4G MIMO Modes/Link Adaption, and 5G NOMA/Key Technologies/ Application Scenerios

6-7 hours

[Zar14] Houman Zarrinkoub, Understanding LTE with MATLAB: From Mathematical Modeling to Simulation and Prototyping, Wiley, 2014, ch6

[RS15] LTE (Release 12) Transmission Modes and Beamforming White Paper (Rhode&Schwartz, 2015)

https://www.rohde-schwarz.com/applications/lte-transmission-modes-and-beamforming-application-note_56280-15744.html

[5GTurtorial] 5G Technologies and Advances, Part I:5G New Radio – An Overview, EASITC 2018 Tutorial A.

3GPP releases (3G-5G)

- 3gpp: 3rd Generation Partnership Project
- Release 99: WCDMA (wideband CDMA), 3G (IMT-2000)
- Release 6: HSPA(high speed packet access)

(HSDPA high speed downlink packet access &
HSUPA high speed uplink packet access)

- Release 7: HSPA+ (HSPA Evolved)
- Release 8 (Mar. 2009): LTE (Long Term Evolution)

New radio interface: OFDMA and SC-FDMA(additional FFT pair, reduce PAPR in UL), Wider BW and MIMO - not backwards compatible

3

- Release 10 (Jun. 2011): LTE-Advanced, 4G(IMT-Advanced)

HetNets (heterogeneous network, e.g. WLAN/ cellular),Carrier aggregation (most often implemented feature), Relay(improve coverage at coverage hole), CoMP (coordination of BSs, inter-cell interference, ICI=>useful signal, especially at the cell borders)

LTE network can be upgraded by software to LTE-Advanced (3G後期開始軟體定義無線電)

- Release 15 (June 2018) Phase I
- Release 16 (2020 expected) Phae II: 5G (IMT-2020)

4

4G Overview

LTE and LTE Advanced Distinguishing Features

- Motivation
- – Very high capacity & throughput
- – Support for video streaming, web browsing, VoIP, mobile apps
- A true global standard
  - Contributions from all across globe
  - Deployed globally
- A true broadband mobile standard

Standard	Low Mobility	High Mobility
EDGE	~250 kbps	
WCDMA / UMTS	2 Mbps	384 kbps
HSDPA	14 Mbps	
HSPA+	42 Mbps	
LTE (R8 or R9)	100 Mbps	
4G Requirement	1 Gbps	100 Mbps
LTE Advanced (*)	> 1 Gbps	> 100 Mbps

How is this remarkable advance possible?

Enabling transmission technology (103中華電信考題)

- OFDMA
- MIMO
- Turbo Coding (較複雜 下學期課程)
- 載波聚合(CA ,Carrier Aggregation) 可以實現100 MHz頻寬，以4G既有之載波為基礎，將數個載波(CCs, Component Carriers)集合起來成為一更寬的載波

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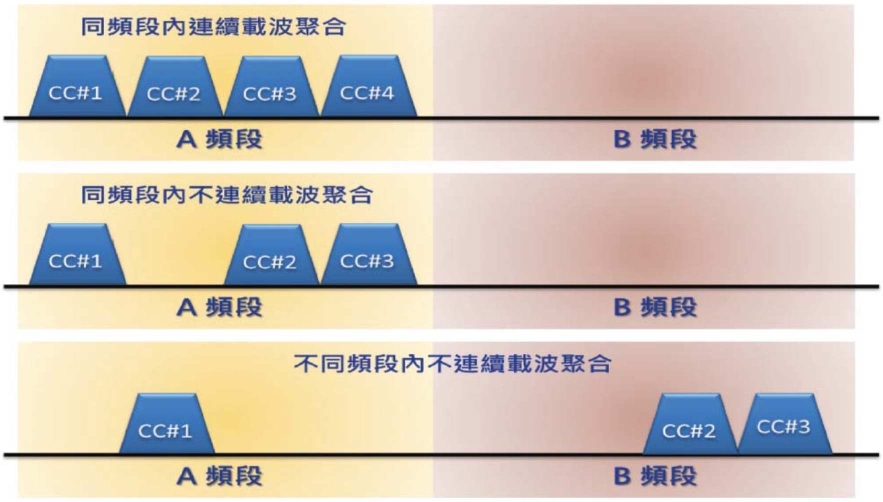
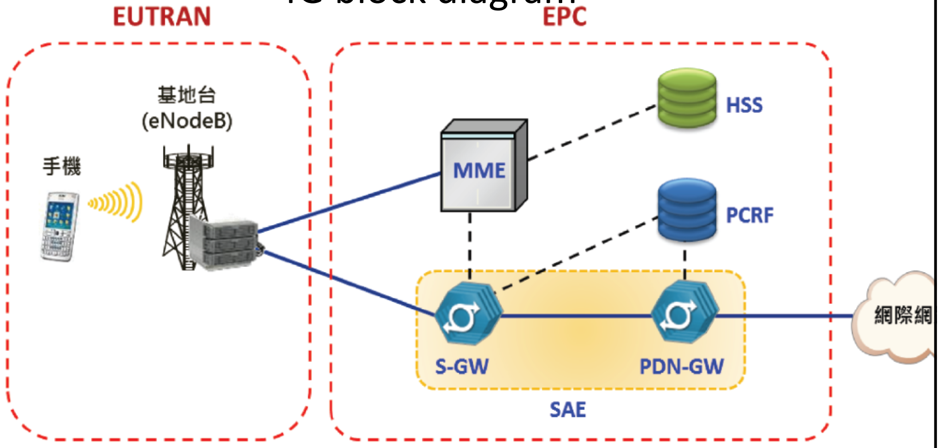


- Smart usage of resources and bandwidth
  - Adaptive modulation
    - QPSK, 16QAM, 64QAM
  - Adaptive coding
    - Coding rates from (1/13) to (12/13) using puncturing (NICT course)
  - Adaptive MIMO
    -- 2x1, 2x2, …,4x2,…, 4x4, 8x8
  - Adaptive bandwidth
    - Up to 100 MHz (LTE-A)

ALL IP 扁平化架構

- LTE行動寬頻通信網路架構可區分
- 演進的UMTS無線接取網路(EUTRAN, Evolved UMTS Terrestrial Radio Access Network)
- 演進的核心網路(EPC, Evolved Packet Core)
- 兩者合稱EPS(Evolved Packet System)

4G block diagram



EUTRAN : Evolved Ur UMTS restrial Radio Access Network, 演進的UMTS無線接取網路
EPC : Evolved Packet Core, 演進的核心網路
SAE : System Architecture Evolution
MME : Mobility Management Entity, 移動管理設備
HSS : Home Subscriber Server, 本籍用戶伺服器
S-GW : Serving Gateway, 服務閘道器
PDN-GW :Packet Data Network Gateway, 數據封包網路閘道器
PCRF : Policy and Charging Rule Function, 策略計費規則控制器

EPC:All IP

- 移除原3G網路的電路交換(Circuit-switch)功能，保留封包交換(Packet-switch)的IP網路，大幅降低LTE核心網路的複雜度
- 將網路之用戶面(User Plane)與控制面(Control Plane)封包分離，有助於網路部署技術演進及靈活的擴充相容
- 相較於傳統3G網路，EPC網路架構相對地扁平化 (see next page)

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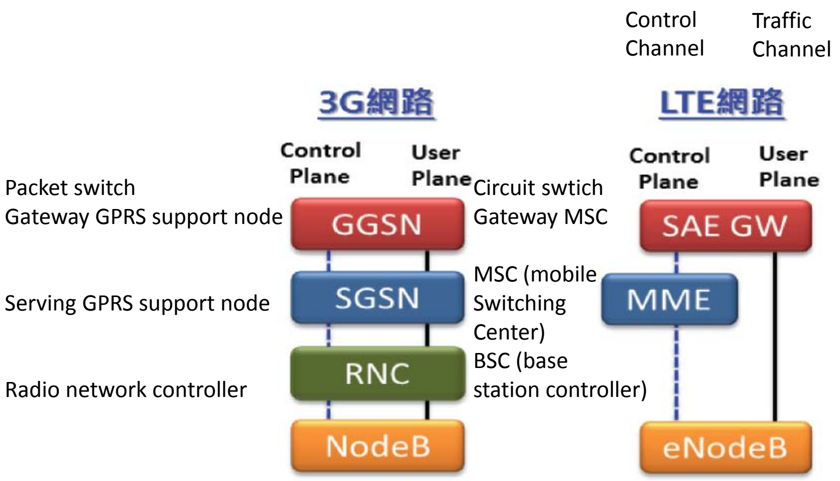
EPC網路架構



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UE category

- LTE UE category allows network to operate with terminals with different data capabilities as well as allows market to differentiate between low end devices with lower data capabilities against high-end devices with higher data rates.

14

User equipment Category	Max. L1 datarate Downlink (Mbit/s)	Max. number of DL MIMO layers	Max. L1 datarate Uplink (Mbit/s)	3GPP Release
0	1.0	1	1.0	*Rel 12 (machine type communication)*
1	10.3	1	5.2	Rel 8
2	51.0	2	25.5	Rel 8
3	102.0	2	51.0	Rel 8
4	150.8	2	51.0	Rel 8
5	299.6	4	75.4	Rel 8
6	301.5	2 or 4	51.0	Rel 10 (begin CA)
7	301.5	2 or 4	102.0	Rel 10
8	2,998.6	8	1,497.8	Rel 10 (theory only)
9	452.2	2 or 4	51.0	Rel 11
10	452.2	2 or 4	102.0	Rel 11
11	603.0	2 or 4	51.0	Rel 11
12	603.0	2 or 4	102.0	Rel 11 (目前常見Cat.)
13	391.7	2 or 4	150.8	Rel 12
14	3,917	8	N/A	Rel 12
15	750	4 or 2	N/A	Rel 12
16	979	4 or 2	N/A	Rel 12

- Note: Maximum data rates shown are for 20 MHz of channel bandwidth. Categories 6 and above include data rates from combining multiple 20 MHz channels . (CA: carrier aggregation)
- Note: These are L1 transport data rates not including the different protocol layers overhead.
- Note: The data rate specified as Category 8 is in theory. Nokia Siemens Networks has demonstrated downlink speeds of 1.4 Gbit/s using 5CA and 8x8 MIMO.

4G transmission modes

Three different types of MIMO: spatial multiplexing, spatial transmit diversity, and beamforming

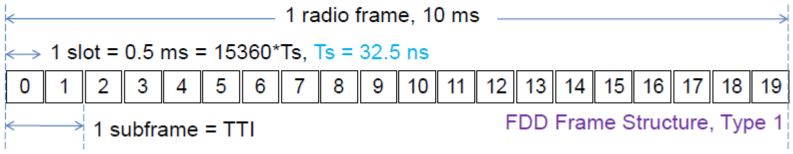
Nomenclature in LTE standards

- Reference signal (RS): pilot signal
- User equipment (UE): mobile station (MS)
- Enhanced NodeB (eNB): base station (BS)
- Physical downlink shared channel (PDSCH): Downlink traffic channel
- Physical downlink control channel (PDCCH): downlink control channel

At the mobile receiver, three types of channel-state information (CSI) are generated and transmitted to the base station:

- The CQI, a measure of downlink radio channel quality that specifies the best modulation constellation and coding rate to match the link quality.
- The PMI, a measure that indicates the best set of precoding matrices for use in closed-loop single- and multi-user spatial multiplexing modes of the LTE standard.
- The RI, which signals the number of useful transmission layers that can be used by the transmitter in spatial multiplexing modes.

FDD Frame Structures



TTI: Transmission Time Interval

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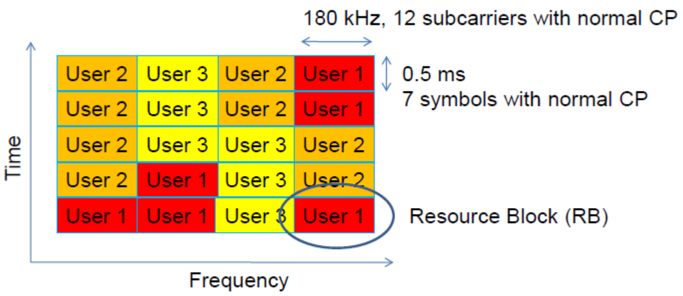
Resource Allocation



- Resources are allocated per user in time and frequency. RB is the basic unit of allocation.
- RB is 180 kHz by 0.5 ms; typically 12 subcarriers by 7 OFDM symbols, but the number of subcarriers and symbols can vary based on CP

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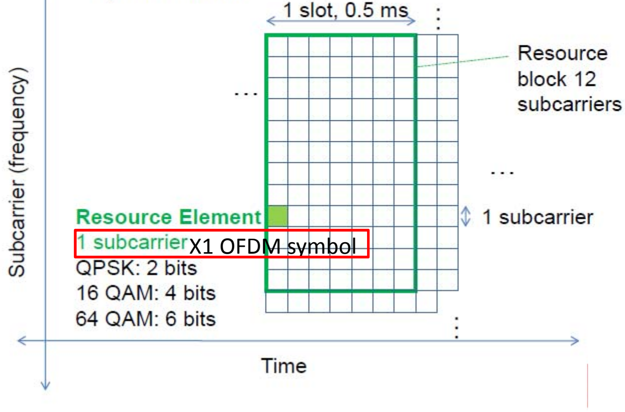
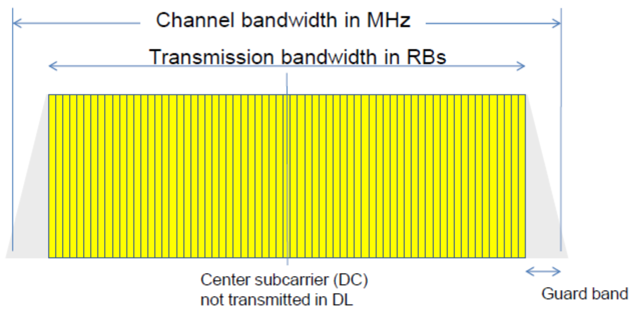
Resource Block =7x12=84 RE

A resource block (RB) is a basic unit of access allocation.
RB bandwidth per slot (0.5 ms) is12 subcarriers times 15 kHz/subcarrier equal to 180 kHz.



Scalable Channel Bandwidth



Channel bw	1.4	3	5	10	15	20	MHz
Transmission bw	1.08	2.7	4.5	9	13.5	18	
# RBs per slot	6	15	25	50	75	100	

18MHz/180kHz=100RB

Maximum Raw Uplink Data Rate

	1 TX
Total bandwidth	20 MHz
Total Resource Blocks	100
Resource Elements per Resource Block	84
Resource Element overhead (uplink reference signals)	12
Available Resource Elements per Resource Block (after overhead)	72
Resource Elements per Resource Block pair (in 1 ms)	144
Total Resource Elements available per subframe	14400
Bits per Resource Element, 64 QAM	6
Total bits per subframe	86400
Raw Channel Bandwidth	**86.4 Mbps**

Source: http://www.lteuniversity.com/blogs/chrisreece/archive/2009/08/04/the-magic-86.aspx

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Maximum Raw Downlink Data Rate

	2x2 MIMO	4x4 MIMO
Total bandwidth	20 MHz	20 MHz
(previous 2 page) Total Resource Blocks	100	100
(7OFDM symbolsx12subcarriers) Resource Elements per Resource Block	84	84
Resource Elements per Resource Block pair (0.5ms=>1ms)	168	168
Resource Element Overhead – PDCCH (Assuming only one OFDM symbol for PDCCH)	12	12
Resource Element Overhead - 3	12	20
Resource Elements per Resource Block pair (in 1 ms)	144	136
Total Resource Elements available per subframe	14400	13600
Bits per Resource Element (64 QAM)	6	6
Total bits per subframe	86400	81600
Throughput per layer	86.4 Mbps	81.6 Mbps
Throughput for 2x2 MIMO, 2 layers (streams)	**172.8 Mbps**	
Throughput for 4x4 MIMO, 4 layers (streams)		**326.4 Mbps**

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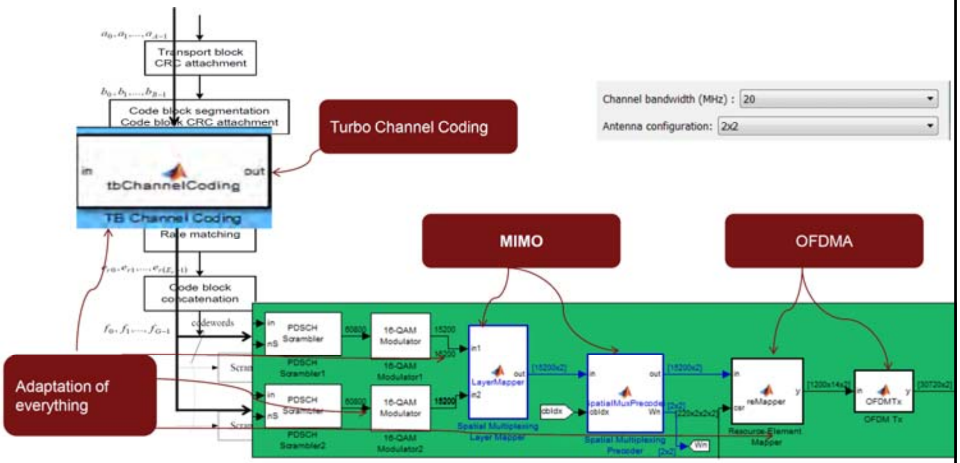
LTE Physical layer model in MATLAB

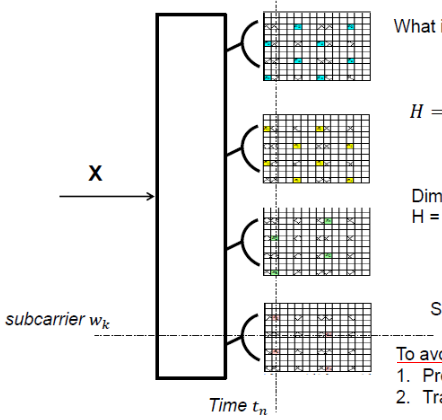


Reference: 3GPP TS 36 211 v10 (2010-12)

25

MIMO-OFDM overview

$Y = H * X + n$



What if 2 rows are linearly dependent?

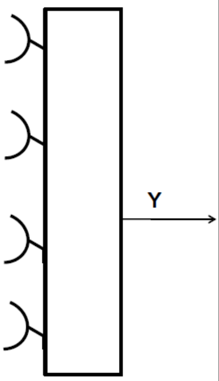
$$H = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_1 & h_2 & h_3 & h_4 \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix}$$

Dimension =4; Rank =3;
H = singular (not invertible)

$H = UDV^H$

Singular Value Decomposition

To avoid singularity:
1. Precode input with pre-selected V
2. Transmit over antennas based on Rank



$y = UDV^H(Vx) + n$

$U^H y = Dx + U^H n$

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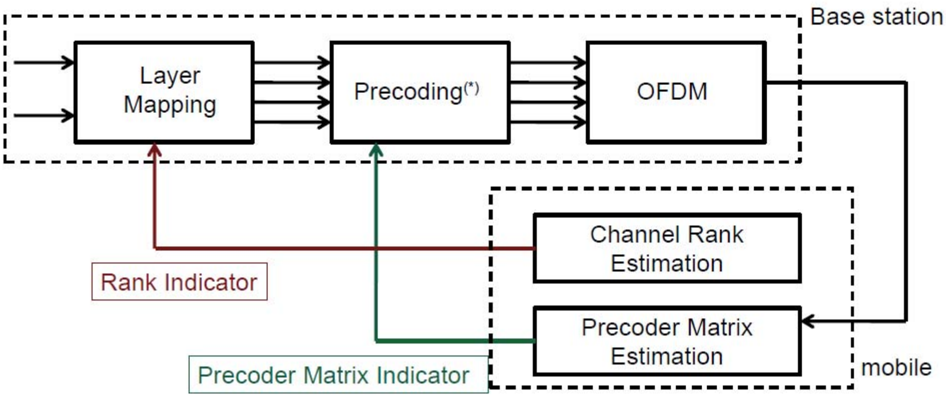
26

Adaptive MIMO: Closed-loop Pre-coding and Layer Mapping



2bits=> 4 kinds of V

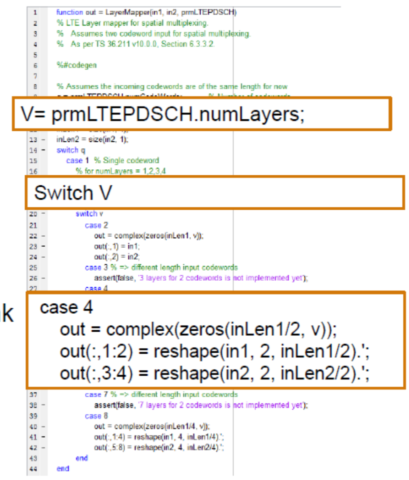
Function layer mapping

Adaptive MIMO in MATLAB

- In Receiver:
- Detect V = Rank of the H Matrix
- = Number of layers

- In Transmitter: (next frame)
- Based on number of layers
- Fill up transmit antennas with available rank

Reshape()



Motivation and Ideas for Precoding [Zar14, p.224]

- Rich-scattering environment not 100% true=> rank deficiency
- Optional precoder require complete channel matrix at TX=> ***SVD*** decomposition
- LTE choose more practical codebook based approach
- **Y**=**HVx**+**n**, where V is precoding matrix whose columns are orthonormal vectors, and V is Hermitian. Thus inv(V)= Hermitian (V)
- ***The precoding matrix columns, like beamforming vector***. **Vx** rotates **x** in various directions. Large phase differences (0, π , π/2 , -π/2) make it more likely the different streams will take different multipath trajectory before arriving at any receive antenna=> more likely full rank

$$\mathbf{Vx} = \sum x_i \mathbf{v}_i, \text{ where } \mathbf{v}_i \text{ is the column of } \mathbf{V}$$

$$\text{Example } \mathbf{v}_1 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ j \end{bmatrix}, \mathbf{v}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -j \end{bmatrix}$$

in Table 4

Downlink Transmission modes in LTE Release 12

Transmission modes	Description	DCI (Main)	Comment
1	Single transmit antenna	1/1A	single antenna port port 0
2	Transmit diversity	1/1A	2 or 4 antennas ports 0,1 (...3)
3	Open loop spatial multiplexing with cyclic delay diversity (CDD)	2A	2 or 4 antennas ports 0,1 (...3)
4	Closed loop spatial multiplexing	2	2 or 4 antennas ports 0,1 (...3)
5	Multi-user MIMO	1D	2 or 4 antennas ports 0,1 (...3)
6	Closed loop spatial multiplexing using a single transmission layer	1B	1 layer (rank 1), 2 or 4 antennas ports 0,1 (...3)
7	Beamforming	1	single antenna port, port 5 (virtual antenna port, actual antenna configuration depends on implementation)
8	Dual-layer beamforming	2B	dual-layer transmission, antenna ports 7 and 8
9	8 layer transmission	2C	Up to 8 layers, antenna ports 7 - 14
10	8 layer transmission	2D	Up to 8 layers, antenna ports 7 - 14

TM7,8 (beamforming),10 (CoMP, 2 BS) not implemented commercially

antenna port (layer of antenna data)

TM7 has 1 antenna port (port 5 is virtual) because 1 data using all antennas

downlink transmission modes

- TM 1 – Single transmit antenna
- TM 2 – Transmit diversity: the default MIMO mode. used as a fallback option for some transmission modes, such as when spatial multiplexing (SM) cannot be used. Control channels, such as PBCH (Physical broadcast channel,information during cell search) and PDCCH(Physical downlink control channel), are also transmitted using transmit diversity.

For two antennas, a frequency-based version of the Alamouti codes (space frequency block code, SFBC) is used, while for four antennas, a combination of SFBC and frequency switched transmit diversity (FSTD) is used.

$$X_n = \overset{\text{Subcarrier}\ \longrightarrow}{\begin{bmatrix} s_{n,1} & s_{n,2} & 0 & 0 \\ 0 & 0 & s_{n,3} & s_{n,4} \\ s_{n,2}^{*} & -s_{n,1}^{*} & 0 & 0 \\ 0 & 0 & s_{n,4}^{*} & -s_{n,3}^{*} \end{bmatrix}} \begin{array}{l} \text{Antenna 0} \\ \text{Antenna 1} \\ \text{Antenna 2} \\ \text{Antenna 3} \end{array}$$

TM2: 2 SFBCs, diff subcarriers, diff antennas=>more diversity

- TM 3 – Open loop spatial multiplexing with CDD: used when channel information is missing or when the channel rapidly changes

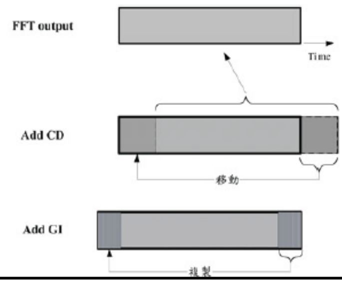
- In addition to the precoding as defined in Table 4, the signal is supplied to every antenna with a specific delay (cyclic delay diversity, or CDD), thus artificially creating frequency diversity.

Spatial multiplexing LTE

Codebook index	Number of layers υ: 1	Number of layers υ: 2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1&0\\0&1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&1\\j&-j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

Table 4: Codebook indices for spatial multiplexing with two antennas, green background for two layers; yellow background for one layer or TM 6 [1]

- 週期性延遲分集(Cyclic Delay Diversity, CDD)，在符元加上保護區間之前，先加上週期性延遲(Cyclic Delay, CD)，將原始資料欲延遲的取樣點移動到最前面，再將處理過後的資料(斜線部分)加上保護區間，成為一個新的OFDM符元



Data in subcarrier i, antenna *j* is repeated at another subcarrier *k*, antenna *l*

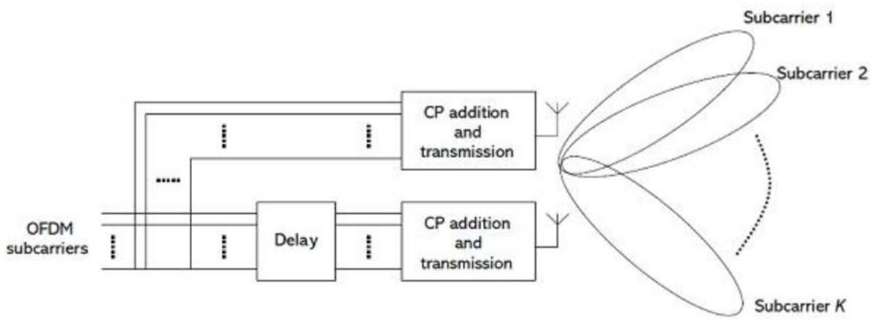


Figure 9: TM 3: Spatial multiplexing with CDD; the individual subcarriers are delayed artificially.

- **TM 4** – Closed loop spatial multiplexing: The UE sends a response regarding the channel situation, which includes information about which precoding is preferred from the defined codebook. This is accomplished using PMI defined in the codebook, a table with possible precoding matrices that is known to both sides.
- TM 5 – Multi-user MIMO: Mode 5 is similar to mode 4. It uses codebook-based closed loop spatial multiplexing, however one layer is dedicated for one UE.

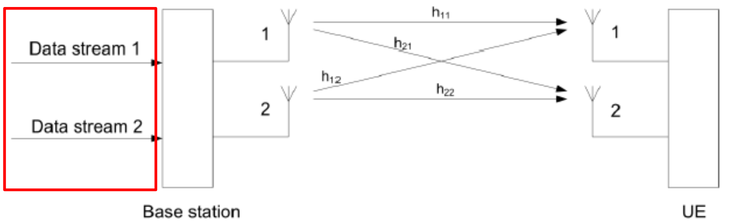


Figure 10: TM 4: single-user MIMO; the two data streams are for one UE only.

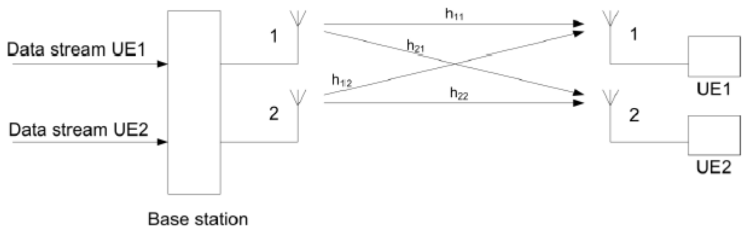


Figure 11: TM 5: Multi-user MIMO; the two data streams are split to two UEs.

[Lim13]

- TM-5 (R8) is a primitive form of the MU-MIMO
- Lack of MU-MIMO-specific CQI reporting and limited precoding mechanism diminish the benefit of dynamic switching between SU-MIMO and MU-MIMO.

- TM 6 – Closed loop spatial multiplexing using a single transmission layer: special type of TM 4, only one layer is used (corresponding to a rank of 1).
- TM 7 – Non-codebook based Beamforming

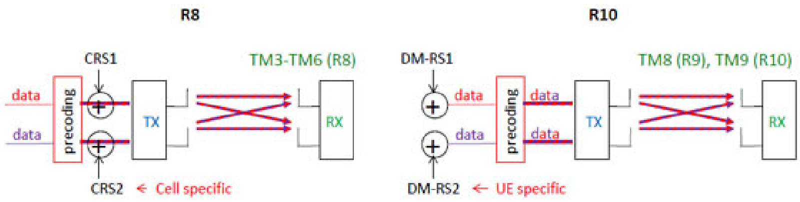
- TM 8 (Release 9) – Dual layer beamforming : permit the base station to weight two layers individually at the antennas so that beamforming can be combined with spatial multiplexing for one or more UEs.
- TM 9 (Release 10)– Up to 8 layer transmission: 8x8 MIMO configurations. Both single user (SU) and multi user (MU) MIMO is possible
- TM 10 (Release 11) – Up to 8 layer transmission: With TM10 Coordinated Multi Point Transmission (CoMP, see [10]) is supported (TM9 is not). CoMP uses in principle the same MIMO technique like TM9, but the transmit antennas may be physically on different base station sites.

* TM 7 8 10 are not used commercially

http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced

- In R10 the DM-RSs (Demodulation Reference Signals) are added to the different data streams before precoding. Knowledge about the reference signal will provide <u>information about the combined influence of radio channel and precoding (for "composite" channel estimation),</u> no pre-knowledge about the precoder is required by the receiver, this case is referred to <u>as non-codebook based precoding</u>, see figure 6.
-

- Figure 6. MIMO DL with precoding and reference signal for demodulation in R8 and R10. CRS is a cell specific reference signal, DM-RS is a UE specific reference signal, also specific per data stream.



Release 12 adds uplink transmission modes

- TM1: Single transmit antenna
- TM2: Closed-loop spatial multiplexing: 2 or 4 antennas, The basic principle is like the downlink spatial multiplexing (TM4). Table 7 shows as an example the codebook indices for the use with two antennas.
-
-

Spatial multiplexing uplink		
Codebook index	Number of layers υ	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	
4	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\end{bmatrix}$	
5	$\frac{1}{\sqrt{2}}\begin{bmatrix}0\\1\end{bmatrix}$	

Table 7: Codebook indices for spatial multiplexing in the uplink with two antennas [1]

4G Link Adaption
CSI: CQI, PMI, and RI estimates

Ch7 in [Zar14]

Table 7.1 Lookup table for mapping SINR estimate to modulation scheme and coding rate [Zar14]

CQI index	Modulation	Coding rate	Spectral efficiency (bps/Hz)	SINR estimate (dB)
1	QPSK	0.0762	0.1523	−6.7
2	QPSK	0.1172	0.2344 -4.7~-2.3 CQI=2	−4.7
3	QPSK	0.1885	0.3770	−2.3
4	QPSK	0.3008	0.6016	0.2
5	QPSK	0.4385	0.8770	2.4
6	QPSK	0.5879	1.1758	4.3
7	16QAM	0.3691	1.4766	5.9
8	16QAM	0.4785	1.9141	8.1
9	16QAM	0.6016	2.4063	10.3
10	64QAM	0.4551	2.7305	11.7
11	64QAM	0.5537	3.3223	14.1
12	64QAM	0.6504	3.9023	16.3
13	64QAM	0.7539	4.5234	18.7
14	64QAM	0.8525	5.1152	21.0
15	64QAM	0.9258	5.5547	22.7

Log2(1+SINR)

7.3.1.2 Spectral Efficiency Lookup [Zar14]

```
function [Ms, Cr]=CQI2indexMCS(sinr)
%#codegen
% Table of SINR threshold values, 15 boundary points for an unbounded quantizer
thresh=[-6.7,-4.7,-2.3,0.2,2.4,4.3,5.9,8.1,10.3,11.7,14.1,16.3,18.7,21,22.7];
% Table of coding rate (16 value)
Map2CodingRate=[0.076, 0.076, 0.117, 0.188, 0.301, 0.438, 0.588, 0.369, 0.479, 0.602, 0.455, 0.554,
    0.650, 0.754, 0.853, 0.926];
% Table of modulation type (1=QPSK, 2=QAM16, 3=QAM64)
Map2Modulator=[1*ones(7,1);2*ones(3,1);3*ones(6,1)]; persistent hQ
if isempty(hQ)
  hQ=dsp.ScalarQuantizerEncoder('Partitioning', 'Unbounded', 'BoundaryPoints', thresh,...
    'OutputIndexDataType','uint8');
end;
indexCQI=step(hQ, sinr);
index1=indexCQI+1;     % 1-based indexing
% Map CQI index to modulation type
Ms = Map2Modulator (index1);
% Map CQI index to coding rate
Cr = Map2CodingRate (index1);
if Cr < 1/3, Cr=1/3;end;
```

7.6.3 [Zar14] CQI-Based Adaptation
CQI measure SINR

Let us define $\boldsymbol{G}$ as the linear (recall LTI system in NWTT1) equalizer that transforms the received signal $Y(n)$ into the equalized signal $\hat{X}(n)$ as the best linear estimate of the transmitted signal $X(n)$ (pilot symbol). The error signal $\boldsymbol{e}(n)$ is then expressed as:

$$\boldsymbol{e}(n) = \hat{X}(n) - X(n) = \boldsymbol{G}Y(n) - X(n) \qquad (7.1)$$

For the CQI estimation, we compute a very simplified approximation of the SINR measure, defined as the ratio of the transmitted signal power to the error signal power

$$\text{SINR} = 10\log_{10}\left(\frac{\sigma_x^2}{\sigma_e^2}\right) \text{(recall NWTT4 CDMA example)}$$

where $\sigma_e^2 = E\left[e^2(n)\right]$ (MSE, mean square error)

Table 7.3 Adaptive modulation and coding: BER, data rates, modulation, and coding rates in different scenarios

Type of modulation	Average data rate (Mbps)	Modulation	Coding rate	Bit error rate
QPSK – no adaptation	28.34	2	0.4932	2.8e−06
16QAM – no adaptation	57.34	4	0.4932	7.9e−04
64QAM – no adaptation	87.01	6	0.4932	3.6e−02
Random selection	56.81	2 or 4 or 6	0.5037	2.5e−02
Adaptive modulation and coding	64.73	2 or 4 or 6	0.333 – 0.94	4.7e−03

˙7.7.1 PMI-Based Adaptation

It employs the Minimum Mean Squared Error (MMSE) criterion to calculate as the output (*cbIdx*) the PMI codebook index per subframe.

Table 7.4 Adaptive precoding: BER, data rates, modulation, and coding rates in different scenarios

Type of modulation	Average data rate (Mbps)	Modulation rate	Coding rate	Bit error rate
No modulation and coding adaptation	35.16	4	1/3	0.1278
No modulation and coding adaptation + adaptive PMI	35.16	4	1/3	0.01191

7.8.1 *RI-Based Adaptation*

```
function y=RIselection(ri, threshold)
Ri=mean(ri); %average over a time duration
% RI estimation
if Ri > threshold, y = 4; else y=2; end
```

- uses a threshold approach to update the transmission mode as a function of an average rank estimation measure.

Adaptive MIMO

- If the estimated rank is equal to the number of transmit antennas, we perform spatial multiplexing. If the rank is less than the number of transmit antennas then we revert to transmit-diversity mode.
- By applying a threshold to the condition number, we propose a wideband rank value for the whole subframe.

Table 7.5 Adaptive rank estimation and MIMO: BER, data rates, modulation, and coding rates in different scenarios

Type of modulation	Average data rate (Mbps)	Modulation rate	Coding rate	Bit error rate
Fixed mode: transmit diversity	15.26	4	2/3	3.4e−07
Fixed mode: spatial multiplexing	19.85	4	1/3	1.3e−03
Adaptive mode based on RI feedback	19.23 (near SM)	4	1/3	7.1e−04 (between SM and TD)

- The parameters used in simulation are summarized in the following MATLAB script, called *commlteMIMO_params*. During the simulation, all of these parameters remain constant except for the modulation scheme specified by the variable *modType*.

commlteMIMO_params

MATLAB script % PDSCH

```
txMode      = 4;  % Transmission mode one of {1, 2, 4}
numTx       = 2;  % Number of transmit antennas
numRx       = 2;  % Number of receive antennas
chanBW      = 6;           % [1,2,3,4,5,6] maps to [1.4, 3, 5, 10, 15, 20]MHz
contReg     = 1;           % {1,2,3} for >=10MHz, {2,3,4} for <10Mhz
modType     = 3;                 % [1,2,3] maps to ['QPSK','16QAM','64QAM']
% DLSCH
cRate       = 1/3; % Rate matching target coding rate
maxIter     = 6;           % Maximum number of turbo decoding iterations
fullDecode  = 0;  % Whether "full" or "early stopping" turbo decoding is performed
% Channel
chanMdl     =  'frequency-selective'; % Channel model
Doppler     = 70;          % Average Doppler shift
% one of {'flat-low-mobility', 'flat-high-mobility','frequency-selective-low-mobility',
% 'frequency-selective-high-mobility', 'EPA 0Hz', 'EPA 5Hz', 'EVA 5Hz', 'EVA 70Hz'} corrLvl= 'Medium';
% Simulation parameters
Eqmode      = 2;           % Type of equalizer used [1,2,3] for ['ZF', 'MMSE','Sphere Decoder'] chEstOn
            = 1;                 % use channel estimation or ideal channel
snrdB       = 20;  % Signal to Noise Ratio in dB
maxNumErrs  = 2e7; % Maximum number of errors found before simulation stops
maxNumBits  = 2e7; % Maximum number of bits processed before simulation stops
visualsOn   = 0;           % Whether to visualize channel response and constellations
numCodeWords = 1; % Number of codewords in PDSCH
enPMIfback  = 0;           % Enable/Disable Precoder Matrix Indicator (PMI) feedback
cbIdx       = 1;                 % Initialize PMI index
```

IMT-2020/5G
R15 Phase I (2018)
R16 Phase II (2020 expected)

59

5G New Radio – An Overview

- Instead of solely enhancing data rates to optimize transmissions of a handful of traffic patterns, the International Telecommunication Union Radio communications Standardization Sector (ITU-R)has announced multifold design goals of 5G mobile networks known as International Mobile Telecommunications 2020 (IMT-2020), which include
- 20 Gb/s peak data rate (currently 1 Gb/s)
- 10 Mb/s/m2 area traffic capacity, 100 devices/km2 connection density, 1 ms latency,
- mobility up to 500 km/h,
- backward compatibility to LTE/LTE-Advanced (LTE-A), and forward compatibility to potential future evolution.

60

- To meet the above design goals, the Third Generation Partnership Project (3GPP)started the standardization activity of 5G New Radio (NR) in 2016, and completed the first phase (Phase I) system in 2018 (Release 15).
- The second phase (Release 16) is expected to be ready in in 2020 (delayed due to COVID-19). The following scope is considered in the 5G specifications.
- Standalone and Non-Standalone NR Operations
- Standalone operation implies that full control plane and data plane functions are provided in NR.
- Non-standalone operation indicates that the control plane functions of LTE and LTE-A (4G) are utilized as an anchor for NR.

61

Spectrum Below and Above 6 GHz.

>6GHz: 28GHz (vendor), 38 GHz (US FCC 5G spectrum in 37 and 39 GHz), 73GHz, etc.

Note: NYU and Aalto U. mmWave in ultra dense environment: path loss 21 dB compared to 5GHz, 29 dB compared to 2GHz=> steerable directional antenna/beamforming required. Pathloss exponent LOS/NLOS very similar to 3.5GHz. Penetration loss: rain not an issue for radius<200m, foliage loss severe.

62

three use cases in R15

In Release 15, three major use cases are emphasized

- Enhanced Mobile Broadband (eMBB):high capacity and high mobility (up to 500 km/h) radio access (with 4 ms user plane latency). Finalized in R15
- Ultra-Reliable and Low Latency Communications (URLLC): urgent and reliable data exchange (with 0.5 ms user plane latency). R16 is not finalized yet due COVID-19
- Massive Machine-Type Communications (mMTC): infrequent, massive, and small packet transmissions for mMTC (with 10 s latency). R16 is not finalized yet due COVID-19

Ref: 3GPP TR 38.913: Study on Scenarios and Requirements for Next Generation

63

Numerologies in NR: physical transmission parameters

- In NR, transmitters and receivers may enjoy a wider bandwidth at high frequency bands.
- subcarrier spacing 15 kHz in 4G => 3.75kHz~960 kHz in 5G
- In addition, high carrier frequencies are also vulnerable to the Doppler effect (fd larger due to fc larger), and a large subcarrier spacing (960KHz mentioned above etc.) may facilitate inter-carrier interference (ICI)mitigation (fd/Δf smaller ex. 2.3 in NWTT7 smaller ranger easy freq sync).

64

- On the other hand, NR should also support a small subcarrier spacing, such as 3.75 kHz as supported by narrowband Internet of Things (NB-IoT, 180kHz BW, 100 kbps in R13, low power, wide area, 抄表、消防監控、環境監測、智慧停車等), to enjoy better power efficiency at low frequency bands.
- Consequently, subcarrier spacings in NR are scalable as a subset or superset of 15 kHz.
- Feasible subcarrier spacings can be 15 kHz*2^m, where m can be a positive/ negative integer or zero.
- For each subcarrier spacing value, multiple CP lengths can be inserted to adapt to different levels of inter-symbol interference (ISI) at different carrier frequencies and mobility.

Frame Structure of NR

- Each slot can carry control signals/channels at the beginning and/or ending OFDM symbol(s).
- This design enables a gNB to immediately allocate resources for URLLC when urgent data arrives.
- OFDM symbols in a slot are able to be all downlink, all uplink, or at least one downlink part and at least one uplink part.
- Therefore, the time-division multiplexing (TDM) scheme in NR is more flexible than that in LTE.

Mini-slot

- To further support small size packet transmissions, mini-slots are additionally adopted in NR
- Each mini-slot is also able to carry control signals/channels at the beginning and/or ending OFDM symbol(s).
- A mini-slot is the minimum unit for resource allocation/scheduling.

67

Multiple Access in NR

- Previous generations of communication standards rely on orthogonal multiple access (OMA).
- Each time/frequency resource block is exclusively assigned to one of the users to ensure no inter-user interference.
- Toward NR, synchronous/scheduling- based OMA continues to play an important role for both DL and UL transmissions.
- Non-orthogonal multiple access (NOMA) transmission, which allows multiple users to share the same time/frequency resource, was recently proposed to enhance the system capacity and accommodate massive connectivity.
- Unlike OMA, multiple NOMA users' signals are multiplexed by using different power allocation coefficients or different signatures such as codebook/codeword, sequence, interleaver, and preamble.

68

Non-orthogonal multiple access (NOMA)

- 1st dimension: frequency (FDMA)
- 2nd dimension: time (TDMA)
- 3rd dimension: spatial (MIMO)
- 4th dimension: power (NOMA)

69

NOMA (CDMA with correlation=1) for 5G

- NOMA improves spectral efficiency and system capacity in 5G.
- In NOMA, the signals of multiple users are multiplexed in the power domain at the transmitter side
- multi-user signal separation is realized via successive interference cancellation (SIC) at the receiver side because it is like CDMA multiuser detection without power control (NWTT5)

70

NOMA better than OMA if NOMA pair users' channels are not equal [Liu17]

Rho: transmit SNR at BS

Beta: resource alloc coeff e.g. FDMA or TDMA

Alpha_m+ Alpha_n=1 power alloc coeff

$$R_m^{\mathrm{OMA}} = \beta \log_2\left(1 + \rho |h_m|^2\right) \tag{3}$$

and

$$R_n^{\mathrm{OMA}} = (1-\beta) \log_2\left(1 + \rho |h_n|^2\right). \tag{4}$$

NOMA: Regarding NOMA, the throughput of user m and user n is given by [32]

$$R_m^{\mathrm{NOMA}} = \log_2\left(1 + \frac{\rho \alpha_m |h_m|^2}{1 + \boxed{\rho \alpha_n |h_m|^2}}\right) \tag{5}$$

NOMA interference

and

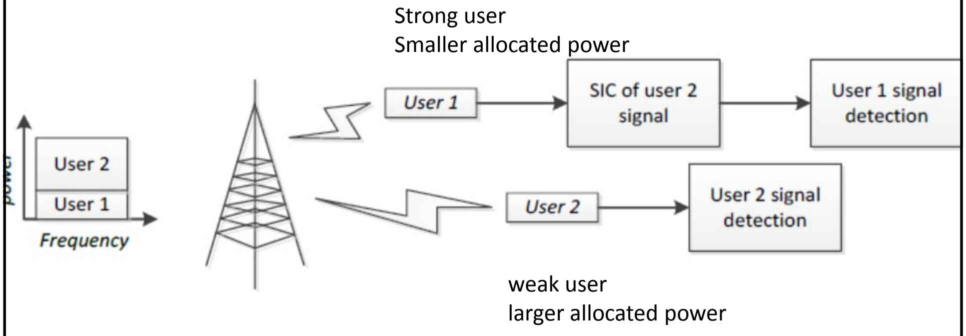
$$R_n^{\mathrm{NOMA}} = \log_2\left(1 + \rho \alpha_n |h_n|^2\right) \tag{6}$$

In order to gain more insights into the spectral efficiency advantage of NOMA over OMA, we investigate the following special case as an example. At high SNRs, assuming that the time/frequency resources are equally allocated to each user, based on (3)–(6), the sum throughput of OMA and NOMA can be expressed as $R_{\mathrm{sum},\infty}^{\mathrm{OMA}} \approx \log_2\left(\rho\sqrt{|h_m|^2 |h_n|^2}\right)$ and $R_{\mathrm{sum},\infty}^{\mathrm{NOMA}} \approx \log_2\left(\rho |h_n|^2\right)$, respectively. Then, we can express the sum throughput gain of NOMA over OMA as follows:

$$R_{\mathrm{sum},\infty}^{\mathrm{Gain}} = R_{\mathrm{sum},\infty}^{\mathrm{NOMA}} - R_{\mathrm{sum},\infty}^{\mathrm{OMA}} = \frac{1}{2}\log_2\left(|h_n|^2 / |h_m|^2\right). \tag{7}$$

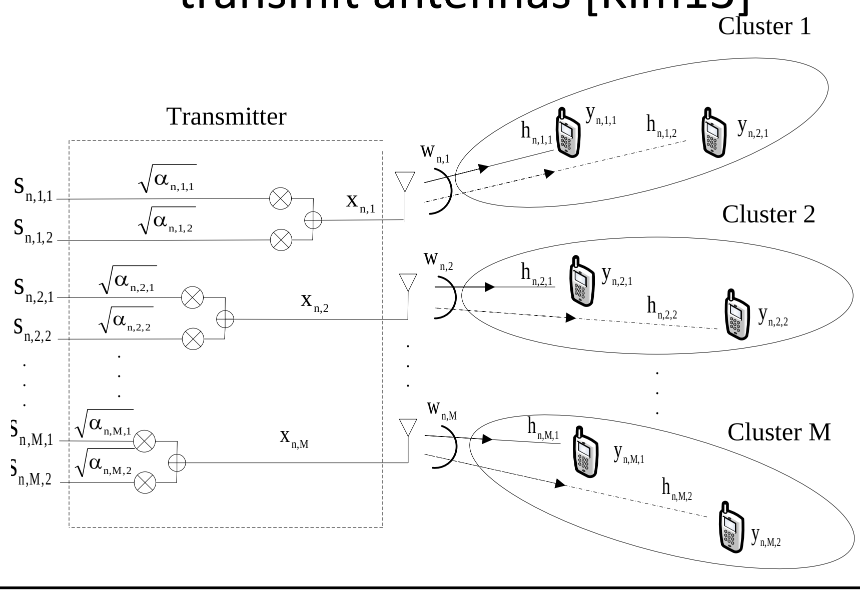
When we have $|h_m|^2 < |h_n|^2$, the sum throughput of NOMA is higher than that of OMA, and this gain is imposed when the channel conditions of the two users become more different. Chen *et al.* [78] provided a rigorous mathematical

Illustration of NOMA via power domain multiplexing



73

MISO-NOMA downlink system with M transmit antennas [Kim13]



74

Receiver signal for user 1 (strong user) and 2 (weak user)

n: subcarrier index, k': cluster index

The received signal of the strong user

$$y_{n,k',1} = h_{n,k',1} w_{n,k'} x_{n,k'} + h_{n,k',1} \sum_{\substack{l=1 \\ l \neq k'}}^{K'} w_{l,k'} x_{l,k'} + n_{n,k',1}$$

$$= h_{n,k',1} w_{n,k'} \left(\sqrt{\alpha_{n,k',1}} s_{n,k',1} + \sqrt{\alpha_{n,k',2}} s_{n,k',2} \right) + \sum_{\substack{l=1 \\ l \neq k'}}^{K'} h_{n.k',1} w_{l,k'} x_{l,k'} + n_{n,k',1}$$

signal + intra - cluster interference + inter - cluster interference

wi ll apply SIC in NWTT5 to intra - cluster interference

will apply ZFBF(zero forcing beamforming) using the cluster heads (strong users) 's channels like decorrelator in NWTT5 to inter - cluster interference

The received signal of the strong user

$$y_{n,k',2} = h_{n,k',2} w_{n,k'} x_{n,k'} + h_{n,k',2} \sum_{\substack{l=1 \\ l \neq k'}}^{K'} w_{l,k'} x_{l,k'} + n_{n,k',1}$$

$$= h_{n,k',2} w_{n,k'} \left(\sqrt{\alpha_{n,k',1}} s_{n,k',1} + \sqrt{\alpha_{n,k',2}} s_{n,k',2} \right) + \sum_{\substack{l=1 \\ l \neq k'}}^{K'} h_{n,k',2} w_{l,k'} x_{l,k'} + n_{n,k',1}$$

75

SINR for user 1 (strong user) and 2 (weak user)

$$\mathrm{SINR}_{n,k',1} = \frac{\left| h_{n,k',1} w_{n,k'} \left(\sqrt{\alpha_{n,k',1}} s_{n,k',1} \right) \right|^2}{\sigma^2_{n,k',1}} = \frac{\left| h_{n,k',1} \right|^2 \alpha_{n,k',1} p_{n,k'}}{\sigma^2_{n,k',1}}$$

$$SINR_{n,k',2} = \frac{\left| h_{n,k',2} w_{n,k'} \right|^2 \alpha_{n,k',2} p_{n,k'}}{\left| h_{n,k',2} w_{n,k'} \right|^2 \alpha_{n,k',1} p_{n,k'} + \left| h_{n,k',2} \sum_{\substack{l=1 \\ l \neq k'}}^{K'} w_{l,k'} x_{l,k'} \right|^2 + \sigma^2_{n,k',2}}$$

where

$x_{k',m}$ consist of transmitted signals of the srong and weak user,

$x_{k',m} = \sqrt{\alpha_{n,k',1}} s_{n,k',1} + \sqrt{\alpha_{n,k',2}} s_{n,k',2}$; $n = 1, \ldots, N$; $k' = 1, \ldots, K'$;

$s_{n,k',1}$ and $s_{n,k',2}$ are the signals for the strong and weak users;

$\alpha_{n,k',1}$ and $\alpha_{n,k',2}$ are the power allocation factors for the strong and weak users;

$\alpha_{n,k',1} + \alpha_{n,k',2} = 1$; $h_{n,k',1}$ and $h_{n,k',2}$ denotes channel vectors are the strong and weak users in k'–th cluster n – th subcarrier.

76

$\mathbf{w}_{n,k'}$ is the corresponding BF vector of of the k'−th cluster and n − th subcarrier $n_{n,k',1}$ and $n_{n,k',2}$ are i.i.d.

AWGN vectors is zero mean and variance of $\sigma^2_{n,k',i}$;

$n = 1,\ldots,N$;

$k' = 1,\ldots,M$; $i = 1,2$

77

User Grouping/Pairing/Selection in NOMA: Exhsustive (best) bound 2018蔡汶達方皓新

```
comb=nchoosek(1:User,4);   %C(n,k)=C(User,4) M=2 clusters
[size_comb,~]=size(comb(:,1)); % number of combinations
[again,~]=size(perms(comb(1,:)));
%P(4,4)=4! Permutations 4 uses in 2 % clusters
usertab=zeros(size_comb*again,4);
j=1;
for i=1:again:again*size_comb
   y=perms(comb(j,:));
   for k=1:again
      usertab(i+k-1,:)=y(k,:);
   end
   j=j+1;
end
```

78

排列組合

- "P" is for "permutation". A permutation is an ordered sequence of elements selected from a given finite set, without repetitions, and not necessarily using all elements of the given set.
- P(n, r) = n!/(n-r)!.
- "C" is for "combination". A combination is an un-ordered collection of distinct elements, usually of a prescribed size and taken from a given set.
- C(n, r) = n!/[r!(n-r)!].

State of the art for standardization of NOMA

- downlink multiuser superposition transmission (MUST) is a study item in 5G.
- Layer division multiplexing (LDM) is included ATSC 3.0

[Liu17] (**Best tutorial of NOMA**) Liu, Y., Qin, Z., Elkashlan, M., Ding, Z., Nallanathan, A., & Hanzo, L. (2017). Nonorthogonal Multiple Access for 5G and Beyond. *Proceedings of the IEEE*, *105*(12), 2347-2381.

"A survey of NOMA: Current status and open research challenges." IEEE Open Journal of the Communications Society 1 (2020): 179-189.

PS. Client/Server(IBM大型主機)+Internet => Cloud (centralized) Ex.
Routing table configured at cloud for easier management
RF ID/wireless sensor network/smart home+Internet=> IoT

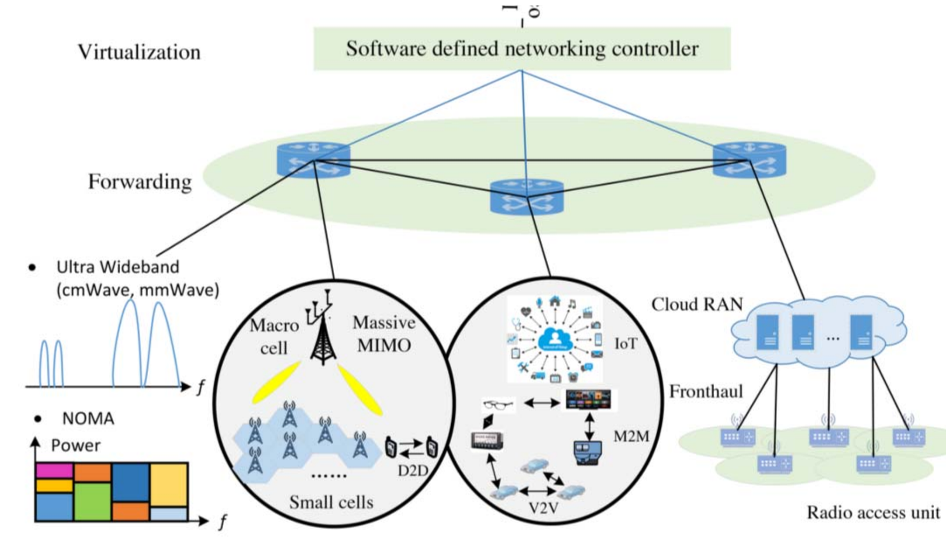


Fig. 2. *Illustration of the future 5G network architecture.*

- 5G key technologies summary
- 5G application scenarios

82

5G key technologies

- Low-density parity check (LDPC) code and Polar code, (examples of linear block code in Argawal ch4): achieving information capacity (bit/sec/Hz)
- Massive MIMO: beamforming for extended range, 64x64 antennas look like tombstone

(gravestone)

- Mobile edge computing (MEC):

Putting server close to user to reduce the delay.

- Short transmission interval: lower

Delay

4G=>5G

- High data rate: 30~100Mbs => 1~20Gbps
- Low latency: 30ms =>1-10 ms
- Large connections: 10 times
- New applications beyond visual range: low latency, 4K VR (180~250Mbps), automatic inspection in industry 4.0, etc.

5G applications scenarios

- Smart manufacturing (Industry 4.0)
- Smart patrol (ChungHua Telecom)
- Connected vehicles (ChungHua Telecom)
- Smart farm (ChungHua Telecom)
- Tele healthcare (ChungHua Telecom)

Smart manufacturing: automatic optical inspection

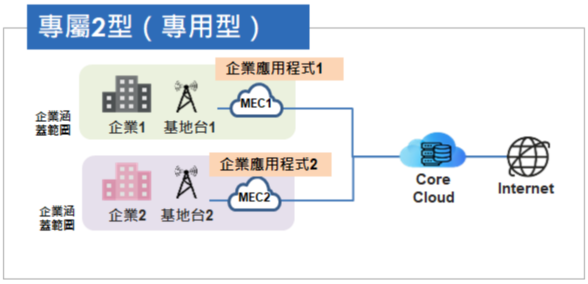
- Inventec (英業達, Aug. 2020) TSMC (台積電, earlier): 5G private networks (eNodeB, MEC, and possible core networks)
- Prior: each production line has its own training data and performs AI training and testing individually because Wi-Fi is contention-based (Agrawal ch 6 Multiple Radio Access) is unstable

- Current: 5G private network, no contention and stable (no dis-connection due to soft handover), lower latency (10% of 4G), high data rate (1Gbps). The cloud collect big data for all production lines, bigger training data, higher accuracy, fewer inspection personnel (90%).

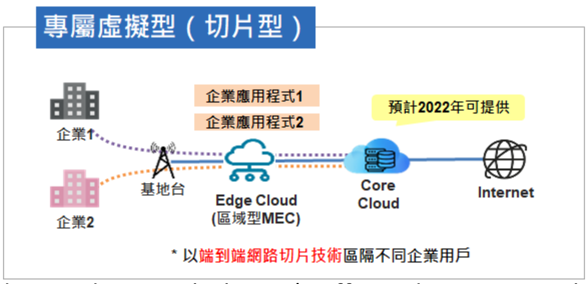
Time is money

- Prior: Wi-Fi uses hard handover and may disconnect. AGV (Automated Guided Vehicle) may go anywhere during disconnection.
- Prior: large data requires large amount time to transmit (no real-time enough), a lot of defected production has already produced when a defect is detected after receiving large data.

5G corporate private network



- Two corporates have separate base station and mobile edge cloud (preserve secrete training data AI etc.) but share core cloud and core network



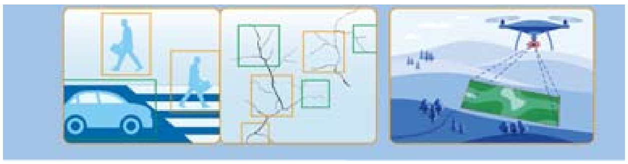
- End-to-end network slicing (traffic and resource isolation) : standard is not finalized (feasibility unknown). Currently VPN (traffic isolation only) is used instead.

Smart Patrol

Smart patrol

- Drones can replace personnel rushing to the scene such as disaster rescue, field inspection, facility inspection, etc
- Using visible light and infrared thermal imaging equipment, real-time 4K videos are sending back to Chunghwa Telecom's Unmanned Aerial Traffic Management (UTM) system, analyzing the images and data through AI to provide commanders with decision making basis, avoiding personnel entering dangerous areas, gaining golden rescue time and reducing casualties.
- 5G makes real time beyond visible range control and real-time 4K video possible.

Decision making through AI big data learning:
(left) Human, vehicle, crack detection
(right) historical video comparison

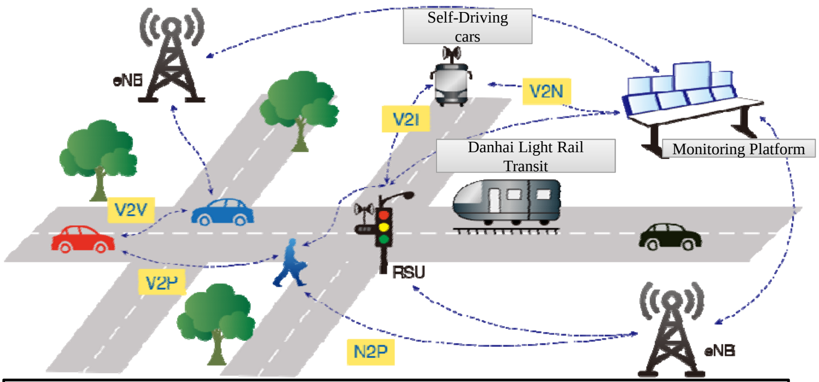


Connected vehicles

- Danhai Light Rail Transit (淡海輕軌,part of Taipei Metro)
- Danhai self-driving bus (C-V2X belong to 3gpp instead of DSRC belong to IEEE 802.11p)
- Danhai traffic sign: know next sign in advance, smart and safe intersection

- 5G connected vehicles aims to realize the collaboration of vehicles, roads, and clouds and 5G application services, establish a smart mobile safe city, and introduce successful experience into an environment that also has commercial benefits, and create a new operating model.
- Through the 5G high-bandwidth and low-latency features, it provides an important reference direction for vehicle control logic, and provides warning messages around the driving environment to ensure driving safety.

Examples:
(left) red light ahead, slow down
(center) person walking in intersection
(right) traffic accident ahead, slow down



V2N （Vehicle to Network）： Self-driving car monitoring platform and and connection to traffic control center
V2I （Vehicle to Infrastructure）： Priority sign, know the next sign in advance, smart and safe intersection
V2P （Vehicle to Pedestrian）：Vulnerable pedestrian warning

Smart farm

Sensor collecting big data, AI analyzing

1. Watering usage
2. Fertilizers usage prediction
3. Bug prediction
4. Disease prediction

The host uses the network to connect to various sensors to collect farmland information

The sensors above the Shutter box include:
Ultraviolet rays, Light

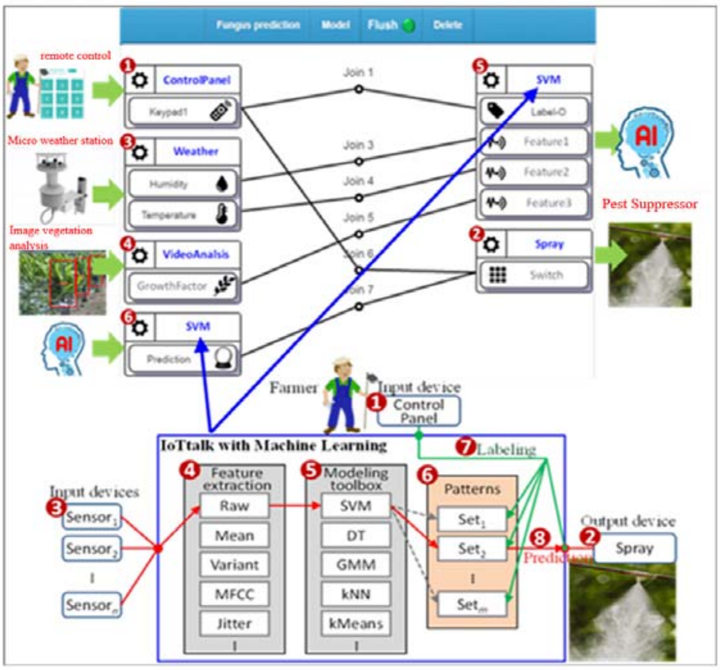
The sensors in the Shutter box include:
Carbon dioxide, Atmospheric pressure,
Temperature, Humidity sensors

The sensor buried in the soil contains:
pH value, temperature and humidity,
Soil EC(Electrical Conductivity) value

AgriTalk application platform

- To accurately perform AI analysis and provide decision-making recommendations, the key is to develop and provide highly stable and reliable sensing equipment as well as to ensure that the correct data is obtained.
- The field sensor is based on the industry-specific MCU, with stable and long-distance transmission UART (Universal Synchronous Asynchronous Receiver Transmitter) and RS485 interface to interface with several environmental sensors. Then use the Ethernet interface that can withstand the largest amount of data transmission, and timely send all the sensor data to the cloud for intelligent analysis and processing.
- The field actuators provide the control modules required for each application scenario including pumps, autos, lights, fill lights, insect repellent lights, fans, etc.

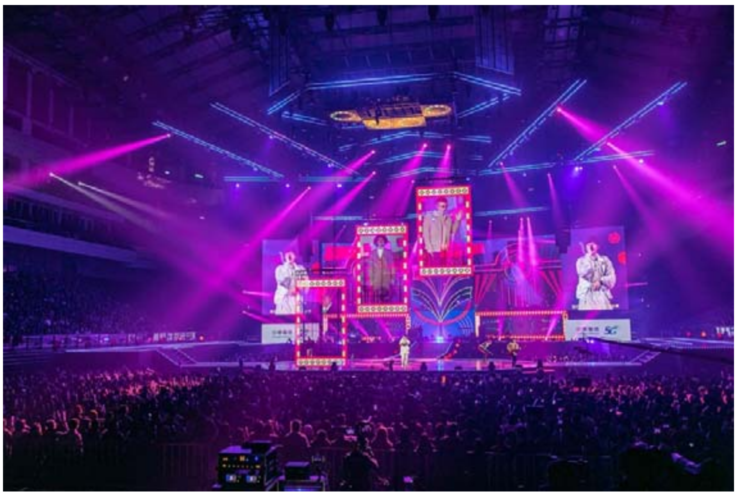
- Aiming at the establishment of agricultural AI, the team has established a general model for the three systems of pests, diseases and soil fertility, and then uses the data collected by the sensors to perform AI calibration and learning in various fields, through transfer learning. In this way, collecting a small amount of key environmental data on the farm and data on the occurrence of diseases and insect pests can be converted from the existing model to the specific type of disease and insect pest prediction AI.
- At the same time, supervised learning is used to learn farmer's experience through machine learning algorithms, learn and adjust the built-in agricultural AI in real time, and achieve an AI decision-making system that is more suitable for specific places and crops (next figure)



Tele healthcare

Nursing home in Chunghua, Taiwan: a medical doctor See everything through AR glasses of the healthcare Personnel to diagnose Remotely.

Entertainment :
On the 15th Annual Billboard, 881, who is at the Taipei Arena, was connected via Chunghwa Telecom's 5G network and sang with 911, who is located 1km away and appeared on the giant transparent LED screen. KKBOX



Conclusions

- Pros of 5G: High data rate (4K video), Low latency (remote real time control), Large connections
- Key sectors for 5G applications: manufacturing, healthcare, traffic, entertainment.
- 5G pushes many corporates to digital transformation.
- 5G corporate private networks are in immediate need.
- Cross field cooperation is a key.