Access procedures : cell selection

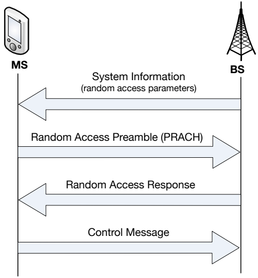
- Goal : find the attachement cell (a cell belonging to the operator and with sufficient radio quality). Steps :

1. the MS powers on
2. the MS scans and make measurements on possible frequency bands and carrier frequencies based on informations contained in its SIM card
3. based on a radio quality criterion, the MS selects a cell (the best server) and performs synchronization (time, frequency, code)
4. the MS decodes the broadcast common channel and checks whether it can access the network of the operator

- Re-selection : the MS makes measurements on neighboring cells, ranks them and may decide a re-selection if a better cell is detected

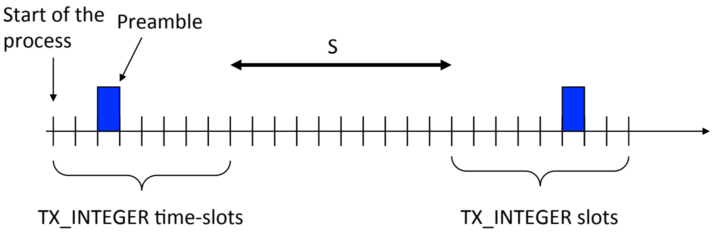
Access procedures : random access

1. the MS acquires random access parameters from the broadcast channel (position of the PRACH, protocol parameters, transmit power, subcarrier spacing, etc)
2. the MS transmits a short *burst* or *preamble* using slotted Aloha. Transmissions are subject to collisions and capture.
3. in case of collision, the MS waits for a random duration (back off) and retransmits the preamble
4. the BS sends a random access response that includes at least the timing advance and an uplink allocation
5. the MS sends a control message on the allocated resource with at least the reason for performing random access (mobile originated call, response to a paging, location update, etc)



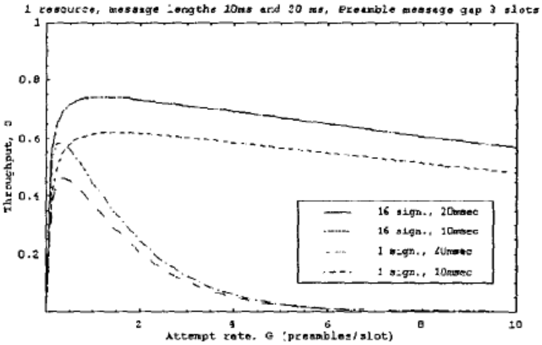
Access procedures : random access protocol I

- All random access protocols are based on slotted ALOHA
- Example of GSM : TX_INTEGER is the back-off window (e.g. bw 8 and 50 slots), S is the minimum delay before retransmissions (e.g. 250 ms), there is a maximum of MAX_TRANS retransmissions
- All parameters are broadcast by the Broadcast Control Channel (in a System Information Block)
- In GSM : the preamble includes a service class and a random number to cope with the capture effect



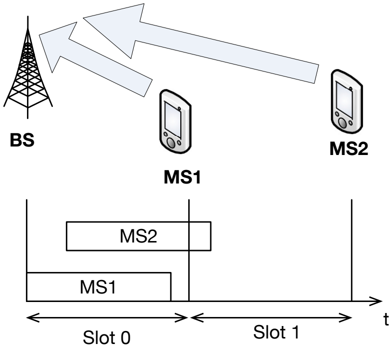
Access procedures : random access protocol II

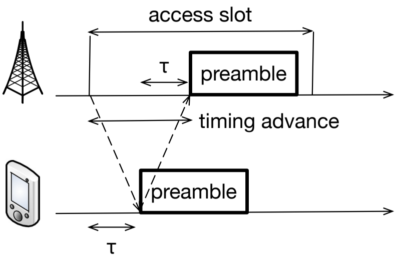
- In UMTS, LTE and NR, the User Equipement (UE) chooses also a random signature (a scrambling code in UMTS, a Zadoff-Chu sequence in LTE/NR)
- UMTS example (source : I. N. Vukovic and T. Brown, "Performance Analysis of the Random Access Channel in WCDMA", IEEE VTC'01) :



Access procedures : timing advance I

- Goal : synchronization of UL signals in order to maintain orthogonality between MSs of a cell
- After random access, the BS transmits a timing offset for all subsequent uplink transmissions of the MS. Timing advance is regularly updated.





Access procedures : timing advance II

Example in GSM :

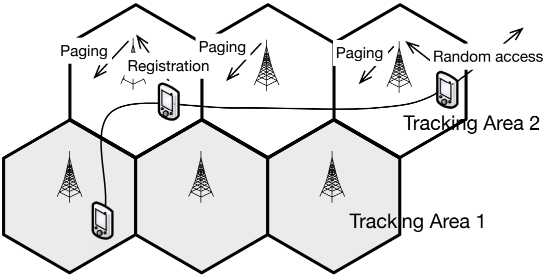
- Slot duration = 0.577 ms = 156.25 symbol durations
- An access burst = 88 symbols, so that 68 symbol durations are left free to cater with the transmission of a MS that does not know its timing advance
- Timing advance can take values between 0 and 63 (symbol durations)
- Every TA step represents 550 m, max cell range is 63×550 m = 35 km
- After successfully receiving an access burst on the RACH, the network sends a response on the Access Grant Channel (AGCH), which contains the TA parameter.

Example in LTE :

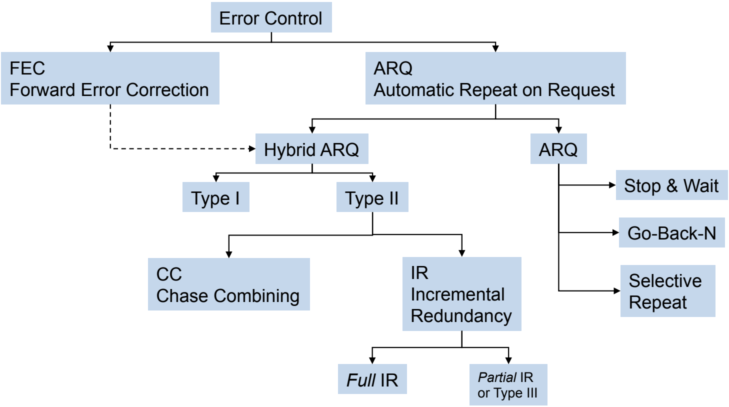
- TA command in Random Access Response is coded on 11 bits, TA indices span between 0 and 1282
- Time adjustment is a multiple of $16T_S$, where $T_S = 1/(2048 \times 15000) = 1/30720000$ s is the sample duration
- Maximum timing adjustment is $1282 \times 16T_S$, which corresponds to a distance of 100 Km

Access procedures : paging

- Paging allows the network to initiate mobile terminated connections
- Cells are grouped in Tracking Areas (TrA)
- The network maintains the TrA of users in idle mode
- Each time a user enters a new TrA, it registers to the network (using random access)
- For an incoming call, paging messages are broadcast within the TrA ; when receiving a message for it, the terminal performs a random access

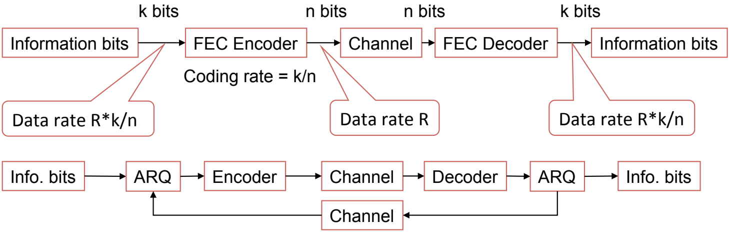


Error control : classification



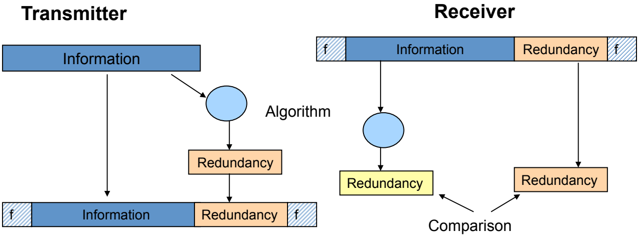
Error control : FEC vs ARQ

- FEC : the transmitter adds redundant information to the useful information and the receiver exploits this redundancy to decode the information bits. E.g. : convolutional codes, LDPC, turbo codes, etc. No need for a feedback channel. There is a data rate vs error correction power trade-off.
- ARQ : based on an error detection code, the receiver sends back an ACK/NACK upon reception of a packet (NB : ARQ can be also implemented at layer 4, cf TCP)



Error control : error detection I

- For every ARQ protocol, there is a need for an error detection scheme (source of the figure : [1])
- Cyclic Redundancy Codes (CRC) are usually used for error detection with very good performances (see [18])



Error control : error detection II

- A *cyclic* code is a linear block code such that :

$$c(0) = [c_0, ..., c_{n-1}] \in C \Leftrightarrow c(1) = [c_{n-1}, c_0, ..., c_{n-2}] \in C.$$

  In polynomial notation :

$$c(0)(x) \in C \Leftrightarrow c(1)(x) = xc(0)(x) \mod (x^n - 1) \in C.$$

- **Property** : code words of a cyclic code (k, n) are multiple of a generator polynom $g(x)$ of degree $n-k$ divisor of $(x^n - 1)$:

$$g(x)h(x) = x^n - 1 \text{ and}$$

$$c(x) \in C \Leftrightarrow \exists a(x) \text{ s.t. } c(x) = g(x)a(x)$$

  $a(x)$ is the message polynomial and $deg(a) < k$.
  $h(x)$ is the parity control polynomial.

Error control : error detection III

- **Property** : for a code word : $c(x)h(x) = a(x)g(x)h(x) = a(x)(x^n - 1) = 0$.
  $y(x)$ is a code word if and only if $y(x)h(x) = 0 \mod (x^n - 1)$.

- Syndrome of $y(x)$: $s(x) = y(x)h(x)$.
- **Non systematic encoding** : to transmit the information message $a(x)$, the transmitter sends the code word $c(x) = a(x)g(x)$.
- **Systematic encoding** : we compute the rest of the division of $x^{n-k}a(x)$ by $g(x)$:

  $$x^{n-k}a(x) = g(x)q(x) + d(x)$$

  The transmitter sends the code word $c(x) = x^{n-k}a(x) - d(x)$.
  $x^{n-k}a(x)$ includes the k information bits, while $d(x)$ includes the $n-k$ redundancy bits.
- **Decoding** : the receiver receives $y(x) = c(x) + e(x)$, where $e(x)$ is the error introduced by the channel. It computes the syndrome :
  $s(x) = y(x)h(x) = e(x)h(x)$. If $s(x) \neq 0$, there is at least one error. Otherwise, it decides that that there is no error.

Error control : error detection IV

Example : we want to encode the sequence : 101011.

- We have : $a(x) = 1 + x^2 + x^4 + x^5$.
- Let $g(x)$ be the generator polynomial of CRC-16 : $g(x) = 1 + x^2 + x^{15} + x^{16}$.
- Systematic encoding : $x^{n-k}a(x) = x^{21} + x^{20} + x^{18} + x^{16} = g(x)q(x) + d(x)$.
- With : $d(x) = x + x^2 + x^3 + x^4 + x^5 + x^7$ and $q(x) = x + x^2 + x^5$
- Redundancy bits are : 0111110100000000
- Transmitted sequence is 0111110100000000101011

(source : T. Ramabadran et S. Gaitonde, "A Tutorial on CRC Computation", IEEE Micro 1988)

Error control : error detection V

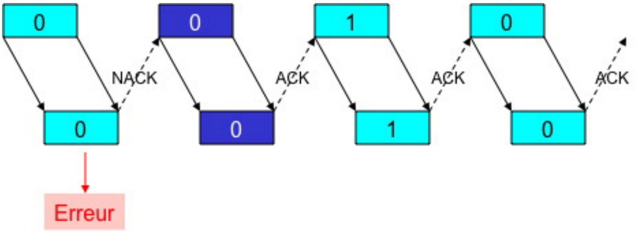
- A bound on the probability to not detect an error is :

$$P_e < 2^{k-n}$$

- Proof : If the bit error probability is $\epsilon = 1/2$, the 2^n n-tuples that are likely to be received with the same probability 2^{-n}. Among these tuples, $2^k - 1$ are recognized as code words and still different from the transmitted code words. We thus have : $P_e = (2^k - 1)2^{-n} = 2^{k-n} - 2^{-n} < 2^{k-n}$.
- CRC-16 achieves very good performance with few bits.
  For $n \leq 32767$, all simple, double, triple and odd numbers of errors can be detected. Error trains of at most 16 bits can be detected. 99.997% of error trains of length 17 and 18 bits can be detected. (source : T. Ramabadran et S. Gaitonde, "A Tutorial on CRC Computation", IEEE Micro 1988)

ARQ : Stop and Wait I

- Frames are numbered modulo 2
- Let n be the number of bits, R the data rate and τ the idle time
- Let $T = \frac{n}{R}$ be the transmission time
- Let $T_{AR} = T + \tau$ be the round trip time.



ARQ : Stop and Wait II

- Consider the Binary Symmetric Channel (BSC) with error probability ϵ
- Let P_c be the probability that a n bit frame has no error.
- Let P_d be the probability that a n bit frame has errors that **can** be detected by the receiver.
- Let P_e be the probability that a n bit frame has errors that **cannot** be detected by the receiver.

$$P_c + P_d + P_e = 1$$

- Let R be the data rate.

ARQ : Stop and Wait III

- The probability to deliver to higher layers a frame with undetected errors is very small :

$$P(E) = \sum_{i=0}^{\infty} P_e P_d^i = \frac{P_e}{1 - P_d}.$$

- Assume error on bits are independent, we have :

$$P_c = (1 - \epsilon)^n$$

- We have a bound for P_e :

$$P_e < 2^{k-n}$$

- Consider a code with $k = 2014$ and $n = k + 34$, then $P(E) = 8.10^{-10}$.
- From now, it is supposed to be negligible.

ARQ : Stop and Wait IV

- Average delay to deliver a frame with Stop and Wait : (assuming P_e is negligible)

$$\delta_{SW} = \sum_{i=1}^{\infty} iT_{AR}P_c(1-P_c)^{i-1} = \frac{T_{AR}}{P_c} = \frac{\frac{n}{R}+\tau}{1-P_d}$$

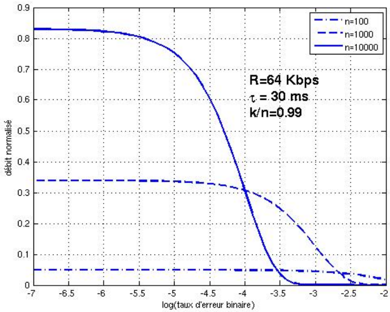
- Goodput of Stop and Wait :

$$\eta_{SW} = \frac{k}{\delta_{SW}} = \frac{1}{1+\frac{\tau R}{n}}\frac{k}{n}R(1-P_d)$$

- Example : $R = 1$ Mbps, $\tau = 700$ ms (satellite link), $\tau R = 7 \cdot 10^5$. In order that $\tau R/n$ be close to 1, we need $n \approx 10^6$ bits. With $n = 10000$ bits, we have already $\tau R/n = 70$.

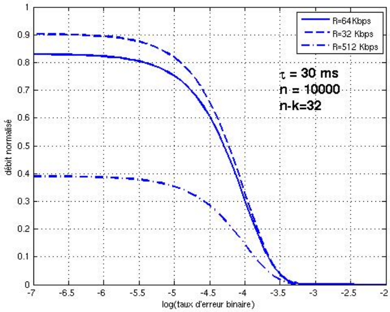
ARQ : Stop and Wait V

- Goodput as a function of the (log of the) bit error rate
- When n increases, τ becomes small in front of $T = n/R$.



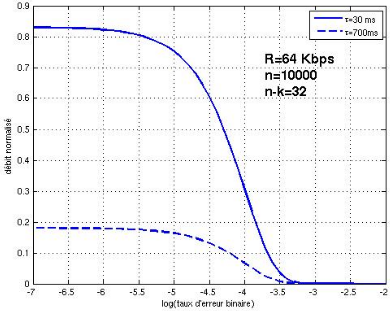
ARQ : Stop and Wait VI

- When R increases, T becomes small in front of τ.



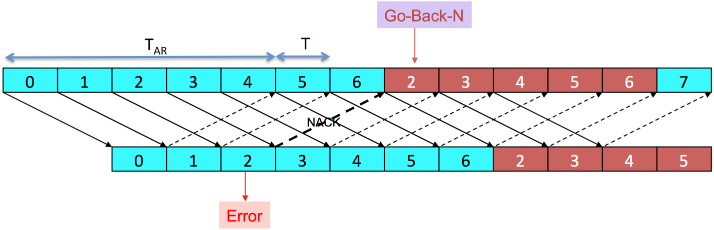
ARQ : Stop and Wait VII

- When τ increases, idle time increases.



ARQ : Go Back N I

- Anticipation window : the transmitter is allowed to transmit up to W frames without receiving corresponding ACKs.
- For a window of W frames, frames have to be numbered modulo $W+1$.
- We assume below that the window size is ideal, i.e., $W = T_{AR}/T$.



ARQ : Go Back N II

- Average delay to deliver a frame with Go Back N :

$$\begin{aligned}
\delta_{GBN} &= \sum_{i=1}^{\infty} T((i-1)W+1)P_c(1-P_c)^{i-1} \\
&= TP_c(W\sum_{i=1}^{\infty} i(1-P_c)^i + \sum_{i=1}^{\infty}(1-P_c)^{i-1}) \\
&= TP_c\left(\frac{W(1-P_c)}{P_c^2} + \frac{1}{P_c}\right) \\
&= T\left(1 + W\frac{1-P_c}{P_c}\right)
\end{aligned}$$

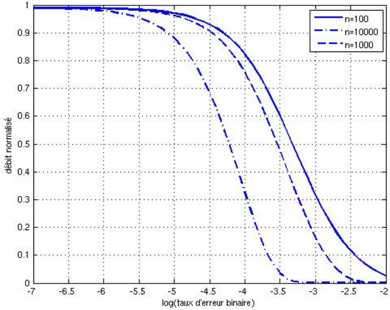
- Goodput of Go back N :

$$\eta_{GBN} = \frac{1}{1+P_d(W-1)}\frac{k}{n}R(1-P_d)$$

- If R and τ are small, W can be set to a small value and the good put of Go Back N is good. If R is high and the propagation time is long, the denominator is high and the goodput is low.

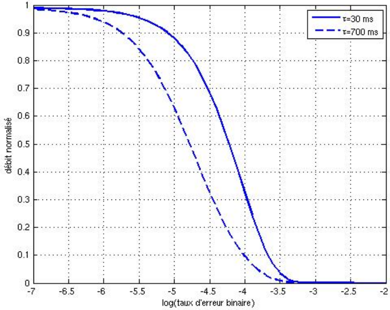
ARQ : Go Back N III

- When n increases, P_d and W increase.



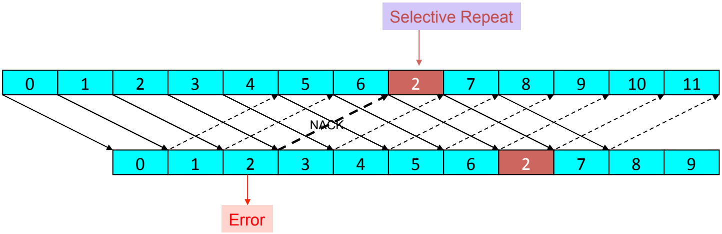
ARQ : Go Back N IV

- When τ increases, W increases.



ARQ : Selective Repeat I

- The transmitter retransmits only the frames for which it received a NACK
- For a window of W frames, frames have to be numbered modulo $2W$.



ARQ : Selective Repeat II

- Average delay to deliver a frame with Selective Repeat :

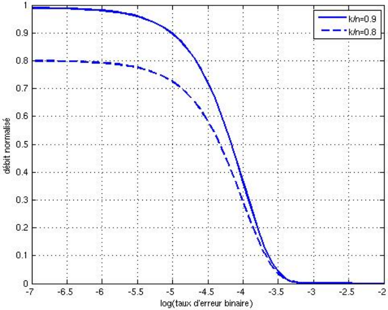
$$
\begin{aligned}
\delta_{SR} &= \sum_{i=1}^{\infty} iTP_c(1-P_c)^{i-1} \\
&= \frac{T}{P_c}
\end{aligned} \tag{1}
$$

- Goodput of Selective Repeat :

$$\eta_{SR} = \frac{k}{n}R(1-P_d)$$

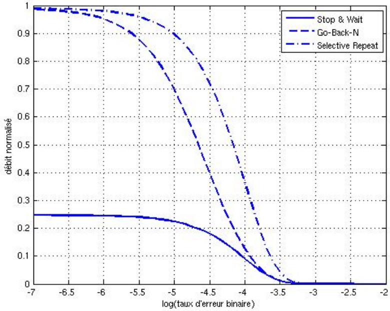
ARQ : Selective Repeat III

- Impact of k/n.



ARQ : Selective Repeat IV

- Comparison in terms of goodput.



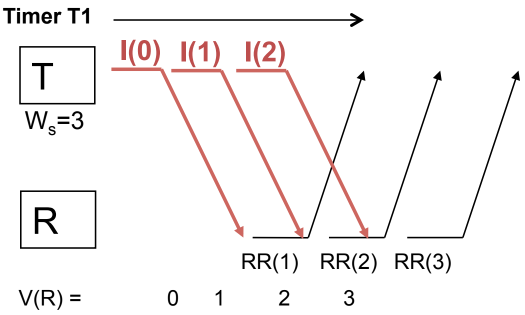
ARQ example : LAP-B I

- Used in X25 but very close to LAP-Dm (used in GSM for control channels) and UMTS/LTE/NR RLC Acknowledge Mode
- Every frame has a sequence number indicated in its header, numbering is done modulo $M \in \{2, 128, 32768\}$
- A connection-oriented protocol : transmitter and receiver sides maintain counters that are initialized when connection is open. After transmissions, connection is closed

- Go-Back-N : the transmitter can send up to W_s frames without receiving corresponding ACKs
- Ready to Receive (RR) : may acknowledge several frames
- After a Reject (REJ) : all frames from the requested SN are retransmitted
- The receiver maintains a counter of the next SN to be received V(R)

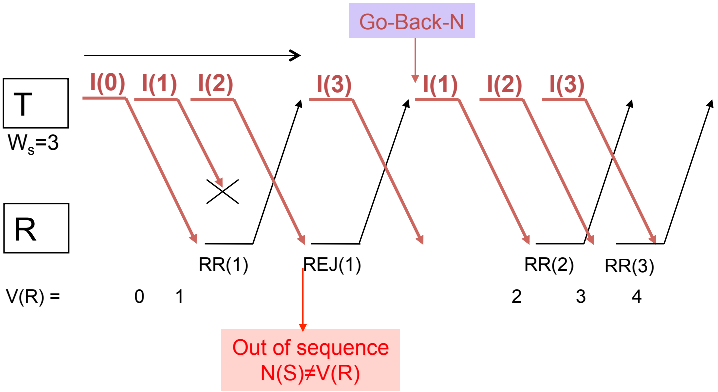
ARQ example : LAP-B II

- Information frames (I) includes N(S) = its sequence number
- RR includes N(R) = sequence number of the next expected frame
- V(R) = receiver counter indicating the next expected frame
- Every transmission is associated to a timer T1



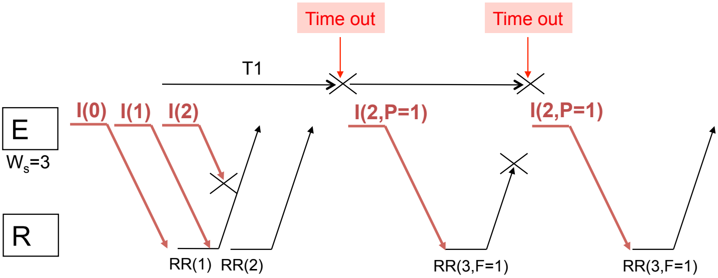
ARQ example : LAP-B III

- Retransmission upon negative acknowledgement (REJ)



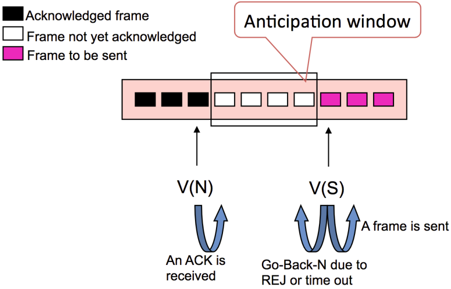
ARQ example : LAP-B IV

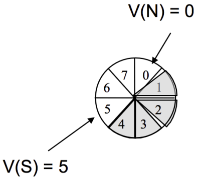
- Retransmission upon T1 time out
- P/F bit : an immediate response is required / immediate response
- There is a maximum number of retransmissions



ARQ example : LAP-B V

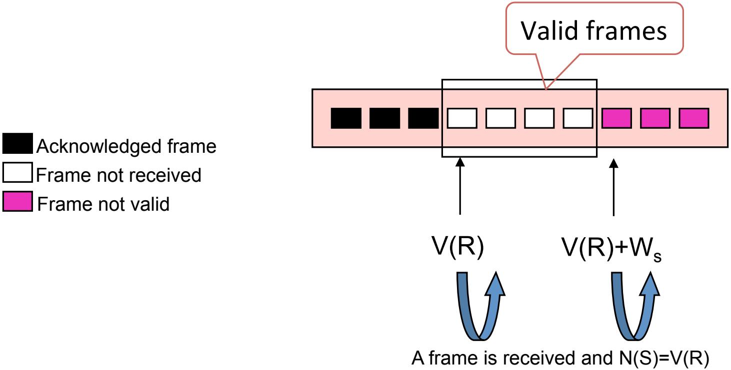
- Transmitter side :
  - V(N) = last acknowledged frame
  - V(S) = next frame to send
  - NB : $V(S) - V(N) - 1 \leq W_s$





ARQ example : LAP-B VI

- Receiver side :
  - V(R) = next expected frame

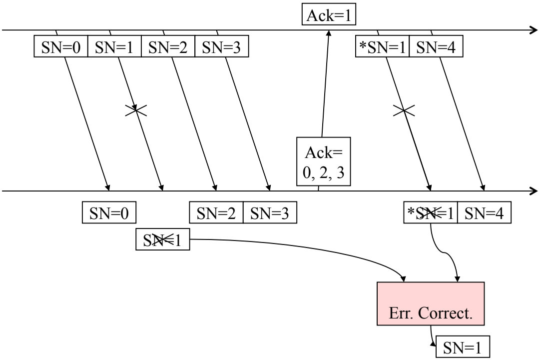


HARQ types

- Type I : FEC and ARQ are well separated
- Type II : the receiver keeps a copy of packets in error and use the information to decode subsequent packets
- Type II with Chase Combining (CC) : all retransmissions are identical
- Type II with Incremental Redundancy (IR) : the coding scheme is modified at each retransmission of the same packet
- Type II Partial IR : every transmission includes information bits + parity bits
- Type II Full IR : the first transmission includes information bits + parity bits, retransmissions includes only parity bits

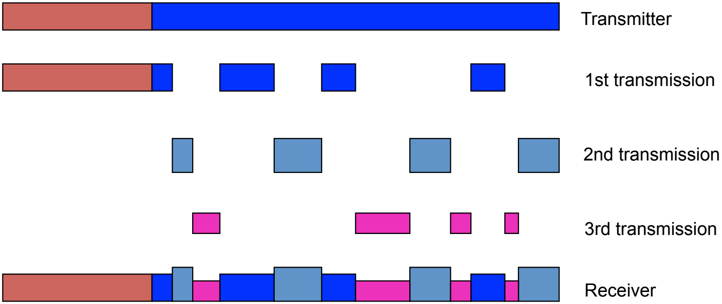
HARQ type II illustrated

- On this example, we can obtain a correct copy of packet with Sequence Number SN=1 from two erroneous receptions
- With CC, the two transmissions of (SN=1) are identical. With IR, the second transmission is re-encoded



HARQ full IR illustrated

- In IR, information is first coded with a low rate code at the transmitter. Information bits and some parity bits are sent at the first transmission
- If a NACK is received, the transmitter sends additional parity bits. The receiver aggregates received bits to those already received
- At every reception, the effective coding rate is decreased
- In Full IR, information is sent only at the first transmission. In Partial IR, information is sent at every transmission



HARQ : Chase combining

To go in more details...

- Main idea : if the initial FEC coding rate is R, then after L transmissions, the effective rate is R/L
- Let $Y_i = (Y_{i,1}, Y_{i,2}, ..., Y_{i,N})$ be the i-th transmitted packet (made of N bits)
- After the second transmission, transmitted bits can be written :

$$(Y_{1,1}, Y_{2,1}, Y_{1,2}, Y_{2,2}, ..., Y_{1,N}, Y_{2,N})$$

  which can be seen as the superposition of the initial FEC and a repetition code. There are $N \times R$ information bits and the packet length is $2N$, so that the new code rate is $NR/(2N) = R/2$
- Decoding can be done using maximum likelihood and Viterbi algorithm
- Maximum likelihood : we look for the sequence s that maximizes $P[s|r]$, where r is the received sequence

HARQ : incremental redundancy I

To go in more details...

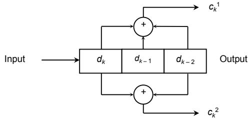
- Main idea : IR is based on a sequence of codes obtained by increasingly puncturing a mother code
- Puncturing : remove periodically some bits from the encoder output (increases code rate and decreases decoding complexity)
- Example : Take a code with rate $R_1 = 1/2$:

$$C_1 = (c_0(1), c_0(2), c_1(1), c_1(2), \dots)$$

We obtain a code of rate $R_2 = 2/3$ by puncturing one bit out of 4 :

$$C_2 = (c_0(1), c_0(2), c_1(1), -, c_2(1), c_2(2), c_3(1), -, \dots)$$

We obtain a code of rate $R_3 = 4/5$ by puncturing 3 bits out of 8, etc



HARQ : incremental redundancy II

- Rate Compatible Punctured Convolutional Codes (RCPC) :
  - A family of codes $\{C_n\}$ is obtained by puncturing a low rate mother code with an increasing number of bits, so that $R_n \leq R_{n+1}$
  - Punctured bits to obtain C_n are included in the set of punctured bits to obtain C_{n+1}
- Example :
  0 bit punctured (mother code) :

$$C_1 = (c_0(1), c_0(2), c_1(1), c_1(2), \dots), \quad R_1 = 1/2$$

  1 bit punctured out of 8 :

$$C_2 = (c_0(1), c_0(2), c_1(1), c_1(2), c_2(1), -, c_3(1), c_3(2), \dots), \quad R_2 = 4/7$$

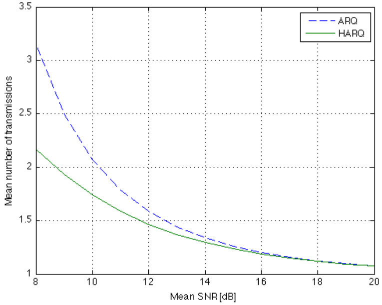
  2 bits punctured out of 8 :

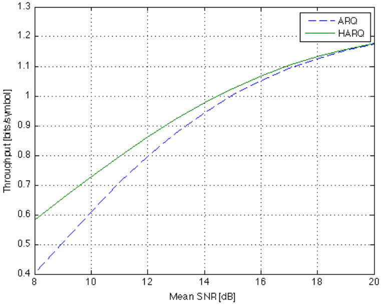
$$C_3 = (c_0(1), c_0(2), c_1(1), c_1(2), c_2(1), -, -, c_3(2), \dots), \quad R_3 = 4/6$$

- C_n offers a higher protection against errors than C_{n+1}, however with a lower useful data rate

HARQ vs ARQ

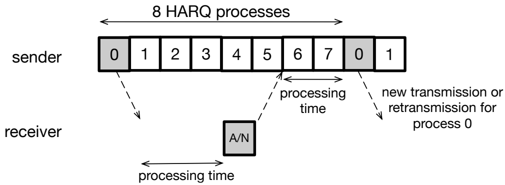
- Performance comparison based on [1] (MCS4, 16-QAM, rate=9/16, 2.25 bits/symbol, $g = 0.664$, $\gamma_M = 7.7$ dB)





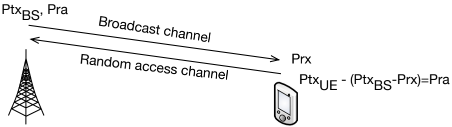
HARQ : Interleaved Stop and Wait

- Stop and Wait suffers from loss of efficiency due to the idle time
- In downlink LTE/NR, several S&W processes are interleaved to avoid this loss
- In NR, up to 16 HARQ processes can be configured

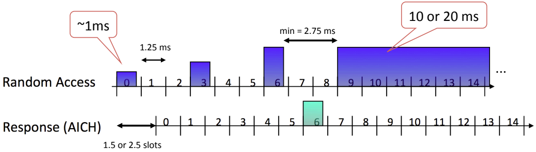


RRM : open loop power control

- Open loop power control : based on BS transmit power (Ptx_{BS}), target received power (Pra) and received power (Prx), the UE sets its transmit power for random access (Ptx_{UE})

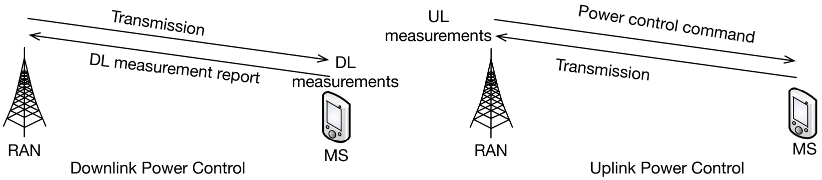


- Power ramping : at each retransmission, transmit power is increased (typically +1 dB) up to some maximum value. Example of UMTS :



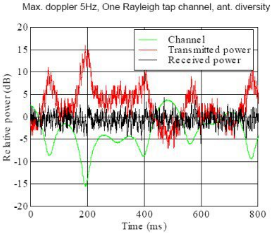
RRM : closed loop power control

- DL : based on DL transmissions, the MS makes DL measurements (signal level and quality) and feedbacks them in a measurement report. The RAN adjusts its transmit power
- UL : based on UL transmissions, the RAN performs UL measurements and sends power control command to the MS, which adjusts its power



RRM : slow and fast power control

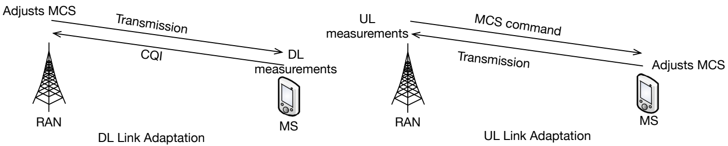
- Slow power control follows the slow variations of the radio channel (due to shadowing). Example in GSM :
  - Measurements reports and PC commands are sent every 480 ms on the SACCH
  - Upon reception of a command, a MS change its transmit power by steps of 2 dB every 60 ms until reaching the target transmit power
- Fast power control follows the fast variations of the channel (due to fast fading). Example in UMTS : Power control rate is every 666 μs (1500 Hz)



Source : mobilewireless.wordpress.com

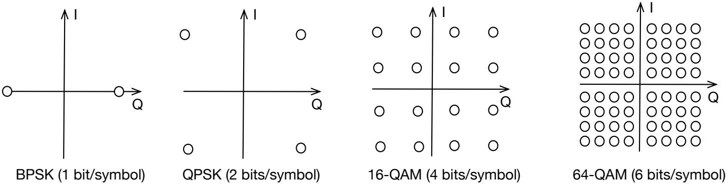
RRM : link adaptation

- A technique to dynamically adjust modulation and coding rate according to the radio channel variations
- Adjustment is based on measurements. DL : the MS makes channel measurements and feeds back a Channel Quality Indicator (CQI), the network adjusts the Modulation and Coding Scheme (MCS). UL : the network makes measurements and sends a MCS command to the MS, which adjusts its transmission



RRM : modulations and coding rate

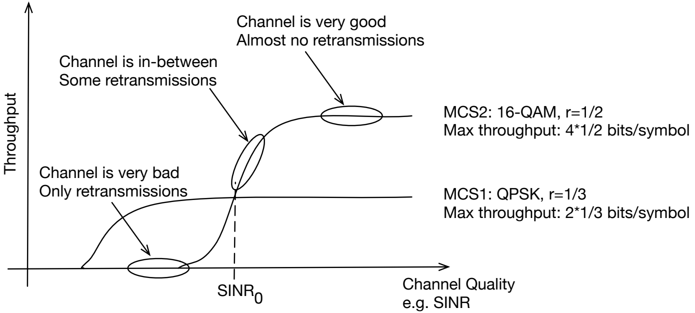
- Traditional modulations used in cellular networks : BPSK, QPSK, GMSK (GSM), 16-QAM, 64-QAM
- Denser is the modulation, the more sensitive it is to noise and the higher the number of bits per symbol



- A FEC encoder takes k bits as input and outputs $n \geq k$ bits. Coding rate is $r = \frac{k}{n}$. For a data rate R, information rate is rR
- When $r \to 1$: few redundancy bits, less error correction, high information rate. When $r \to 0$: many redundancy bits, more error correction, low information rate.

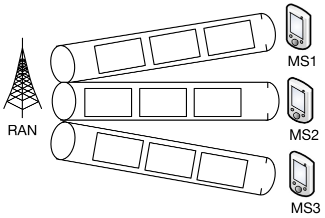
RRM : example of algorithm

- If SINR $\leq$ $SINR_0$, then choose MCS1
- If SINR $>$ $SINR_0$, then choose MCS2

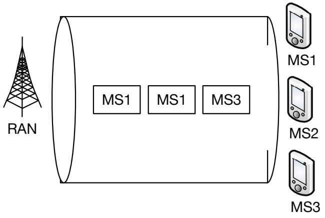


RRM : dedicated vs. shared channel

- Dedicated channel (GSM, UMTS R'99) : the traffic of a user is transmitted over dedicated resources (slot, frequency, code) allocated for the whole connection duration. No need to address frames. Channel reconfiguration may be performed by RRC.
- Shared channel (HSPA, LTE, NR) : the whole user traffic is transmitted over a single channel. Allocation is done by the scheduling algorithm at a very short time scale. Every frame includes an address.



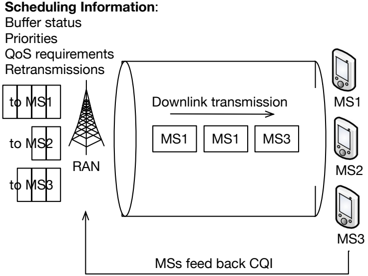
Dedicated channels



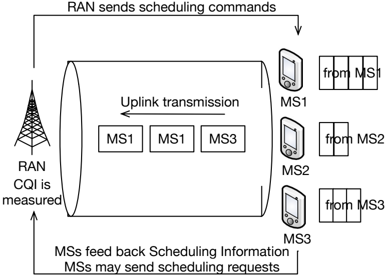
Shared channel

RRM : one-to-many vs. many-to-one scheduling

- One-to-many for the DL : scheduling information is available at the scheduler, CQI is fed back by MSs
- Many-to-one for the UL : scheduling is still controlled by the network through scheduling commands. Scheduling information is fed back from the MSs. CQI is measured on UL signals. If a MS is not known from the scheduler, this MS can send some scheduling request.



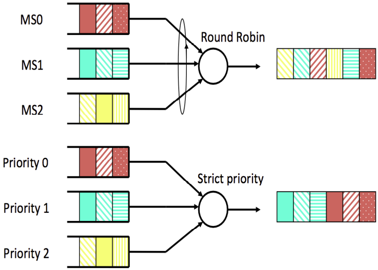
One-to-many scheduling

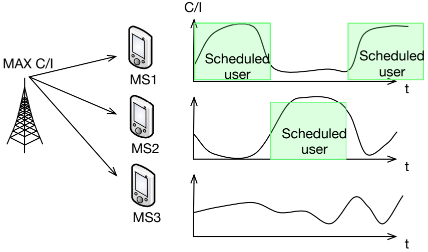


Many-to-one scheduling

RRM : examples of scheduling algorithms

- Round Robin : fairness in resource
- Strict priority : as long as there is traffic for a higher priority queue, it is served
- Max C/I : the MS with the best instantaneous channel is served
- Proportional fair scheduler : the scheduler allocated the resource to the MS with the best $\frac{r_i(t)}{\bar{R}_i}$ ratio, where $r_i(t)$ is the instantaneous data rate and $\bar{R}_i$ is the average throughput





References

Lagrange, X. (2011). Performance analysis of HARQ protocols with link adaptation on fading channels. annals of telecommunications - Annales des télécommunications, 66(11-12), 695-705.

Acronyms I

ACK	Acknowledgment
AGCH	Access Grant Channel
ARQ	Automatic Repeat on Request
BPSK	Binary Phase Shift Keying
BS	Base Station
BSC	Binary Symmetric Channel
CC	Chase Combining
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Code
DL	Downlink
FEC	Forward Error Correction
GMSK	Gaussian Minimum Shift Keying
GSM	Groupe Spécial Mobile
HARQ	Hybrid Automatic Repeat on Request
HSPA	High Speed Packet Access
IR	Incremental Redundancy
LAP-Dm	Link Access Protocol on the D channel - mobile
LDPC	Low Density Parity Check
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MS	Mobile Station
NACK	Negative Acknowledgment
PC	Power Control
PLMN	Public Land Mobile Network
PRACH	Physical Random Access Channel
QAM	Qadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying

Acronyms II

RACH	Random Access Channel
RAN	Radio Access Network
RCPC	Rate Compatible Punctured Codes
REJ	Reject
RLC	Radio Link Control
RR	Ready to Receive
RRC	Radio Resource Control
RRM	Radio Resource Management
SACCH	Slow Associated Control Channel
SIB	System Information Block
SIM	Subscriber Identity Module
SN	Sequence Number
SINR	Signal to Interference plus Noise Ratio
TA	Timing Advance
TCP	Transport Control Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UL	Uplink
WCDMA	Wideband Code Division Multiple Access