Deterministic Access Schemes

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25 Jan. 2023

Outlines

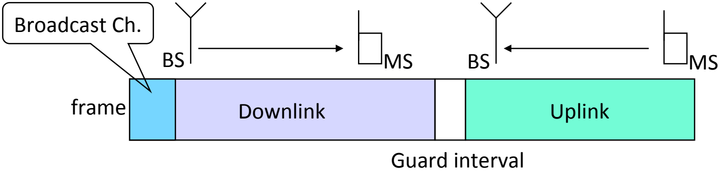
- Duplexing
- Multiplexing
- Capacity regions

Duplexing schemes

- Uplink : communications from the Mobile Station (MS) to the Base Station (BS)
- Downlink : communications from BS to MS
- Duplexing : the way uplink and downlink are allocated to orthogonal radio resources
- Two main approaches : Time Division Duplex (TDD) and Frequency Division Duplex (FDD)
- A new paradigm : Full duplex

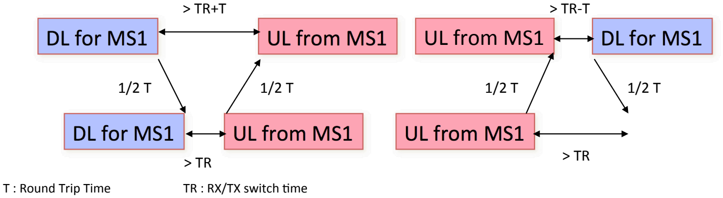
Duplexing : TDD I

- Time is divided in frames and every frame in two sub-frames
- UL and DL use the same carrier frequency during different sub-frames
- There is a guard interval between UL and DL sub-frames to maintain orthogonality bw links despite propagation delays
- Synchronization is needed bw UL and DL



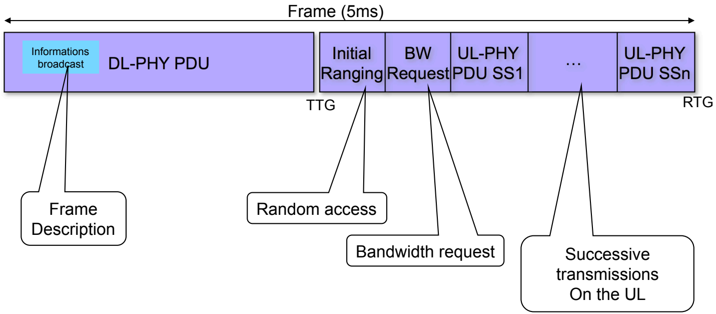
Duplexing : TDD II

- No need for stations to support duplex
- TDD systems can be deployed on non-peered spectrum bands
- Channels characteristics are similar on both links : open loop channel estimation is possible (and useful for MIMO, beamforming and power control)
- TDD is more adapted to small cells because of the small propagation time



Duplexing : TDD III

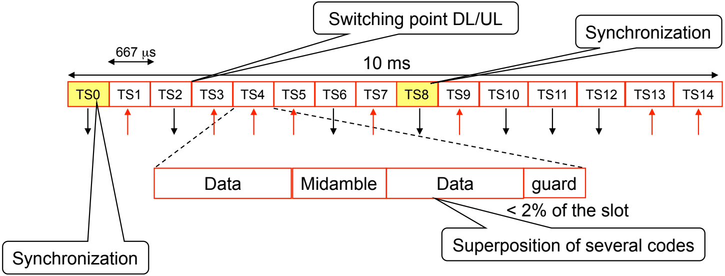
Example : WiMAX (802.16)



TTG : Tx/Rx Transmission Gap, RTG : Rx/Tx Transmission Gap, PDU :Packet Data Unit, BW : Bandwidth, SS : Subscriber Station

Duplexing : TDD IV

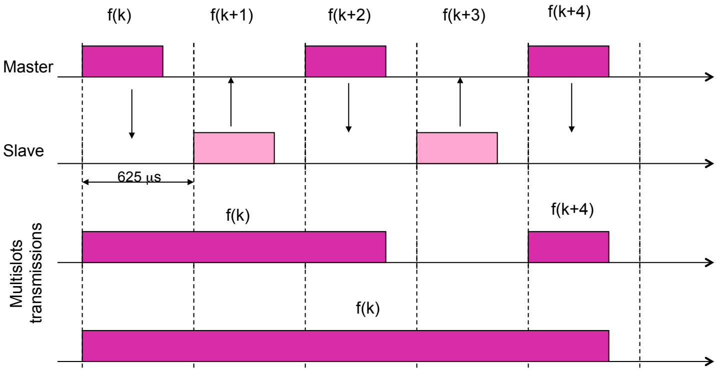
Example : UMTS TDD



- It is possible to dynamically allocate slots to UL and DL
- Different frame parts can be allocated to different BSs

Duplexing : TDD V

Example : Bluetooth (802.15.1) TDD or FDD ?



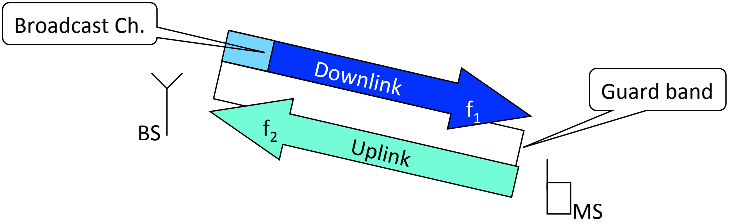
Duplexing : TDD VI

Other systems using TDD :

- DECT (Digital Enhanced Cordless Telecommunications)
- TD-SCDMA (Time Division Synchronous CDMA) "Chinese 3G"
- LTE-TDD
- CSMA/CA based standards (WiFi 802.11, Zigbee 802.15.4)
- 5G New Radio

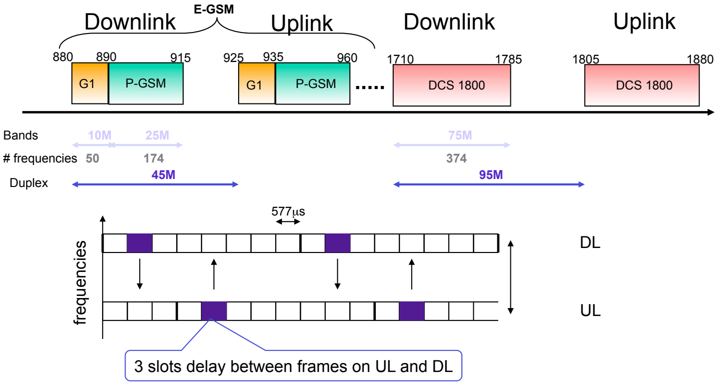
Duplexing : FDD I

- UL and DL use different carrier frequencies
- In duplex mode, RX and TX can be simultaneous (e.g. in UMTS or LTE)
- In half-duplex, RX and TX cannot be simultaneous (e.g. in GSM)
- Two peered frequency bands are usually needed
- Time synchronization is not needed in duplex mode
- Channel conditions on UL and DL are independent



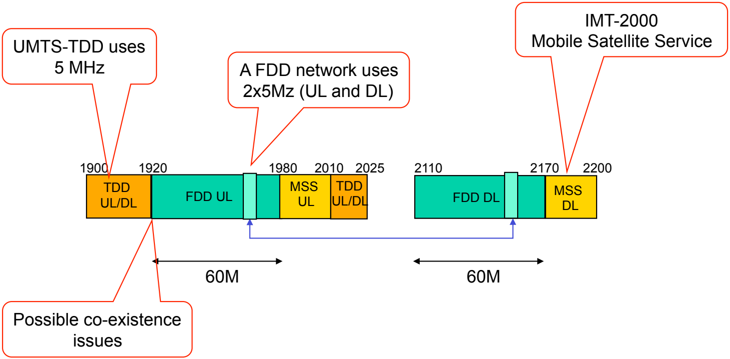
Duplexing : FDD II

Example : GSM (GSM900 and DCS1800 - Digital Cellular System)



Duplexing : FDD III

Example : UMTS FDD

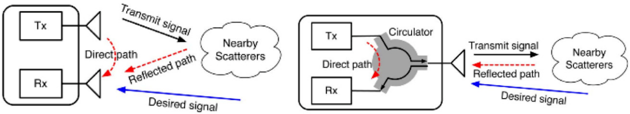


Duplexing : Full Duplex I

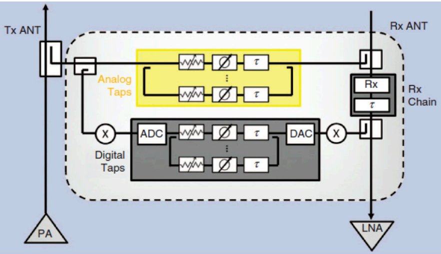
- Full Duplex consists in transmitting and receiving at the same time on the same frequency channel
- The main challenge resides in self-interference :
  Assume GSM 900 MHz, UL with path-loss model in void :
  $PL(R) = 32.4 + 20\log_{10}(f) + 20\log_{10}(R)$, where f is in MHz and R in km
  Transmit power of a MS is $P_e = 33$ dBm
  Antenna gains are $G_e = 0$ dBi (MS) and $G_r = 17$ dBi (BS)
  For a MS located at 1 km, received power at BS is :
  $P_r = P_e + G_e + G_r - PL(1) = -41.5$ dBm, i.e., a difference of 74.5 dBm with the transmit power.
- It is now feasible to have up to 110 dB self-interference cancellation and there have been recently several full duplex prototypes (85 dB could be sufficient for Zigbee)

Duplexing : Full Duplex II

Self-interference can be partly cancelled thanks to a mixture of propagation isolation, analog and digital cancellation [1, 2].

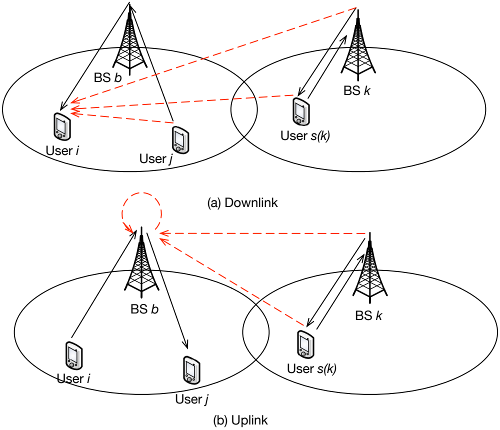


(a) Separated antennas (b) Shared antennas



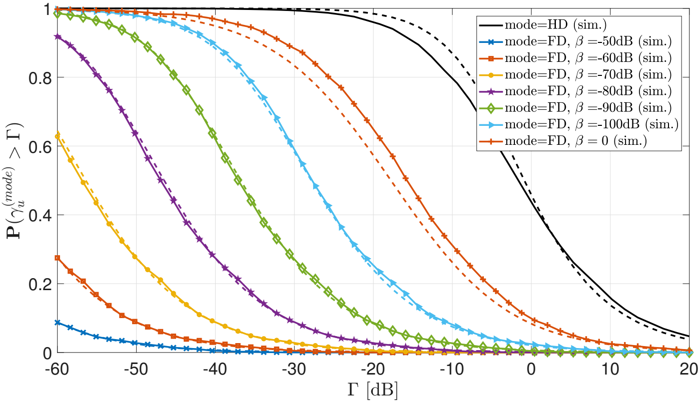
Duplexing : Full Duplex III

New interference situations arise :



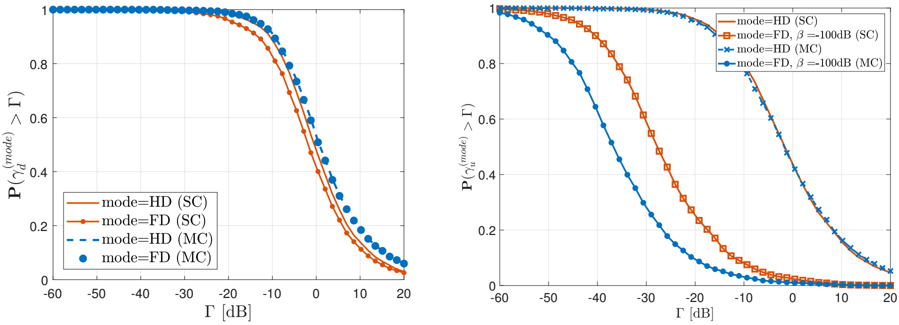
Duplexing : Full Duplex IV

The UL is degraded [3].



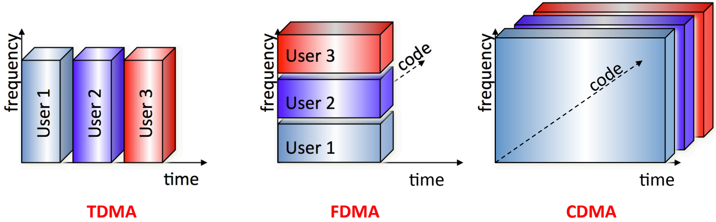
Duplexing : Full Duplex V

UL performance is worse in macro-cells (MC) than in small cells (SC) [3].



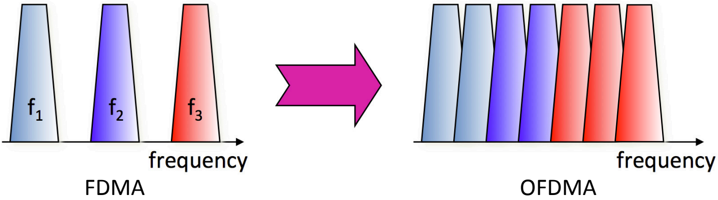
Multiplexing schemes : TDMA, FDMA, CDMA

- Multiplexing schemes allocate different radio resources to different users sharing a common link (UL or DL)
- Signal space can be divided in time, frequency or codes to obtain TDMA, FDMA or CDMA (Time/Frequency/Code Multiple Access)



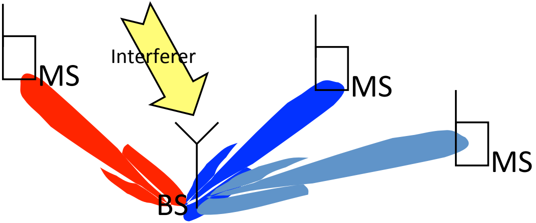
Multiplexing schemes : OFDMA

- OFDMA (Orthogonal Frequency Division Multiple Access) can be seen as a special case of FDMA
- Every elementary frequency band is called a *sub-carrier*
- Main advantages : ease of implementation, better spectral efficiency, easy egalization, flexible resource allocation
- Main drawbacks : high peak to average power ratio, inter-carrier interference



Multiplexing schemes : SDMA

- The use of beamforming or Multi-user MIMO adds a new dimension : Space Division Multiple Access (SDMA)

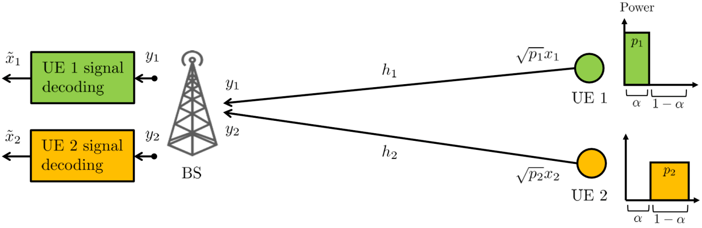


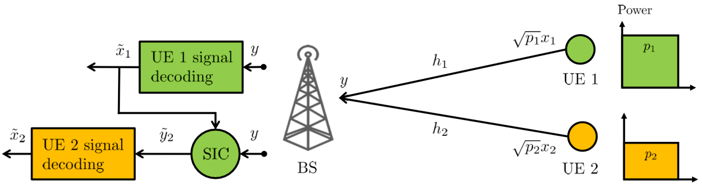
Multiplexing schemes : NOMA I

- Orthogonal multiplexing schemes like TDMA, FDMA, OFDMA have the advantage of avoiding interference between users inside a cell
- However, the sum-rate capacity may not be achieved and at a given instant few users can access the channel
- Adopting a non-orthogonal multiplexing scheme may have several advantages :
  - Improved spectral efficiency : the rate region of NOMA may be wider than with OMA
  - Massive connectivity for IoT : the number of scheduled users is not strictly limited by the amount of radio resources
  - Low transmission latency and signaling cost : the traditional procedure involving scheduling request – uplink grant – data transmission can be avoided
- NOMA is based either on power domain multiplexing (using Successive Interference Cancellation) or code domain multiplexing (similar to CDMA)

Multiplexing schemes : NOMA II

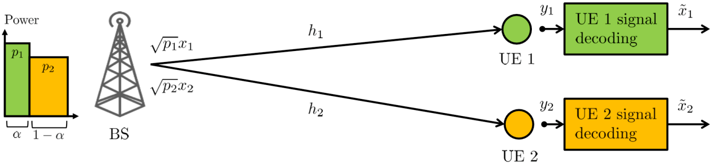
Orthogonal multiple access vs NOMA on the uplink :

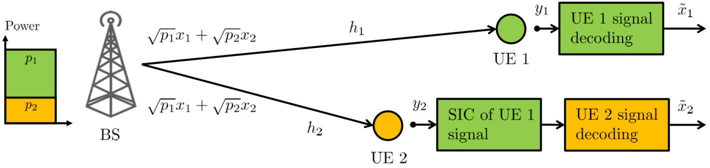




Multiplexing schemes : NOMA III

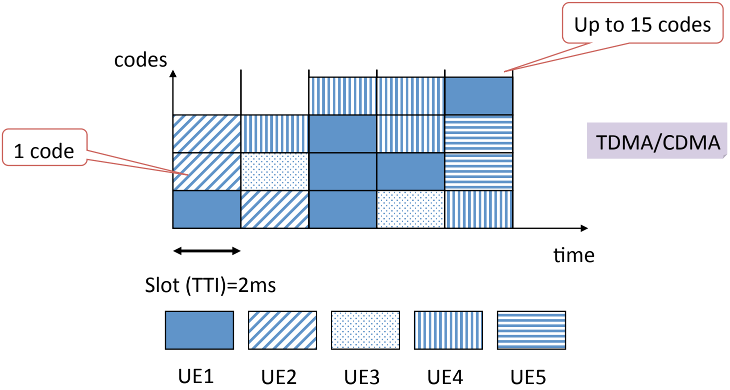
Orthogonal multiple access vs NOMA on the downlink :





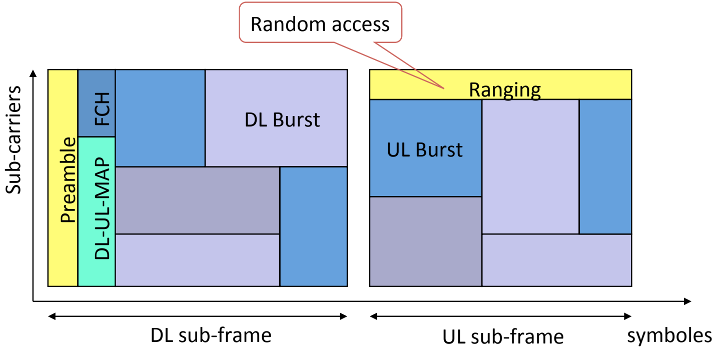
Multiplexing schemes : Examples I

- In HSPA, a data channel is slotted and shared by all DL User Equipments (UE). Several UEs can receive data on the same slot (or Transmission Time Interval – TTI) but encoded with different orthogonal codes



Multiplexing schemes : Examples II

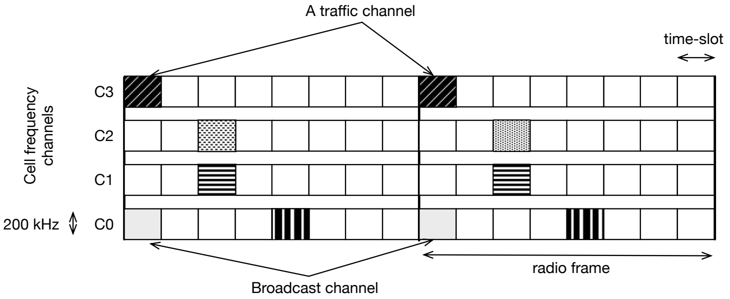
- In WiMAX there are two degrees of freedom for multiplexing : sub-carriers (of an OFDM symbol) and time (OFDM symbols)
- Duplexing scheme is TDD



TDMA/OFDMA

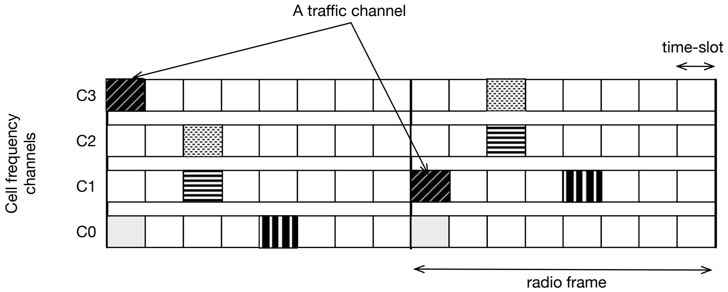
Multiplexing schemes : Examples III

- In GSM, operator spectrum is divided in 200 kHz channels, each frequency channel is divided in 8 slots. Duplexing scheme is FDD.



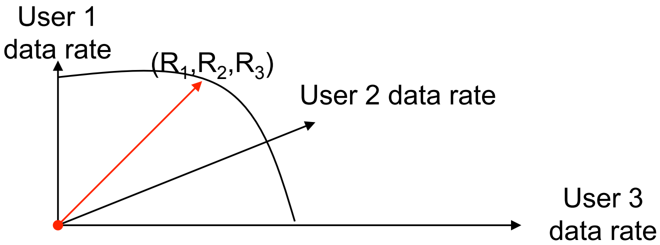
Multiplexing schemes : Examples IV

- With frequency hopping :



Capacity regions : some definitions

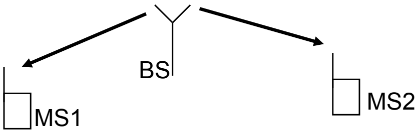
- Capacity region : in a multi-user system, the set $\mathcal{C}$ of all achievable data rates



- Downlink is called the "broadcast channel" (one transmitter, several receivers)
- Uplink is called the "medium access channel" (several transmitters, one receiver)
- Symmetric capacity : $C_{sym} = \max_{(R,\ldots,R)\in\mathcal{C}} R$
- Sum capacity : $C_{sum} = \max_{R_1,\ldots,R_K} \in \mathcal{C} \sum_k R_k$

Capacity regions : broadcast channel

- Model :
  - 2 users
  - Signal bandwidth : B
  - AWGN channel of power $N_0 B$
  - Channel gain g_i for user i
  - Budget power at transmitter : P



- Remark : let $C_i = B\log_2(1 + \frac{Pg_i}{N_0 B})$ be the Shannon capacity for user i, then $(C_1, 0)$ and $(0, C_2)$ are in $\mathcal{C}$.

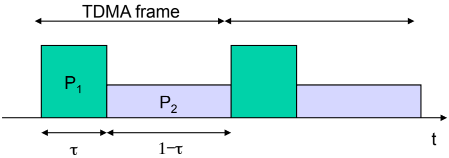
Capacity regions : TDMA broadcast channel I

TDMA multi-user capacity (variable time allocation, variable power) :

$$C_{TDMA} = \bigcup_{\{\tau, P_1, P_2 : 0 \leq \tau \leq 1,\ \tau P_1 + (1-\tau) P_2 = P\}} \left(\tau B \log_2\left(1 + \frac{P_1 g_1}{N_0 B}\right) ; (1-\tau) B \log_2\left(1 + \frac{P_2 g_2}{N_0 B}\right)\right)$$

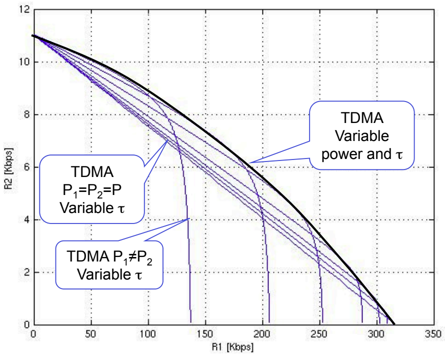
where :

- τ is the proportion of resources dedicated to user 1
- P_i is the power dedicated to user i



Capacity regions : TDMA broadcast channel II

Example : $B = 100$ kHz, $SNR_1 = 9$ dB and $SNR_2 = -11$ dB for $P_1 = P_2$



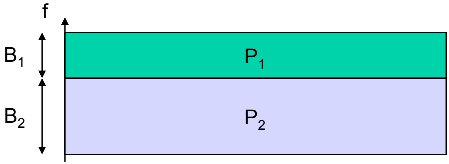
Capacity regions : FDMA broadcast channel I

FDMA multi-user capacity (variable band allocation, variable power) :

$$C_{FDMA} = \bigcup_{\{B_1, B_2, P_1, P_2 : B_1 + B_2 = B,\ P_1 + P_2 = P\}} \left(B_1 \log_2 \left(1 + \frac{P_1 g_1}{N_0 B_1}\right) ; B_2 \log_2 \left(1 + \frac{P_2 g_2}{N_0 B_2}\right)\right)$$

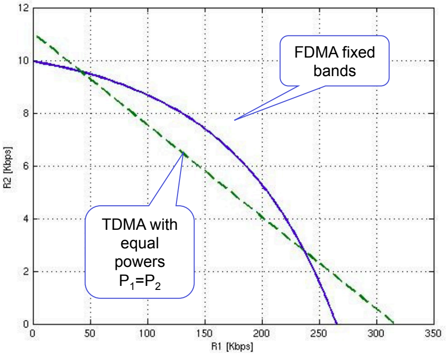
where :

- B_i is the bandwidth dedicated to user 1
- P_i is the power dedicated to user i
- Note : capacity region is identical to TDMA with variable power



Capacity regions : FDMA broadcast channel II

Example : $B = 100$ kHz, $SNR_1 = 9$ dB and $SNR_2 = -11$ dB for $P_1 = P_2$, $B_1 = 0.75B$, $B_2 = 0.25B$

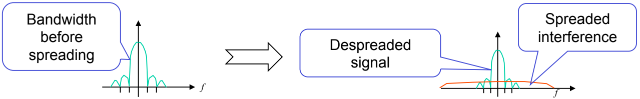


Note : if $SNR_1 > SNR_2$, there always exist P_1 and P_2 such that R_1 and R_2 are better than with TDMA with equal powers.

Capacity regions : CDMA broadcast channel

CDMA multi-user capacity (variable power, processing gain G) :

$$C_{CDMA} = \bigcup_{\{P_1, P_2 : P_1 + P_2 = P\}} \left(\frac{B}{G} \log_2 \left(1 + \frac{P_1 g_1}{\frac{N_0 B}{G} + \frac{P_2 g_1}{G}} \right) ; \frac{B}{G} \log_2 \left(1 + \frac{P_2 g_2}{\frac{N_0 B}{G} + \frac{P_1 g_2}{G}} \right) \right)$$

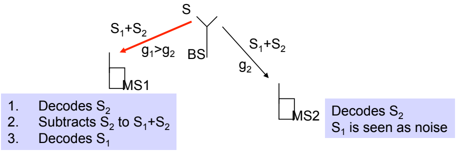


Capacity regions : Successive Interference Cancellation (NOMA) broadcast channel I

SIC (NOMA) capacity region

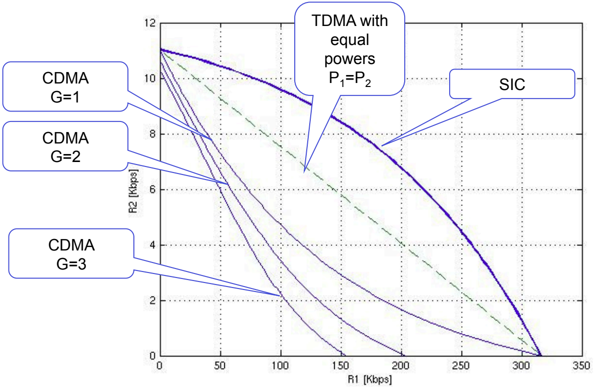
- Assume $g_1 \geq g_2$
- The transmitter superposes both signals
- If user 2 can decode R_2, then user 1 can do it also (with an arbitrary small BER)
- User 1 decodes the signal for user 2 and subtracts the results from the received signal

$$C_{NOMA} = \bigcup_{\{P_1, P_2 : P_1 + P_2 = P\}} \left(B \log_2 \left(1 + \frac{P_1 g_1}{N_0 B} \right) ; B \log_2 \left(1 + \frac{P_2 g_2}{N_0 B + P_1 g_2} \right) \right)$$



Capacity regions : Successive Interference Cancellation (NOMA) broadcast channel II

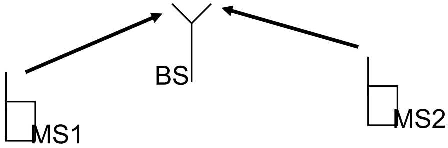
Example : $B = 100$ kHz, $SNR_1 = 9$ dB and $SNR_2 = -11$ dB, $P_1 = P_2$



Capacity regions : the multiple access channel I

Model :

- 2 users
- Signal bandwidth : B
- AWGN channel power $N_0 B$
- Channel gain g_i for user i
- Every user transmits at power P_i



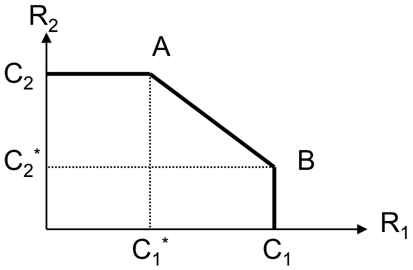
Multiple Access Channel

Capacity regions : the multiple access channel II

The optimal scheme is based on successive interference cancellation :

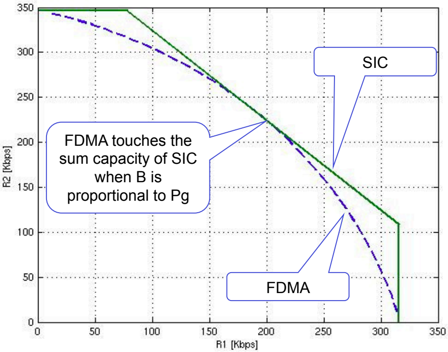
- The receiver decodes signal 2, it can achieve C_2^*
- It subtracts signal 2 from the received signal
- It decodes signal 1 is presence of thermal noise only and achieves C_1
- Roles of users 1 and 2 are symmetric
- The A-B segment is obtained by time-division

$$
\begin{aligned}
C_2^* &= B\log_2\left(1+\frac{P_2 g_2}{N_0 B + P_1 g_1}\right) \\
C_1 &= B\log_2\left(1+\frac{P_1 g_1}{N_0 B}\right) \\
C_1^* &= B\log_2\left(1+\frac{P_1 g_1}{N_0 B + P_2 g_2}\right) \\
C_2 &= B\log_2\left(1+\frac{P_2 g_2}{N_0 B}\right)
\end{aligned}
$$



Capacity regions : the multiple access channel III

Example : $B = 100$ kHz, $SNR_1 = 9$ dB and $SNR_2 = 10$ dB



Conclusion

Two important notions :

- Duplexing : link separation
- Multiplexing : user separation

Duplexing techniques :

- FDD : manly for large cells until 4G
- TDD : suitable for small cells, fixed wireless access, 5G massive MIMO
- Full Duplex : a promising technique to increase the spectral efficiency

Multiplexing techniques :

- Usually a combination of FDMA/OFDMA, TDMA, CDMA
- Optimal multiplexing assumes successive interference cancellation
- NOMA is a good candidate for capacity improvement and massive access

Acronyms I

AWGN	Average White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Acces/Collision Avoidance
DCS	Digital Cellular System
DECT	Digital Enhanced Cordless Telecommunications
DL	Downlink
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GSM	Groupe Spécial Mobile
HSPA	High Speed Packet Access
IoT	Internet of Things
IMT	International Mobile Telecommunications
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MS	Mobile Station
NOMA	Non Orthogonal Multiple Access
OFDMA	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Orthogonal Multiple Access
PDU	Packet Data Unit
RX	Reception
SDMA	Space Division Multiple Access
SIC	Successive Interference Cancellation
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access

Acronyms II

TTI	Transmission Time Interval
TS	Time-Slot
TX	Transmission
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UL	Uplink

References

[1] Ashutosh Sabharwal, Philip Schniter, Dongning Guo, Daniel W. Bliss, Sampath Rangarajan, and Risto Wichman. In-Band Full-Duplex Wireless : Challenges and Opportuni- ties. IEEE Journal on Selected Areas in Communications, 32(9) :1637–1652, September 2014

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