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Towards LTE-Advanced

An Overview of the “Official” 4G Technology!

March 18, 2014

About Xona Partners – In Brief!

A Boutique Advisory Firm Specialized in Technology Business Incubation & Growth Strategies

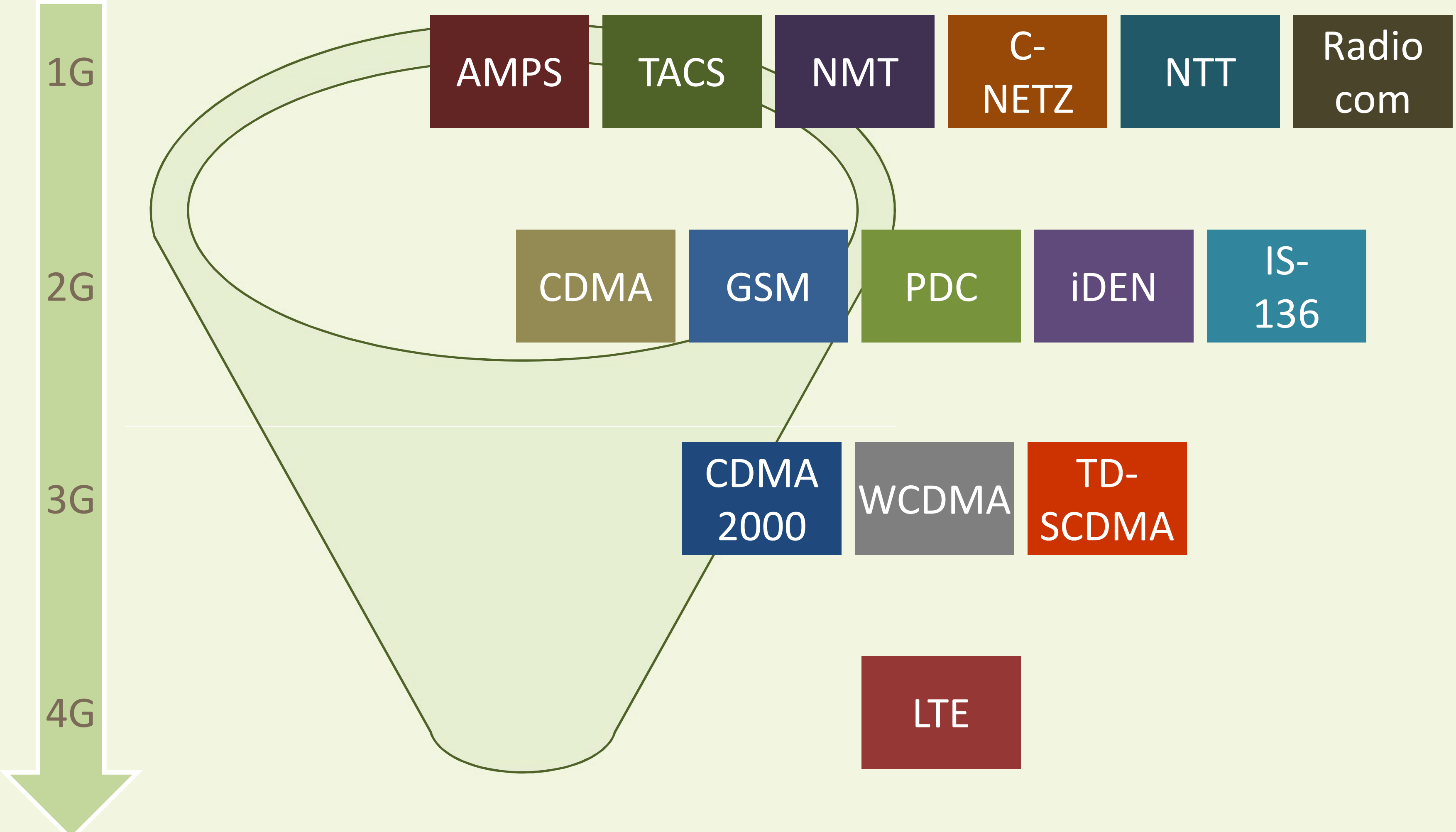
Assist CxOs in developing new streams of revenue through spin-ins, acquisitions, re-structuring & partnerships

Private Equity & Venture Funds

Technology Corporations

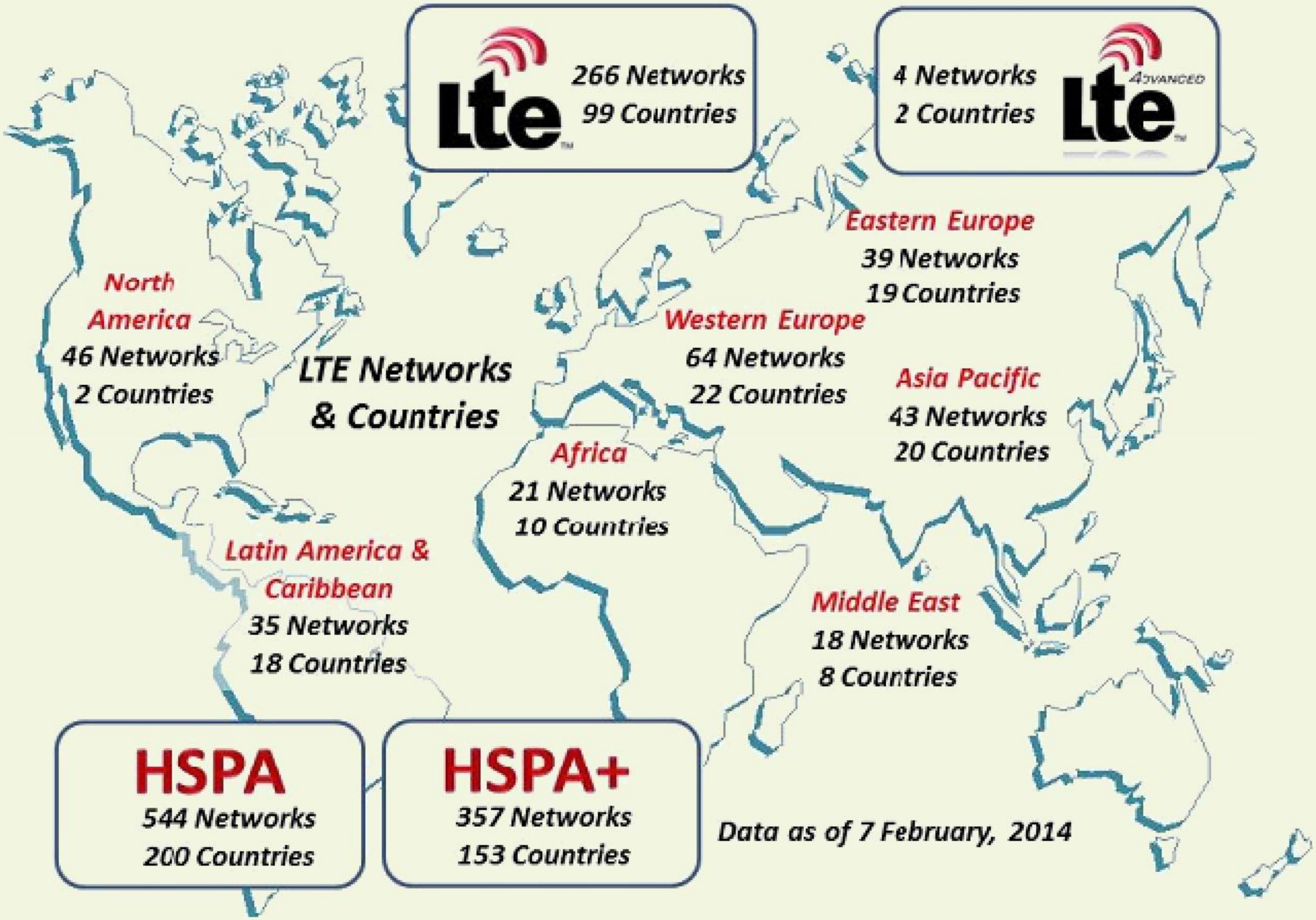
Governments, Regulatory & Policy Makers

A Historical Perspective



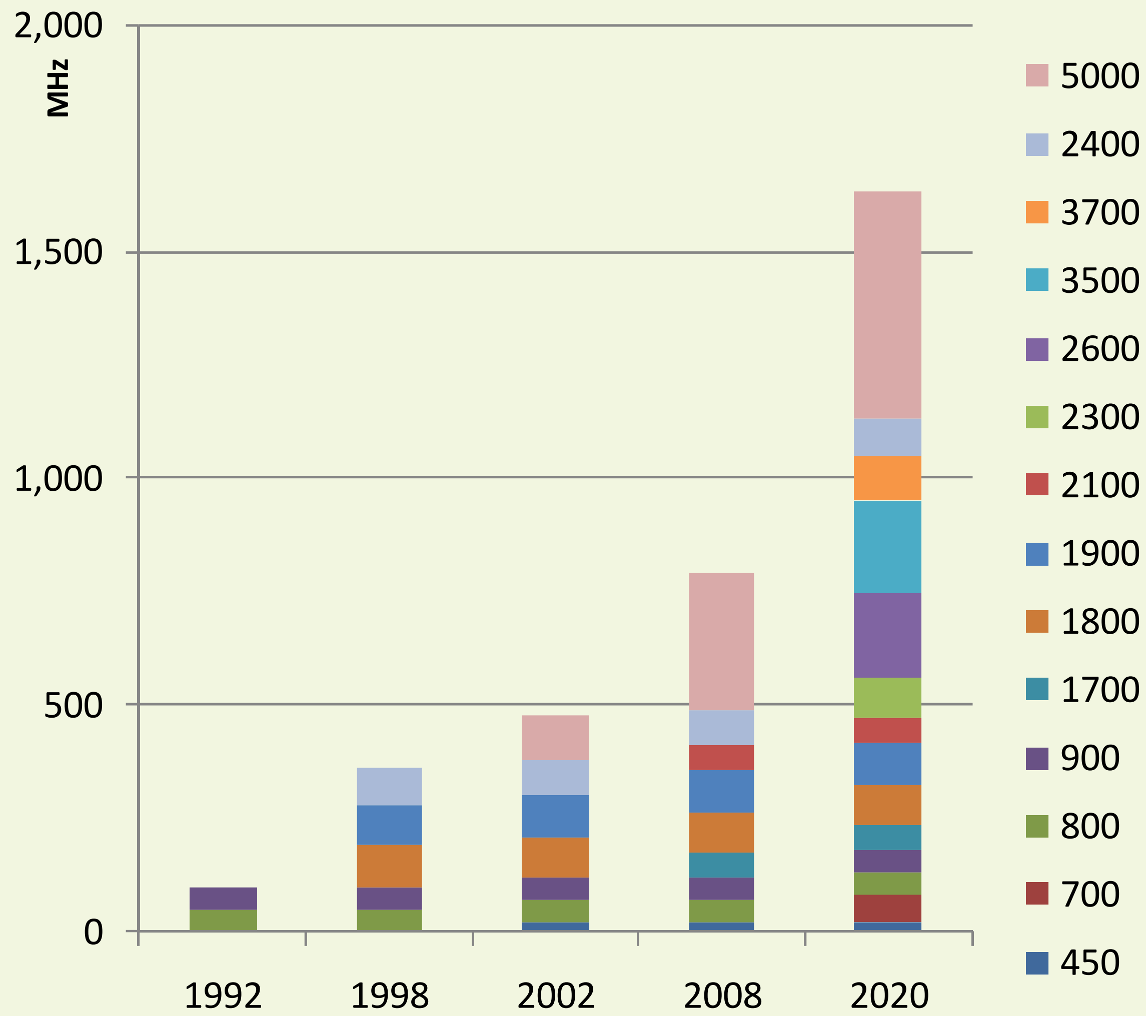
Finally converged on a single universal standard!

3G / 4G Deployment Status



Lists are compiled from public announcements and information provided by Informa Telecoms & Media World Cellular Information Service Database (WCIS+)

Access Spectrum



In the meantime access spectrum is increasing…

Band Proliferation

Band	3GPP Band Number	Uplink Frequency Range (MHz)	Downlink Frequency Range (MHz)	Total Spectrum
2100 (IMT)	1	1920 – 1980	2110 – 2170	2 x 60 MHz
1900 (PCS)	2	1850 – 1910	1930 – 1990	2 x 60 MHz
1800 (DCS)	3	1710 – 1785	1805 – 1880	2 x 75 MHz
1.7/2.1 GHz (AWS)	4	1710 – 1755	2110 – 2155	2 x 45 MHz
850 (CLR)	5	824 – 849	869 – 894	2 x 25 MHz
800 (UMTS)	6	830 – 840	875 – 885	2 x 10 MHz
2.6 GHz (IMT-E)	7	2500 – 2570	2620 – 2690	2 x 70 MHz
900 (GSM/UMTS)	8	[illegible]	925 – 960	2 x 35 MHz
1700 (UMTS)	9	[illegible]	1844.9 - 1879.9	2 x 35 MHz
1700 (UMTS)	10	[illegible]	2110 – 2170	2 x 60 MHz
1500 (PDC)	11	[illegible]	1475.9 - 1495.9	2 x 20 MHz
700	12	[illegible]	729 – 746	2 x 17 MHz
700	13	777 – 787	746 – 756	2 x 10 MHz
700	14	788 – 798	758 – 768	2 x 10 MHz
	17	704 – 716	734 – 746	2 x 12 MHz
	18	815 – 830	860 – 875	2 x 15 MHz
800	19	830 – 845	875 – 890	2 x 15 MHz
800 MHz Digital Dividend	20	[illegible]	791 – 821	2 x 30 MHz
	21	[illegible]	1495.9 - 1510.9	2 x 15 MHz
	22	[illegible]	3510 – 3590	2 x 80 MHz
	23	[illegible]	2180 – 2200	2 x 20 MHz
L-Band	24	[illegible]	1525 – 1559	2 x 34 MHz
	25	1850 – 1915	1930 – 1995	2 x 65 MHz
3G Core Band	33	1900 – 1920		20 MHz
3G Core Band	34	2010 – 2025		15 MHz
PCS Uplink	35	1850 – 1910		60 MHz
PCS Downlink	36	[illegible]		60 MHz
	37	[illegible]		20 MHz
3G Extension Band	38	[illegible]		50 MHz
TD-SCDMA China Band	39	[illegible]		40 MHz
IMT-2000 - China	40	[illegible]		100 MHz
US 2.5 GHz	41	2496 – 2690		194 MHz
EU 3.5 GHz	42	3400 – 3600		200 MHz
EU 3.8 GHz	43	3600 – 3800		200 MHz
APT700	44	703 – 803		100 MHz

44 LTE Profiles

LTE "Not Really" 4G – Technically Speaking

		IMT-Advanced	LTE 3GPP Rel 8	LTE-Advanced 3GPP Rel 10
Transmission bandwidth (MHz)		≤ 100 MHz	≤ 20 MHz	≤ 100
Peak data rate (DL/UL) (Mbps)		1000 (low mobility) 100 (high mobility)	300/75	1000/500
Peak spectral efficiency (b/s/Hz)	DL (4x4/8x8)	15/-	15/-	16/30
	UL (2x2/4x4)	6.75	3.75	8.4/16.8 (FDD) 8.1/16.1 (TDD)
Latency (ms)	User plane	< 10	< 6	< 6
	Control plane	< 100	50	50

System Performance Improvement in Rel 10

			LTE (R8)	LTE-Advanced (R10)	% Improvement
Spectral Efficiency (bit/s/Hz/cell), 3 km/h, 500 m ISD	Downlink	2 x 2	1.69	2.4	42%
		4 x 2	1.87	2.6	39%
		4 x 4	2.67	3.7	39%
	Uplink	1 x 2	0.74	1.2	62%
		2 x 4	--	2.0	
Cell-edge User Throughput (bit/s/Hz/cell/user), 5 percentile, 10 users, 500 m ISD	Downlink	2 x 2	0.05	0.07	40%
		4 x 2	0.06	0.09	50%
		4 x 4	0.08	0.12	50%
	Uplink	1 x 2	0.024	0.04	67%
		2 x 4	--	0.07	

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LTE-Advanced Features

Release 10	Release 11
Carrier Aggregation	Coordinated Multipoint
Downlink MIMO 8x8	CA Enhancements
Uplink MIMO 4x4	Network Energy Savings
eICIC	Enhanced DL Control Ch.
Enhanced SC-FDMA	In-device Co-existence
SON Enhancements	Service Continuity for eMBMS
Relays	Network-based positioning (UTDOA)
	RAN Enh. For Diverse Data Applications
	Further enhanced ICIC (feICIC)
	Minimization of Drive Test (MDT)

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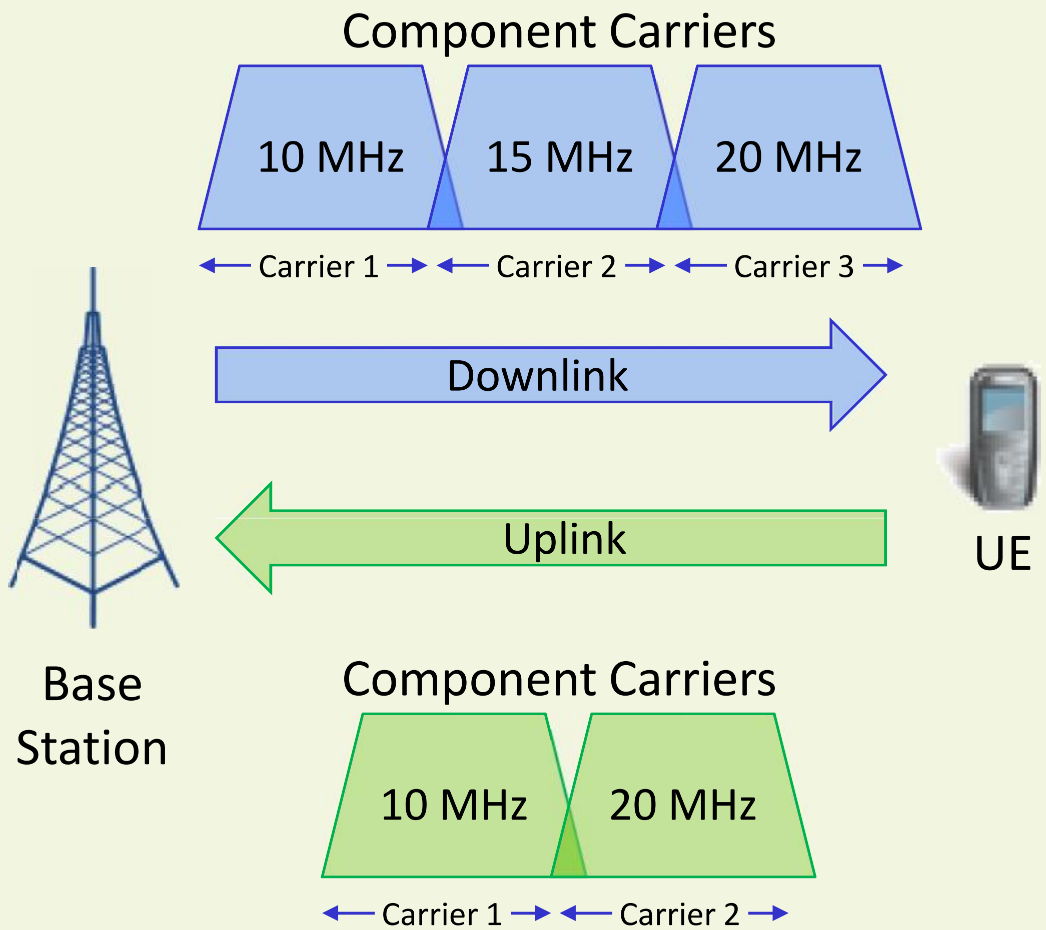
Feature 1: Carrier Aggregation (CA)

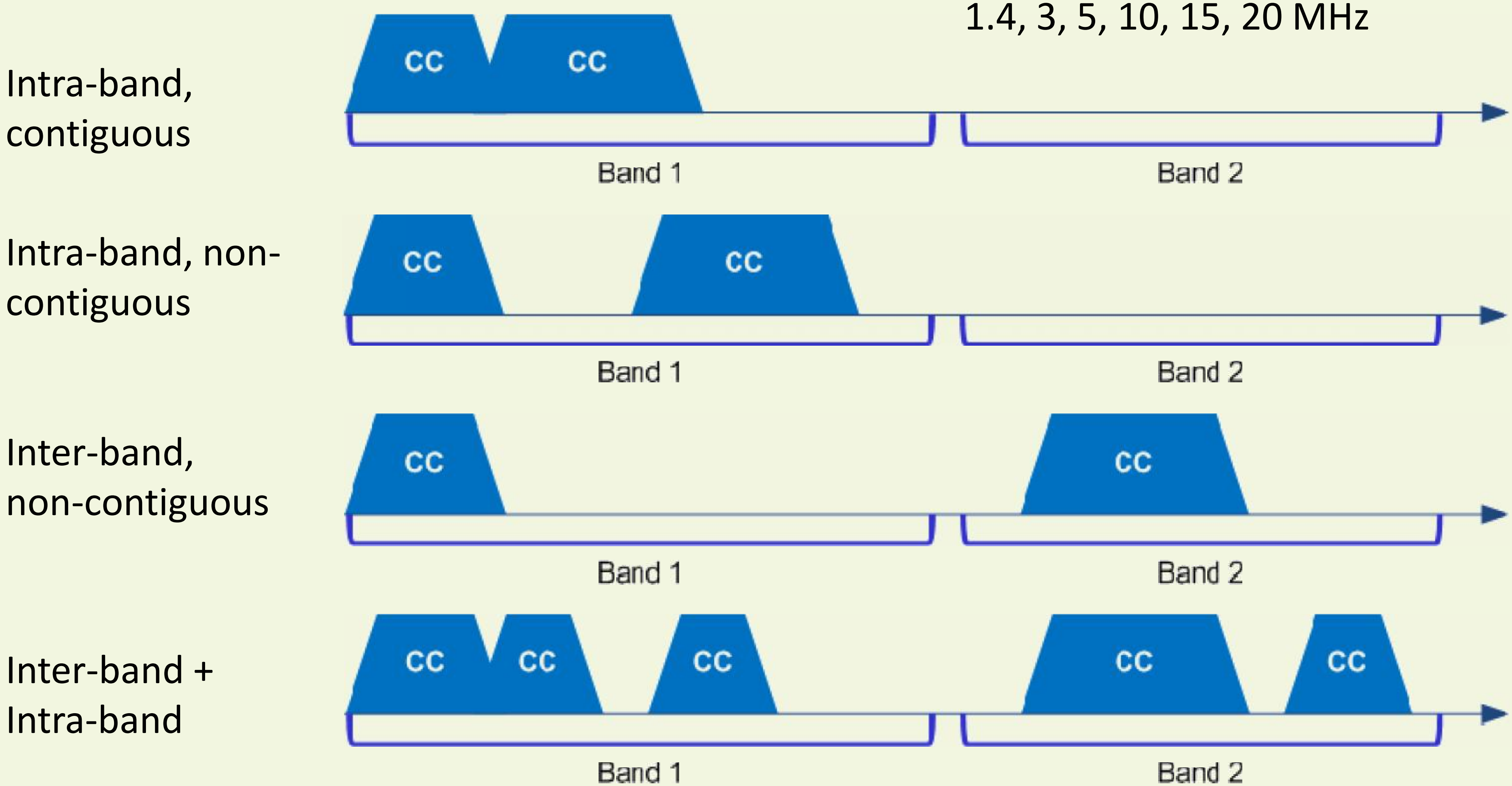
- Two to five "Component Carriers" (CC) aggregated into a larger bandwidth
- CCs are backward compatible (Rel 8 carriers)
- Permits use of 100 MHz of spectrum (5 x 20 MHz)
- Flexible CC allocation allows efficient use of RF spectrum



Release 10 limited to 2 downlink and 1 uplink carriers

Types of Aggregation

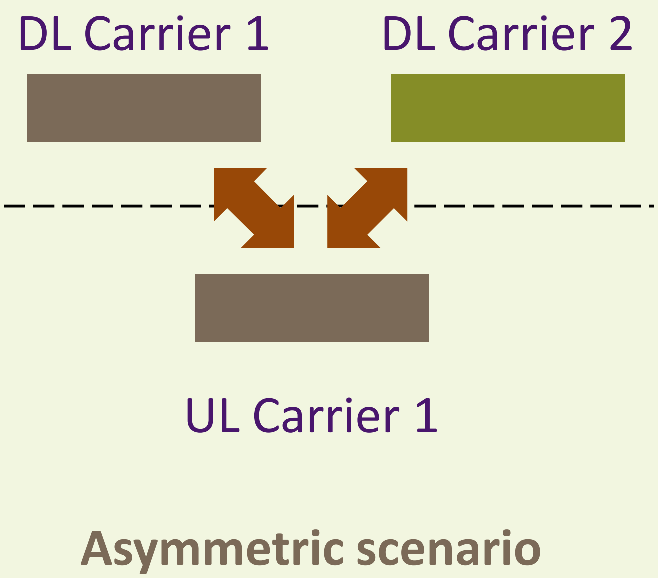
Carrier bandwidth options:
1.4, 3, 5, 10, 15, 20 MHz

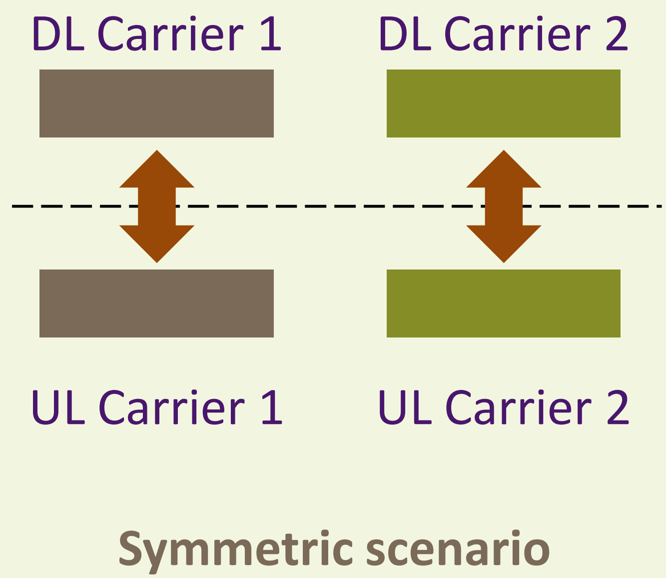


Up to 5 carriers of 20 MHz: Total 100 MHz

Symmetric vs. Asymmetric Aggregation

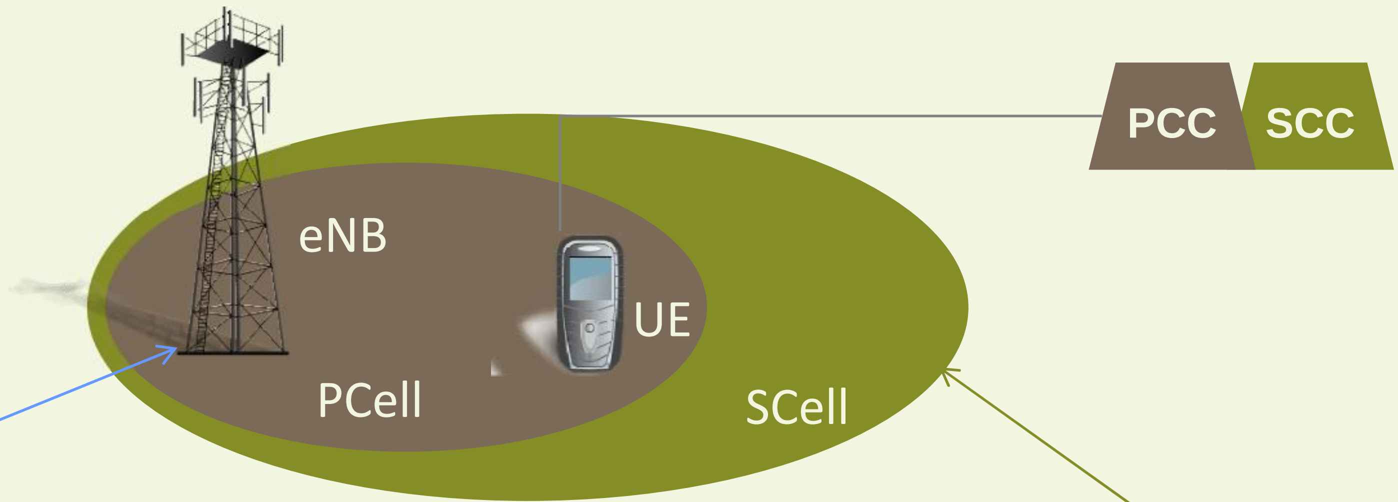
- Asymmetric bandwidth in downlink and uplink





Definition of Serving Cells

- In LTE-A each CC (to be aggregated) appears as a separate cell ID/eARFCN to the mobile unit
- Two types of serving cells are defined for CA



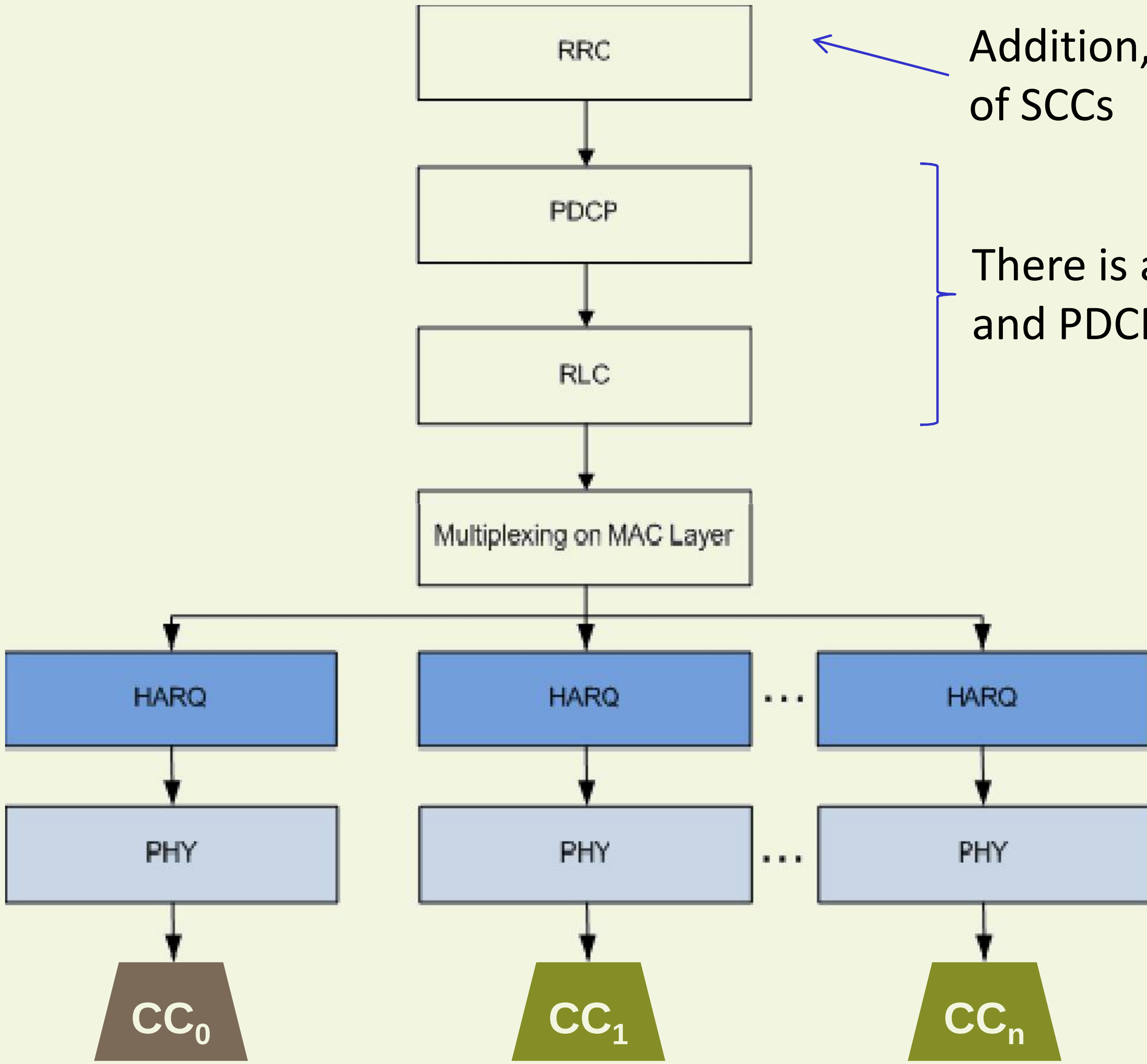
A Primary Serving Cell (PCell) is the cell in which the UE either performs the initial connection establishment procedure or initiates a connection re-establishment procedure.

The component carriers on which the PCell is based is a DL Primary Component Carrier (PCC) linked with an UL PCC.

A Secondary Serving Cell (SCell) are additional cells which may be configured once an RRC connection is established to provide additional radio resources.

The component carrier on which each SCell is based is a DL Secondary Component Carrier (SCC) linked with an UL SCC.

Aggregation Structure



Addition, removal, and reconfiguration of SCCs

There is a single RLC and PDCP Layer

Independent HARQ, Re-Tx handling for TBs

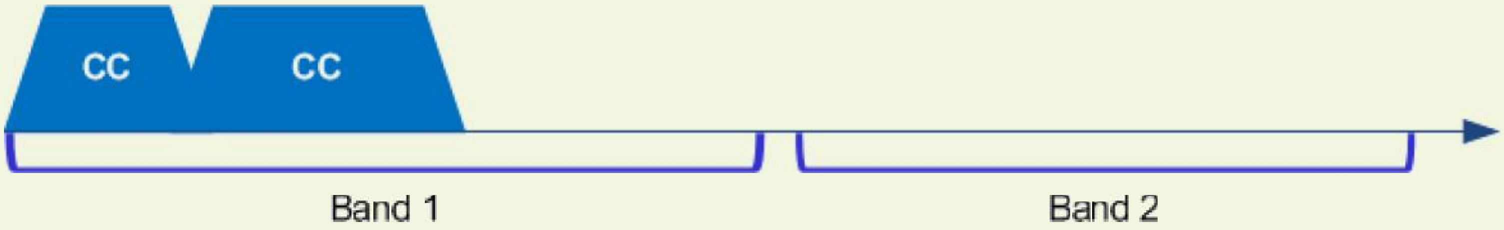
Independent Tx mode, modulation & coding

Aggregation of CCs is performed on the MAC and PHY layers

Configured SCCs are activated or deactivated at MAC layer

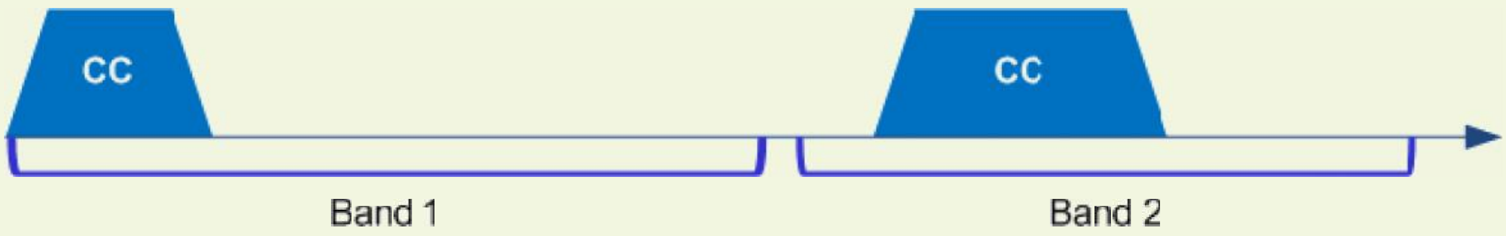
Each CC has its own independent HARQ entity

Rel 10 CA: Intra-band Contiguous



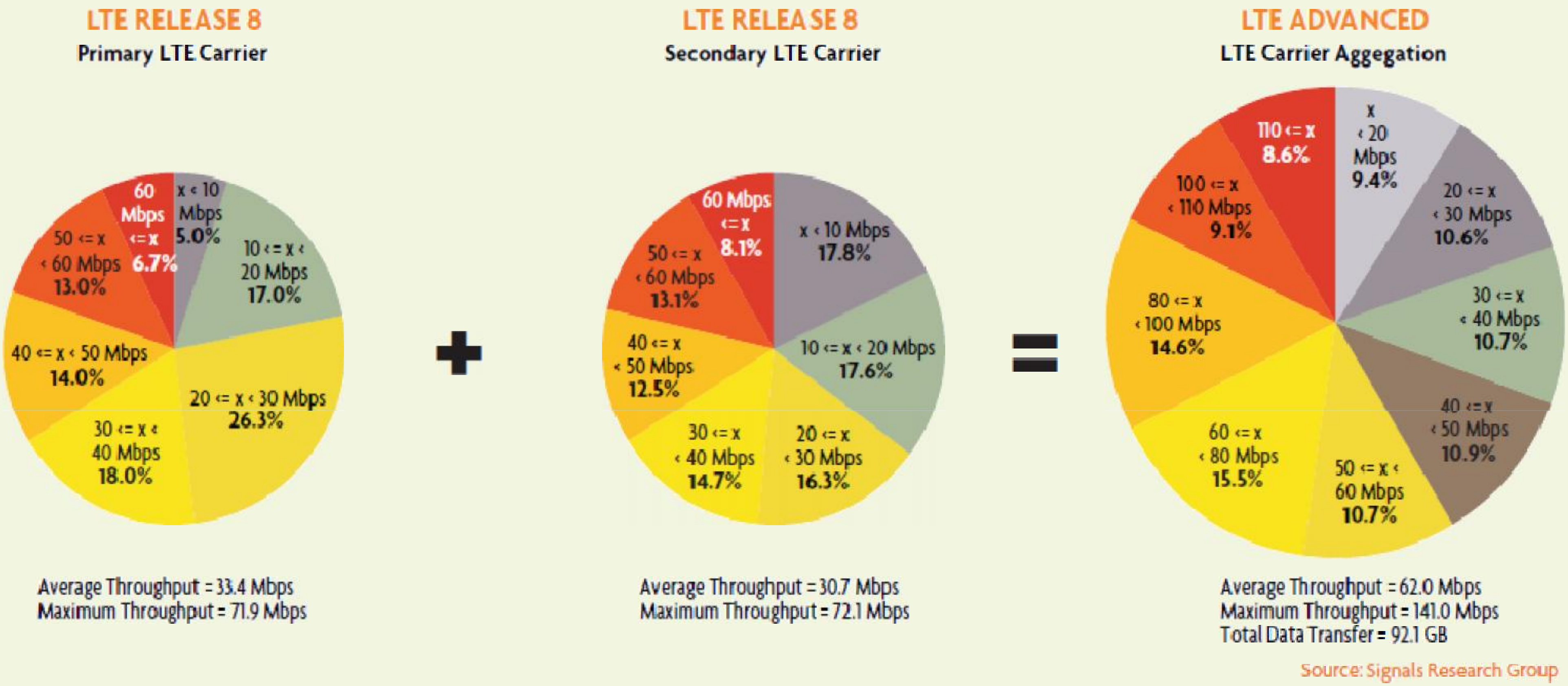
- CA_1C
  - Band 1 (FDD) 1920-1980 MHz/2110-2170 MHz supports 15 and 20 MHz
- CA_40C
  - Band 40 (TDD) 2300-2400 MHz supports 10, 15, and 20 MHz

Initial Bands Defined in Rel 10: Inter-band



- CA_1A_5A
  - Band 1 1920-1980/2110-2170 MHz supports 10 (5, 15, and 20 MHz FFS)
  - Band 5 824-849/869-894 MHz supports 10 (5 FFS)
- CA_3A_7A
  - Both bands (1710-1785/1805-1880 MHz and 2500-2570/2620-2690 MHz) supports 10, 15, and 20 MHz
- CA_4A_13A
  - Both bands (1710-1765/2110-2155 MHz and 777-787/746-756 MHz) support 10 MHz
- CA_4A_17A
  - Both bands (704-716/734-746 MHz) support 10 MHz

CA Downlink Throughput – Field Performance



- Statistics for over 100 GB of data collected in Gangnam District of Seoul, South Korea over 22 sq. km^2
- Average data rate: 62.0 Mbps; Peak data rate: 141.0 Mbps

Carrier Aggregation Sample Test Results*

Country	Operator	Max DL Speeds(Mbps)
Australia	Telstra (2x20 MHz, 1800/2600 MHz, Ericsson)	300
Australia	Optus (TD-LTE, 2x20 MHz, 2300 MHz, Huawei) (TD-LTE, 4x20 MHz, 2300 MHz, Huawei)	160 520
Austria	A1 Telekom Austria (NSN)	580
France	SFR (2x10 MHz, 800/2600 MHz, Ericsson)	174
China	China Mobile (TD-LTE, 2x20 MHz, ZTE)	233
Japan	NTT DOCOMO	300
Philippines	Smart Communications (Huawei)	211
Portugal	Optimus (Huawei)	300
Russia	Yota (Huawei)	300
South Africa	Telkom Mobile (TD-LTE, 2x20 MHz, 2300 MHz, Huawei)	200
South Korea	SK Telecom (2x10 MHz 800/1800 MHz, Samsung, Ericsson, NSN)	150
South Korea	LG U+ (2x10 MHz, 800/2100 MHz, Samsung, Ericsson, NSN)	150
South Korea	Korea Telecom (2x10 MHz, 900/1800 MHz, Samsung, Ericsson, NSN)	150
Turkey	Turkcell (Huawei)	900
UK	EE (2x20 MHz, 1800/2600 MHz)	300
US	Clearwire (TD-LTE: Triband 800/1900/2500, NSN) (Single band 120 MHz, 2500 MHz, NSN)	1300 2600

Commercial

* Headline news – peak rate.

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Carrier Aggregation Example: Sprint Spark

Devices

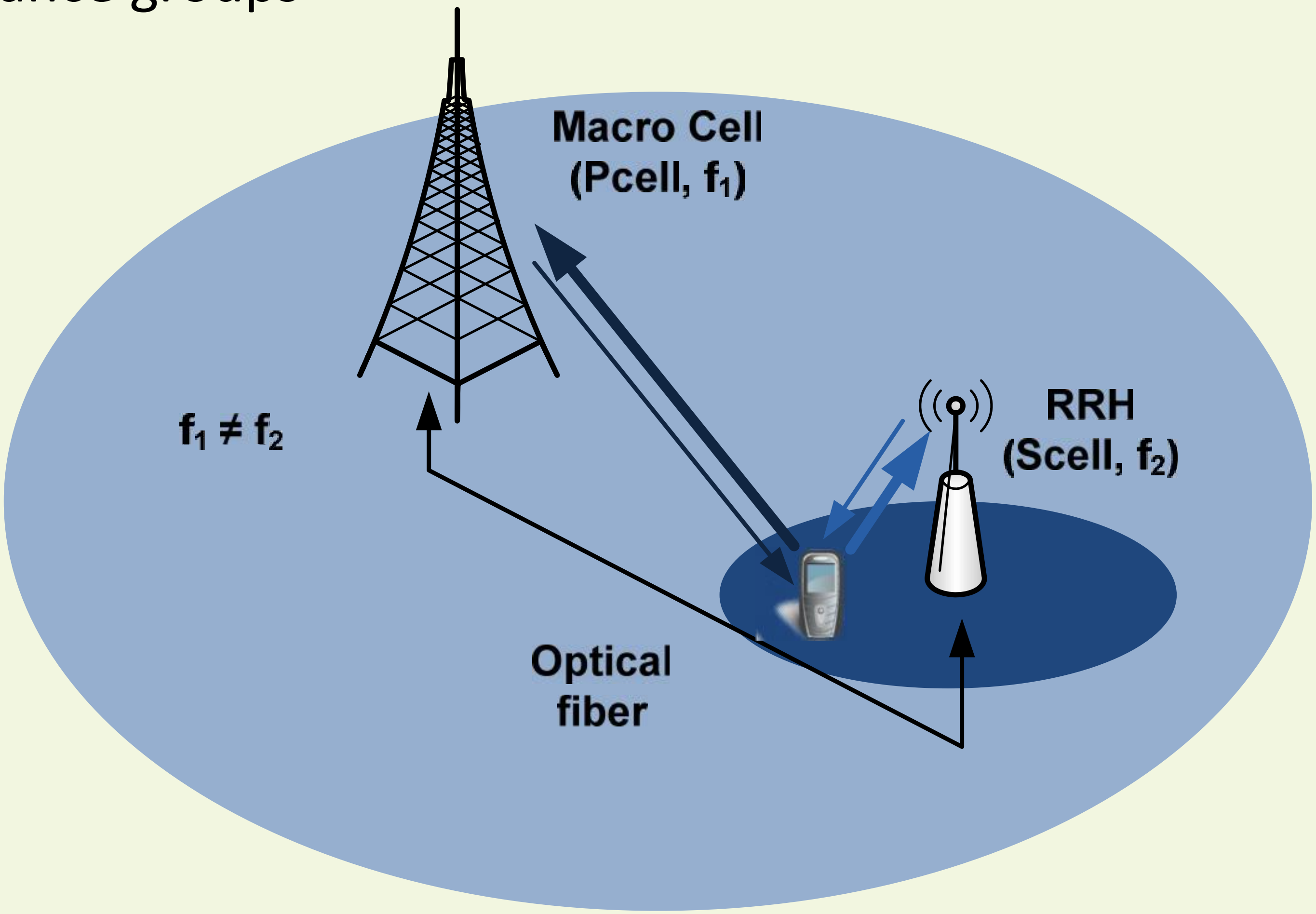
- LG G Flex
- NETGEAR LTE Gateway 6100D
- HTC One Max
- Samsung Galaxy S4 (Sprint Spark support added via product refresh)
- Samsung Galaxy S4 mini (Sprint Spark support expected via update)
- Samsung Galaxy Mega™ (Sprint Spark support expected via update)
- Google Nexus 5 (Sprint Spark support expected via update)
- The LG G2 (Sprint Spark support expected via update)
- Netgear Zing Mobile Hotspot
- Netgear 341U USB Modem
- MiFi 500 LTE by Novatel Wireless

Network

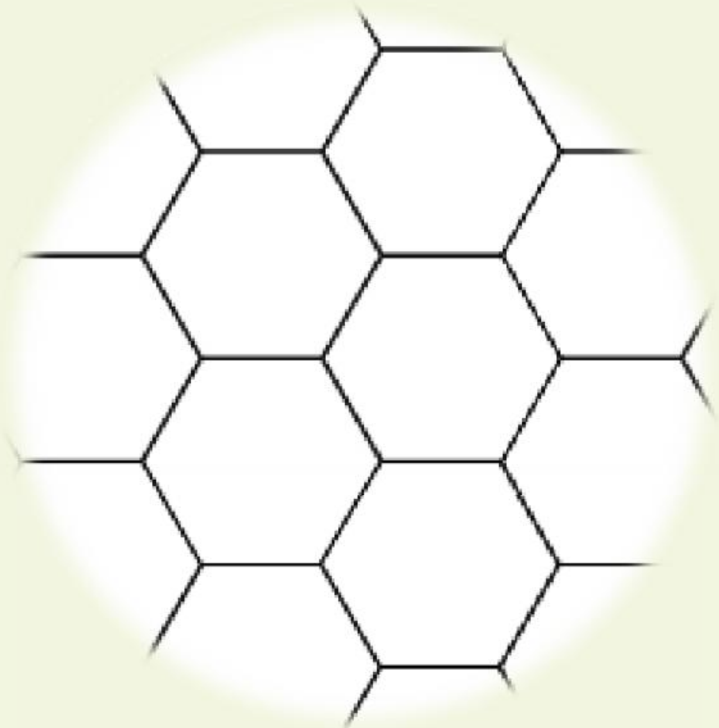
- Combines 800 MHz, 1.9 GHz and 2.5 GHz
- Top 100 U.S. markets during the next three years
  - Launched in 14 markets, including: Philadelphia, Baltimore, Kansas City, New York, Los Angeles, Chicago, Miami, and Tampa
- Advertised peak speed of 50-60 Mbps with up to 150-180 Mbps 'real-world' speed in 2 years

Future Improvements

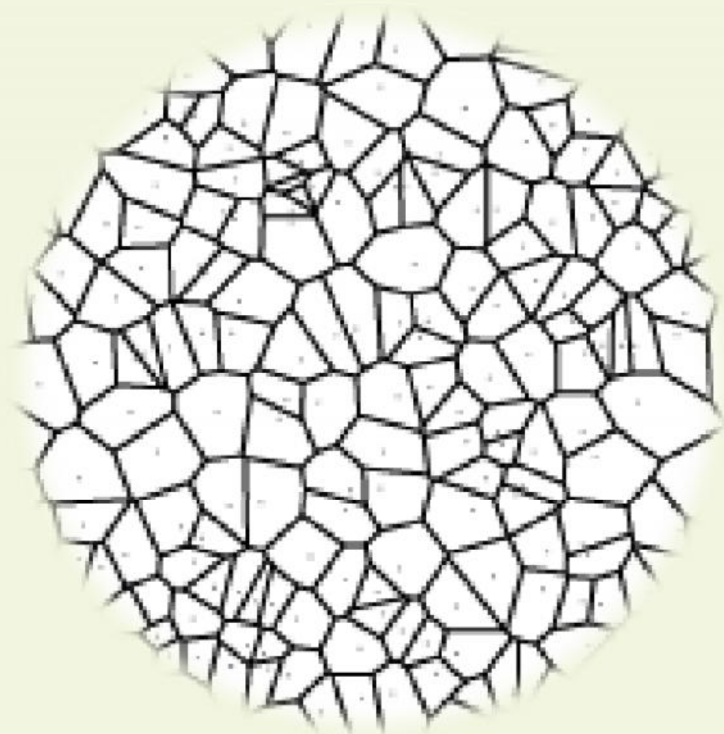
- Uplink carrier aggregation
  - Timing advance groups



Feature 2: Network Densification - HetNets



Capacity ∝ *M* macro cells



Capacity ∝ *M* + *n* small cells

Small cells increase cell edge area

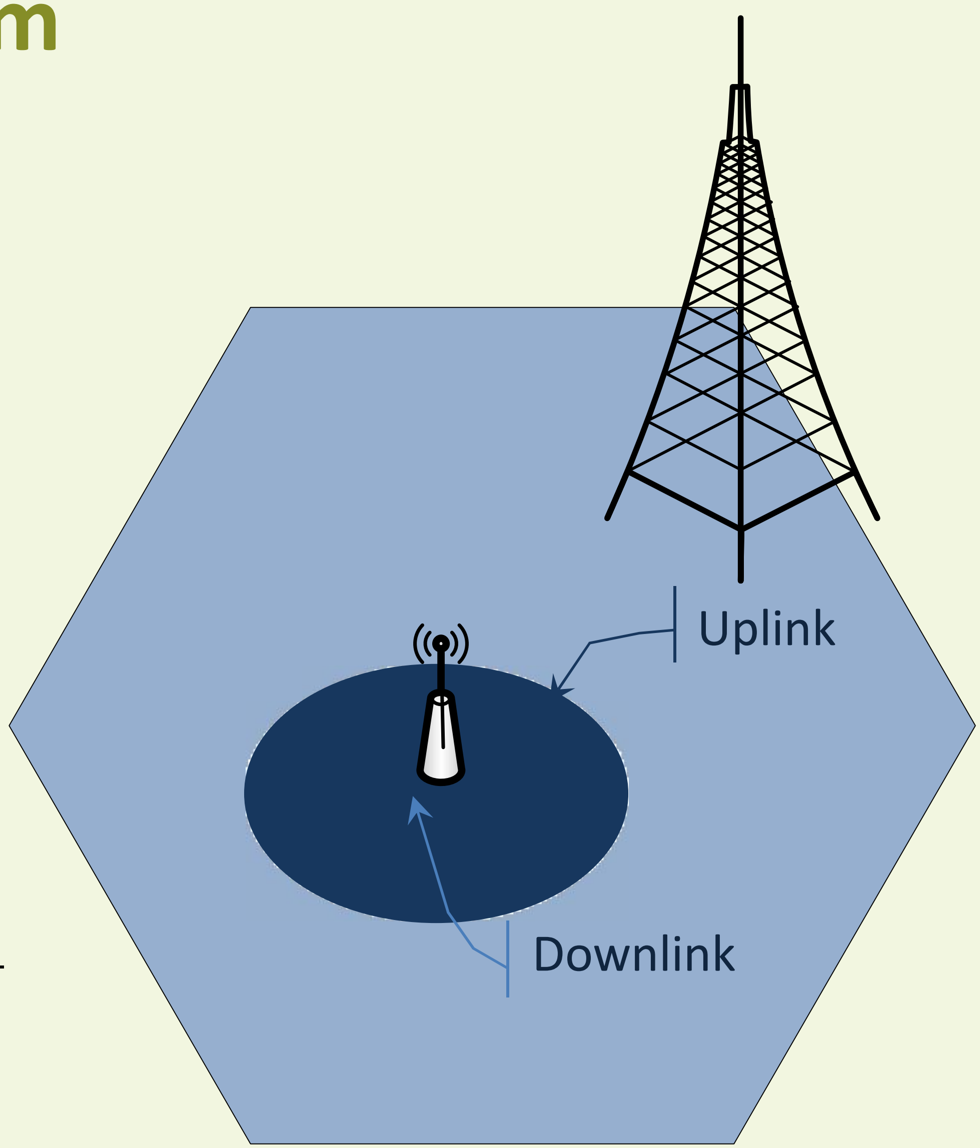
Cell Edge Area Problem

Macro cell

RF Power	=	40 dBm
Antenna Gain	=	16 dBi

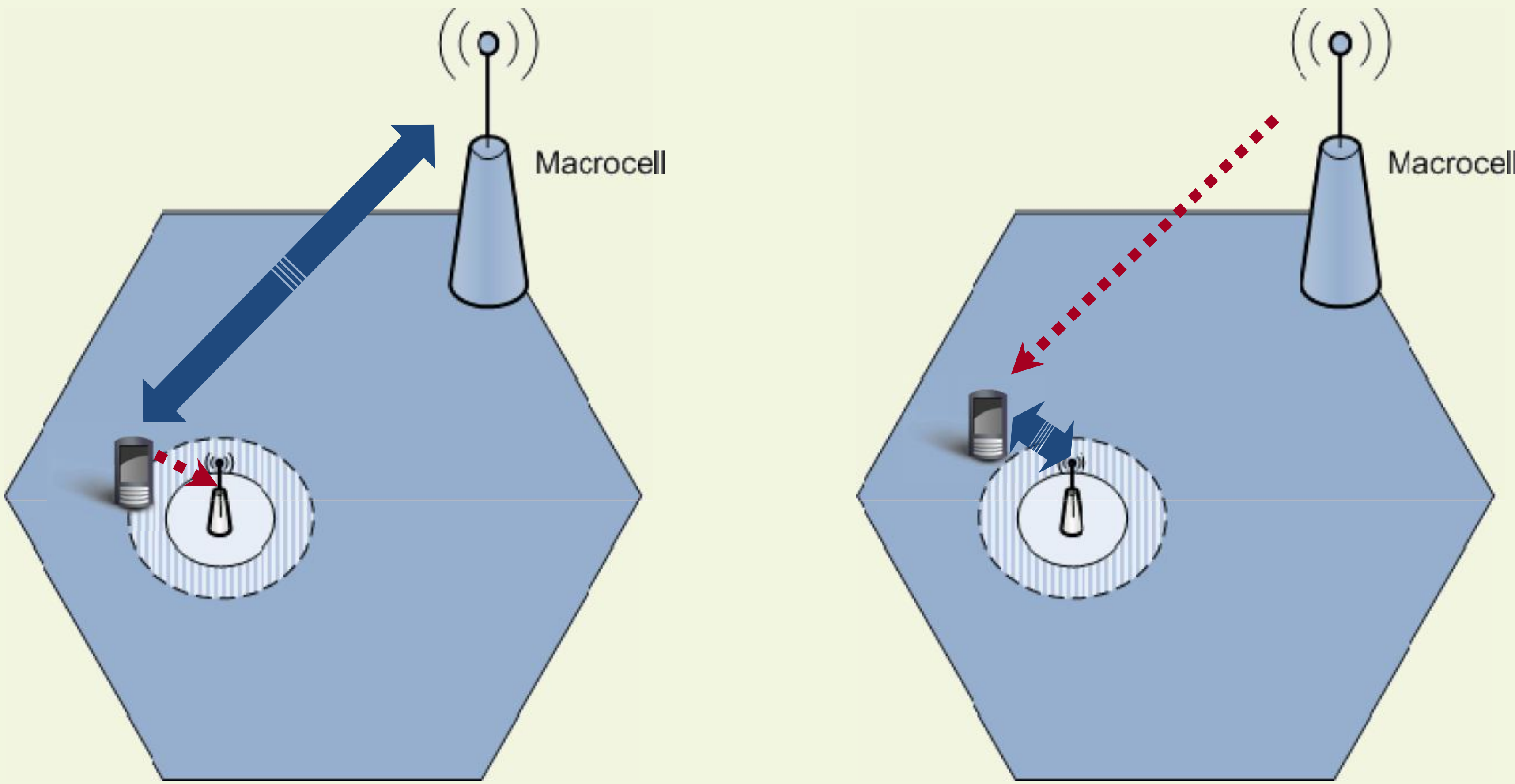
Small cell

RF Power	=	30 dBm
Antenna Gain	=	6 dBi
D		**20 dB** (x100)



1- Uplink interference to small cell (very damaging)
2- Downlink interference to small cell edge subscribers

Interference in Small Cell Deployments



Uplink Co-Channel Interference

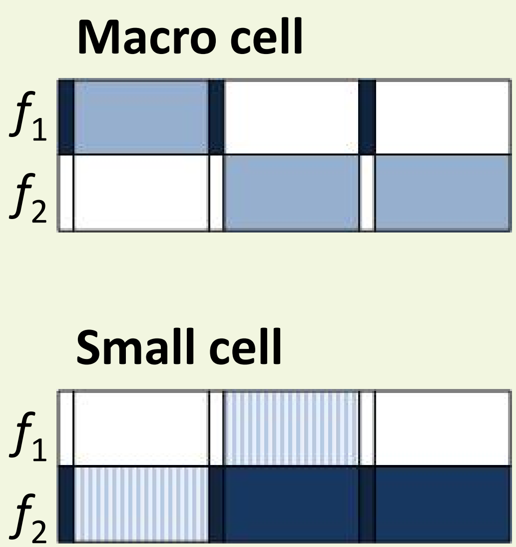
Downlink Co-Channel Interference

Direction of Interference

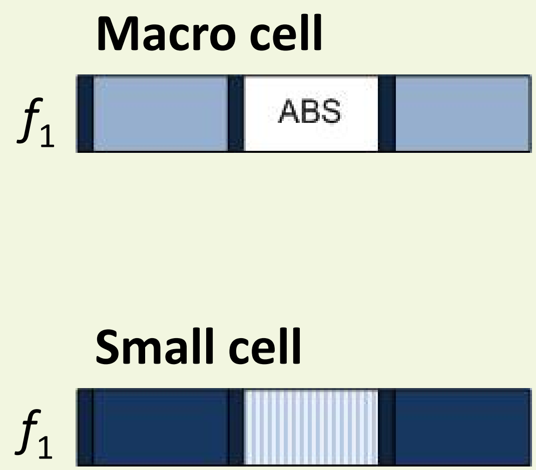
Communication Link

Enhanced Intercell Interference Coordination

Carrier Aggregation



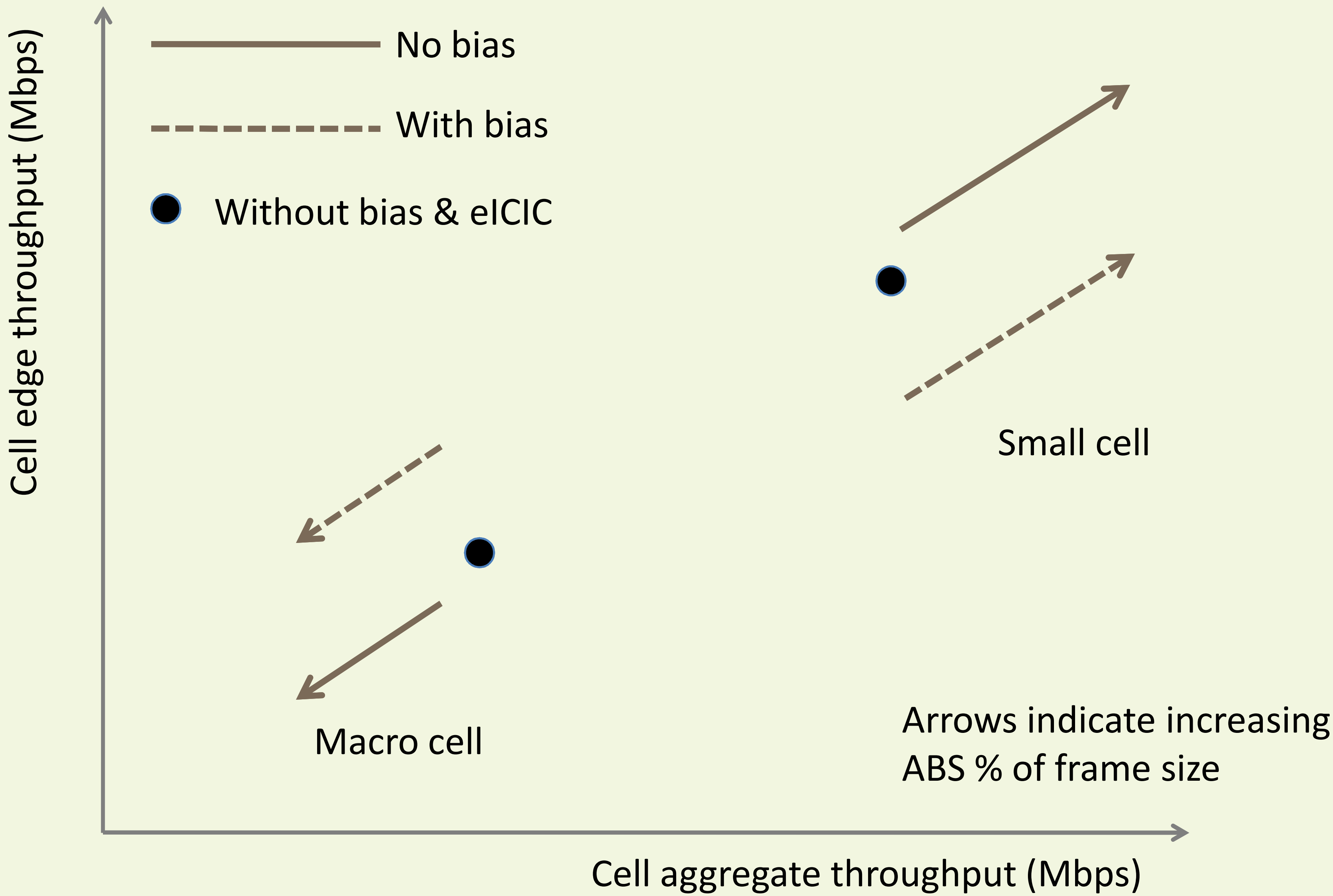
Almost Blank Sub-frames



Macro cell data | Small cell data – cell edge | Small cell data – cell center

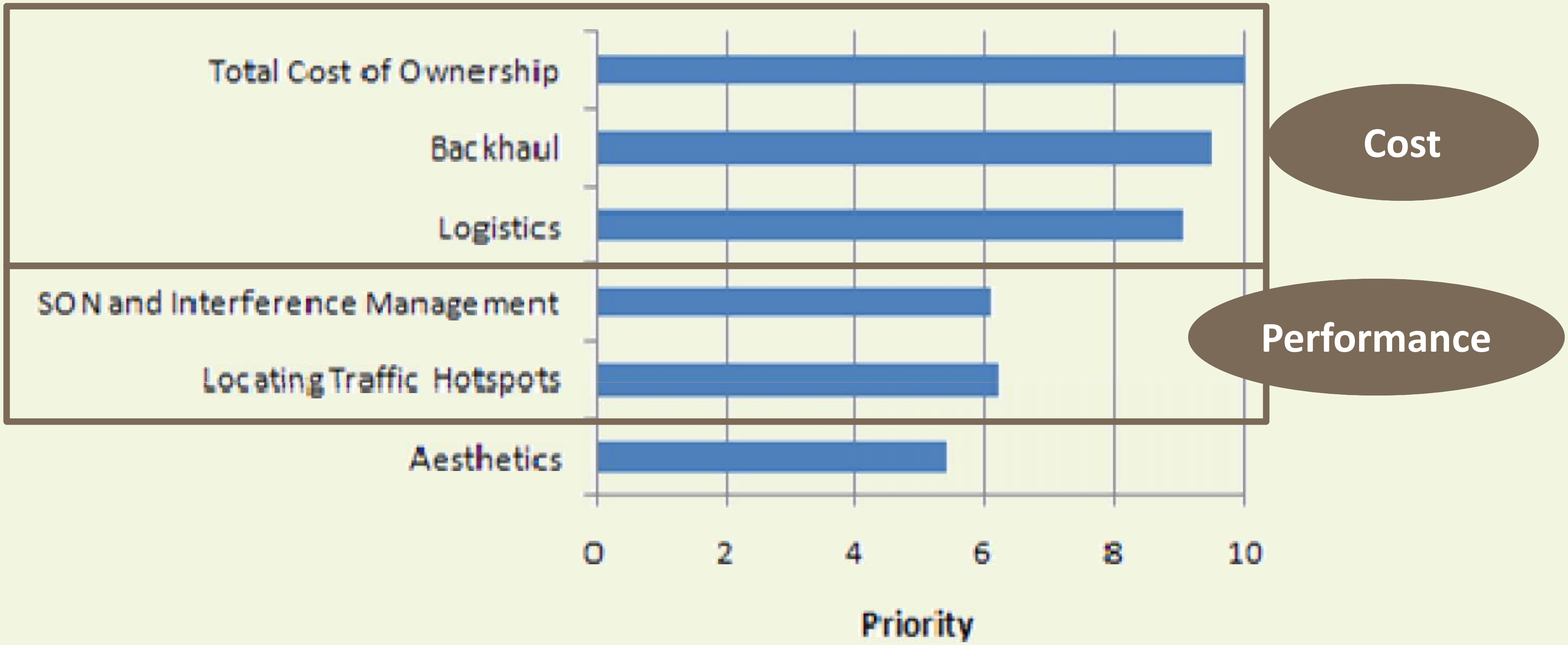
eICIC = Enhanced intercell interference coordination

Performance of ABS eICIC



Bias ≡ Range Expansion (RE)

Top Challenges to Small Cell Deployments: Operator Survey



Top challenge to small cell deployments is cost

Source: [Small Cell New Order, ExelixisNet & Xona Partners, October 2013]

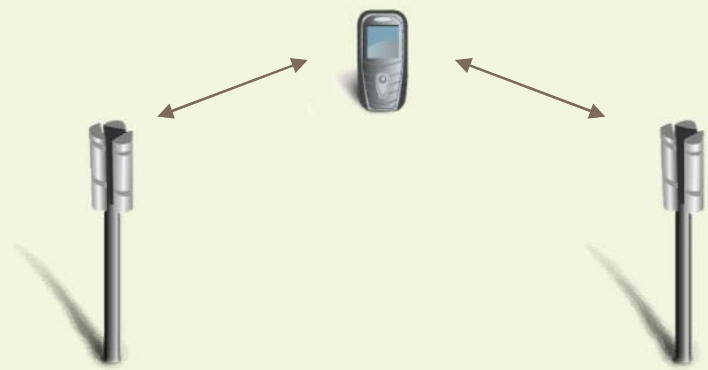
Future Improvements

- Greater efficiency can be achieved from having small cells and macro cells working in tighter coordination than eICIC mode
  - ABS reduces capacity on macro cell
    - Some interference on control signaling
  - Carrier aggregation reduces spectrum utilization
- Release 12: massive small cell deployments
  - Greater coordination of macro cell and small cell through ‘soft-cell concepts’
    - Separate user and control plane

Feature 3: Coordinated Multipoint

- Communication between mobile device and multiple geographically distributed base station antennas
  - Specific techniques applied in
    - Downlink CoMP
    - Uplink CoMP
    - FDD Systems
    - TDD Systems
- Benefits
  - Improves cell edge performance
  - Improves average cell performance

Joint transmission: DL/UL cooperative MIMO; Joint processing of received signals



Coordinated Multiple Point Transmission and Reception (CoMP)

Uplink CoMP

- Channel information available at base station without need of feedback transmission
- No modifications required for mobile handsets
  - Base station upgrade only
- Easier to implement than downlink CoMP

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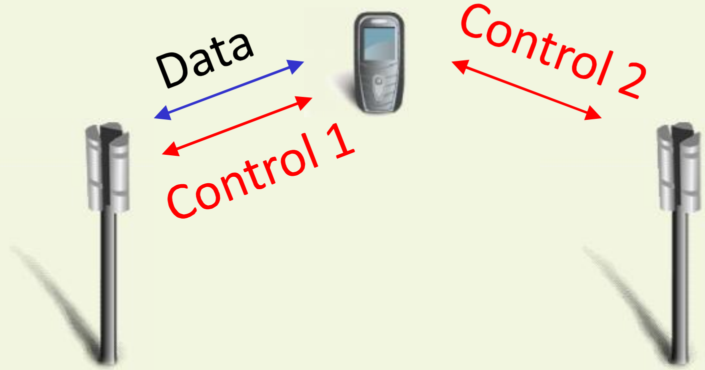
Types of UL CoMP

- Interference-aware detection
  - No cooperation between base stations is necessary
  - Base station estimates links to interfering mobiles when calculating receiver filters
- Joint multicell scheduling, interference prediction, or multicell link adaptation
  - Requires exchange of channel information and/or scheduling decisions over X2 interface between base stations
- Joint multicell signal processing
  - Several degrees of freedom exist in the way signals from mobiles are decoded, either in centralized or decentralized way and to which extent the signals are pre-processed before information exchanged between base stations

Downlink CoMP Techniques: CB/CS

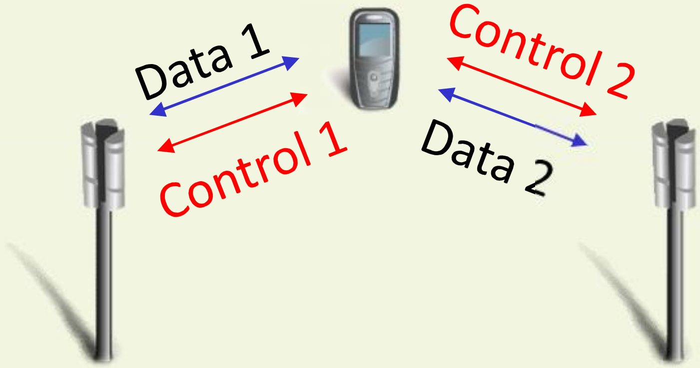
- Coordinated Beam Forming/Scheduling (CB/CS)
  - Data transmission over one radio path
  - Channel information from multiple paths
  - Data for single mobile device is only available at a serving cell and transmitted from the serving cell
  - Scheduling/weight decision are made in coordinated fashion among cooperating points
  - Intelligently mitigate destructive inter-cell interference



Downlink CoMP: Coordinated Beamforming/Scheduling

Downlink CoMP Techniques: JP/T

- Joint Processing/Transmission (JP/T)
  - Data transmission over multiple radio paths
    - Transmission is simultaneous from "CoMP transmission points"
  - Channel information from multiple paths
  - Turns destructive inter-cell interference (ICI) into a constructive signal among neighboring cells
  - Acts like soft handover, SHO (in 3G systems)
  - Provides MIMO transmission/reception from geographically distributed antennas
  - Also called Network MIMO



Downlink CoMP: Joint Processing/Transmission

DL CoMP Performance (FDD)

		Scenario 1		Scenario 2 (9 cell cluster)	
		X-Pol	ULA	X-Pol	ULA
Downlink CS/CB, SU MIMO 2x2	Cell Average	3.67%	5.15%	1.46%	4.03%
	Cell Edge	9.63%	11.64%	2.86%	4.42%
Downlink JT, MU MIMO 2x2	Cell Average	2.68%	12.68%	4.07%	13.53%
	Cell Edge	26.13%	36.68%	40.72%	40.5%
Uplink JR, SU MIMO 1x2	Cell Average	22.25%	12.15%	31.46%	13.90%
	Cell Edge	41.19%	22%	65.89%	32%

Note: Results are averages of simulations
ULA: Uniform linear array
X-Pol: Cross polarized antenna
For more data, see 3GPP TR 36.819

DL CoMP Performance (FDD) – Scenarios 3/4

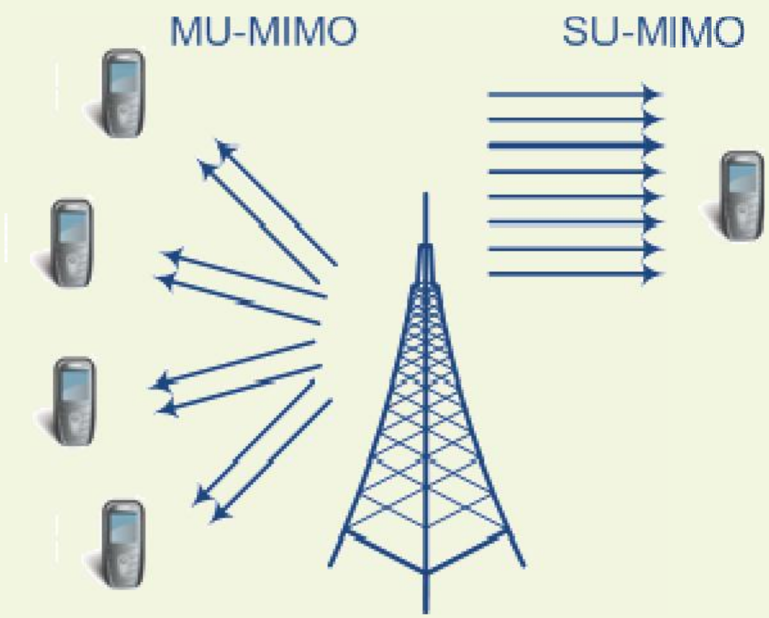
		CS/CB with eICIC	JP with eICIC	CS/CB without eICIC	JP without eICIC
Downlink	Macro cell area average	2.70%	3.30%	5.1%	3.0%
	5% Worst user	19.70%	52.80%	24.8%	24.1%

		JR without eICIC
Uplink JR, SU MIMO 1x2	Macro cell area average	13.5%
	5% Worst user	39.70%

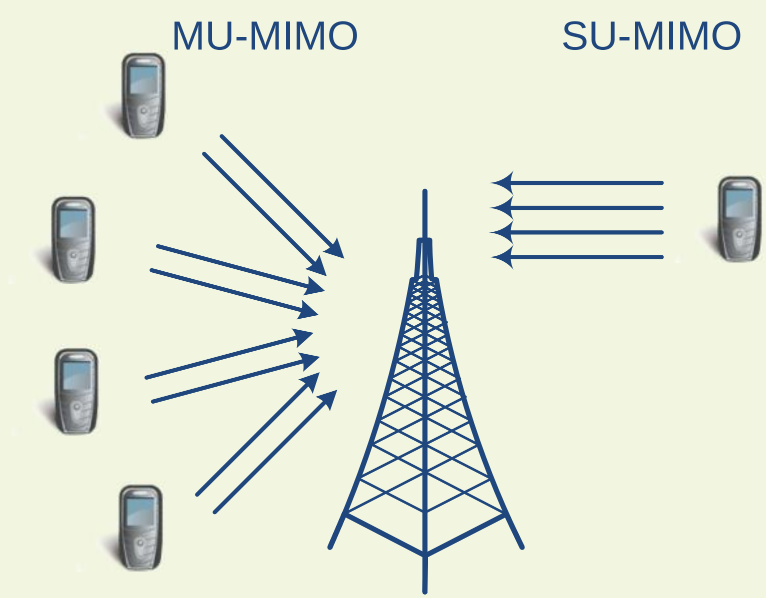
Note: Results are averages of simulations
For more data, see 3GPP TR 36.819

Feature 4: Enhanced MIMO

- Single user and multiple user in the downlink and uplink
- Increased Tx antennas to 8 and Rx antennas to 4
- Introduced new transmission mode to support multi-user MIMO

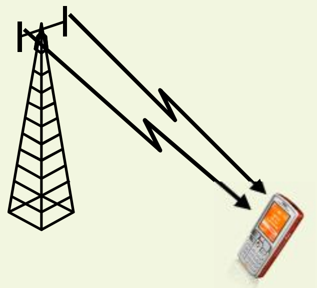


Downlink

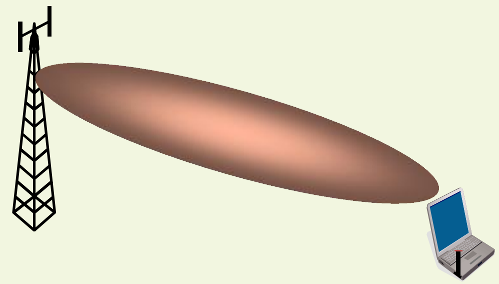


Uplink

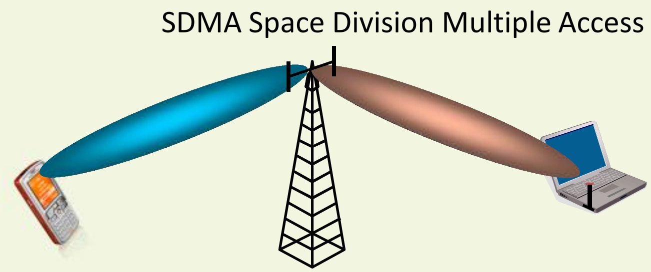
Multi-Antenna Transmission Techniques



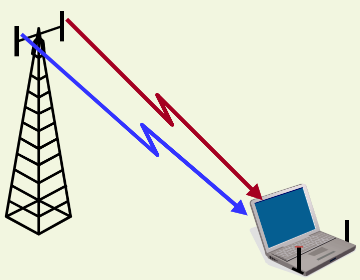
Diversity for improved system peformance



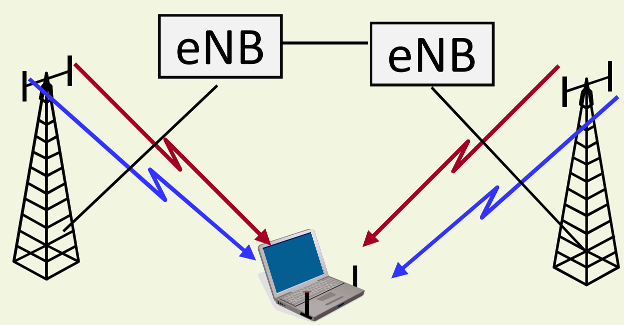
Beam-forming for improved coverage



SDMA for improved capacity (more users per cell)



Multi-layer transmisson (”MIMO”)
for higher data rates in a given bandwidth



Coordinated Multipoint (CoMP)
joint tx for higher data rates (Rel 10)

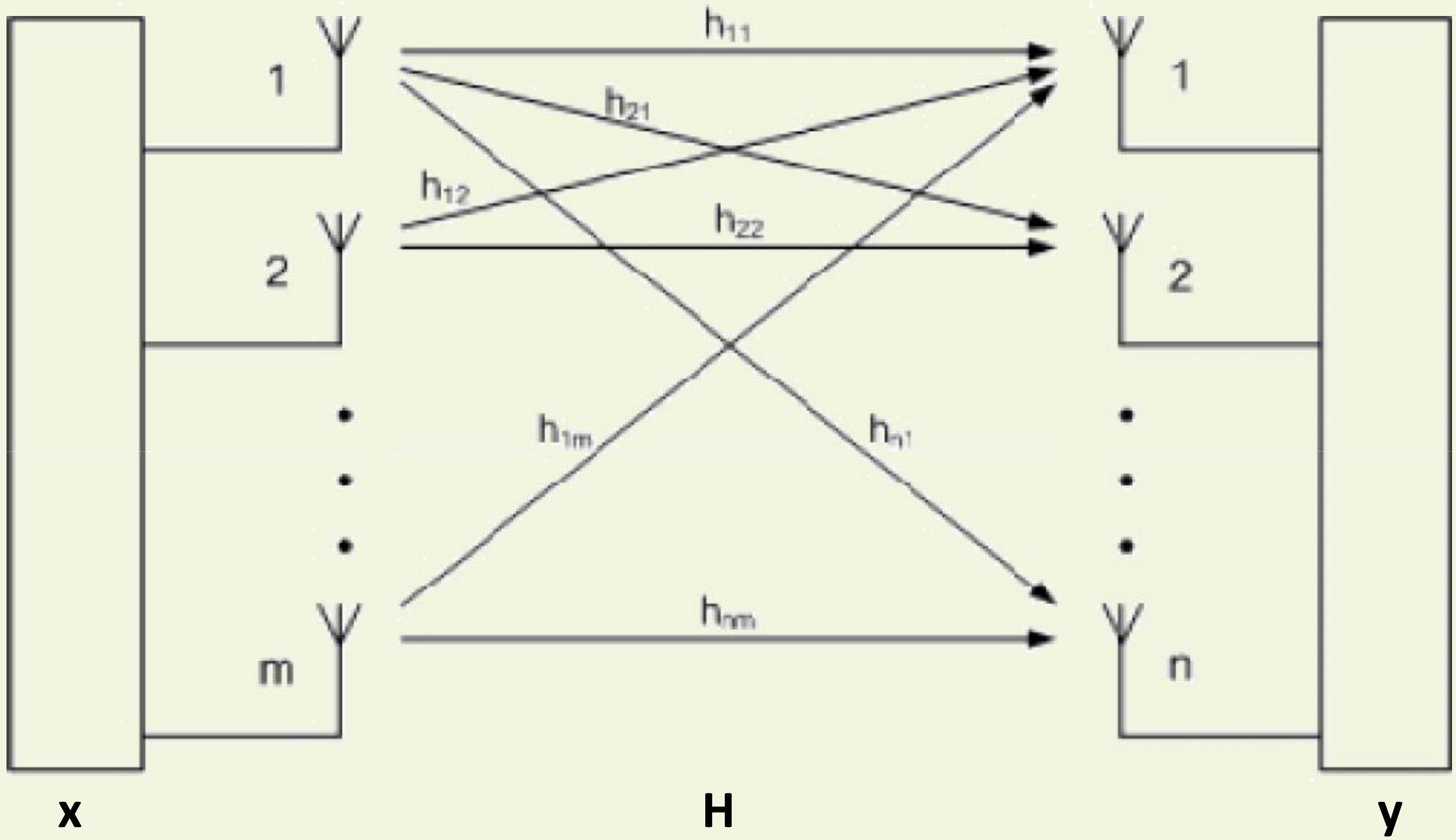
MIMO Enhancements From Rel 8 to Rel 10

Release 8	Release 10
4 Antennas in Downlink	8 Antennas in Downlink
1 Antenna in Uplink	4 Antennas in Uplink
Single type of reference signals: cell-specific reference signals are not precoded	Two types of reference signals. DM-RS are precoded with the same precoding vector/matrix as the user data/control information
CSI measurement is based on cell-specific reference signals, which is also used for data demodulation	The CSI measurement is based on a set of newly designed CSI-RS signals (are low duty-cycle and low-density, and allow a higher reuse factor compared to cell-specific reference signals)
Finite set codebook for SU-MIMO	Non-codebook-based precoding schemes (benefits MU-MIMO)

MIMO Basics

m transmit antennas

n receive antennas



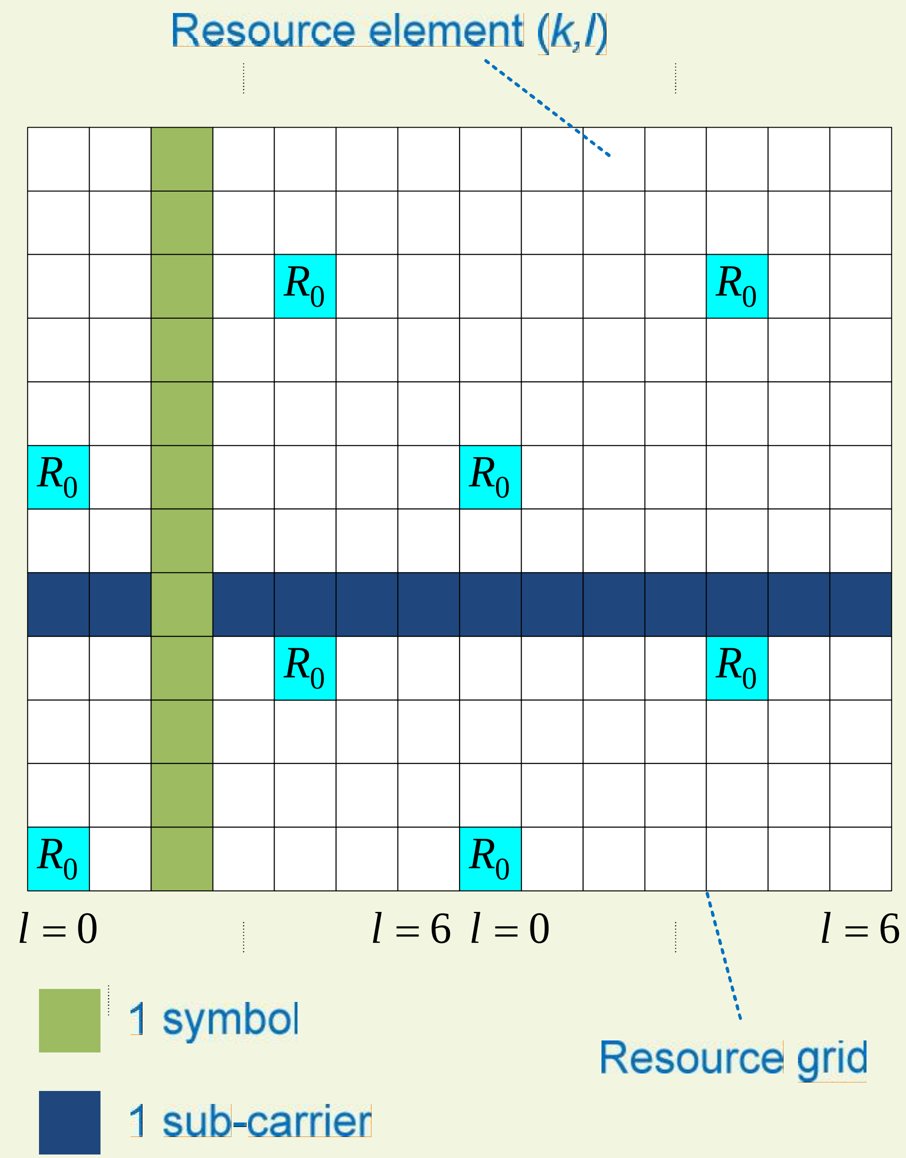
Time domain $$y_n(t) = \sum_{m=1}^{N_{Tx}} h_{nm}(t) * x_m(t) + n_n(t)$$

Frequency domain $$Y_n(\mu) = H_{nm}(\mu) X_m(\mu) + N_n(\mu)$$

Flat fading channel $$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

Cell-Specific Reference Signals (CRS)*: Rel 8, Downlink

- Used for
  - Cell search and initial acquisition
  - DL channel estimation for coherent demodulation/detection at the mobile
  - DL channel quality measurements
- 16.7% overhead, duty cycle: every subframe (4 antennas)



How to reduce reference signal overhead with greater number of antennas?

* Sometimes also called "Common Reference Signals"

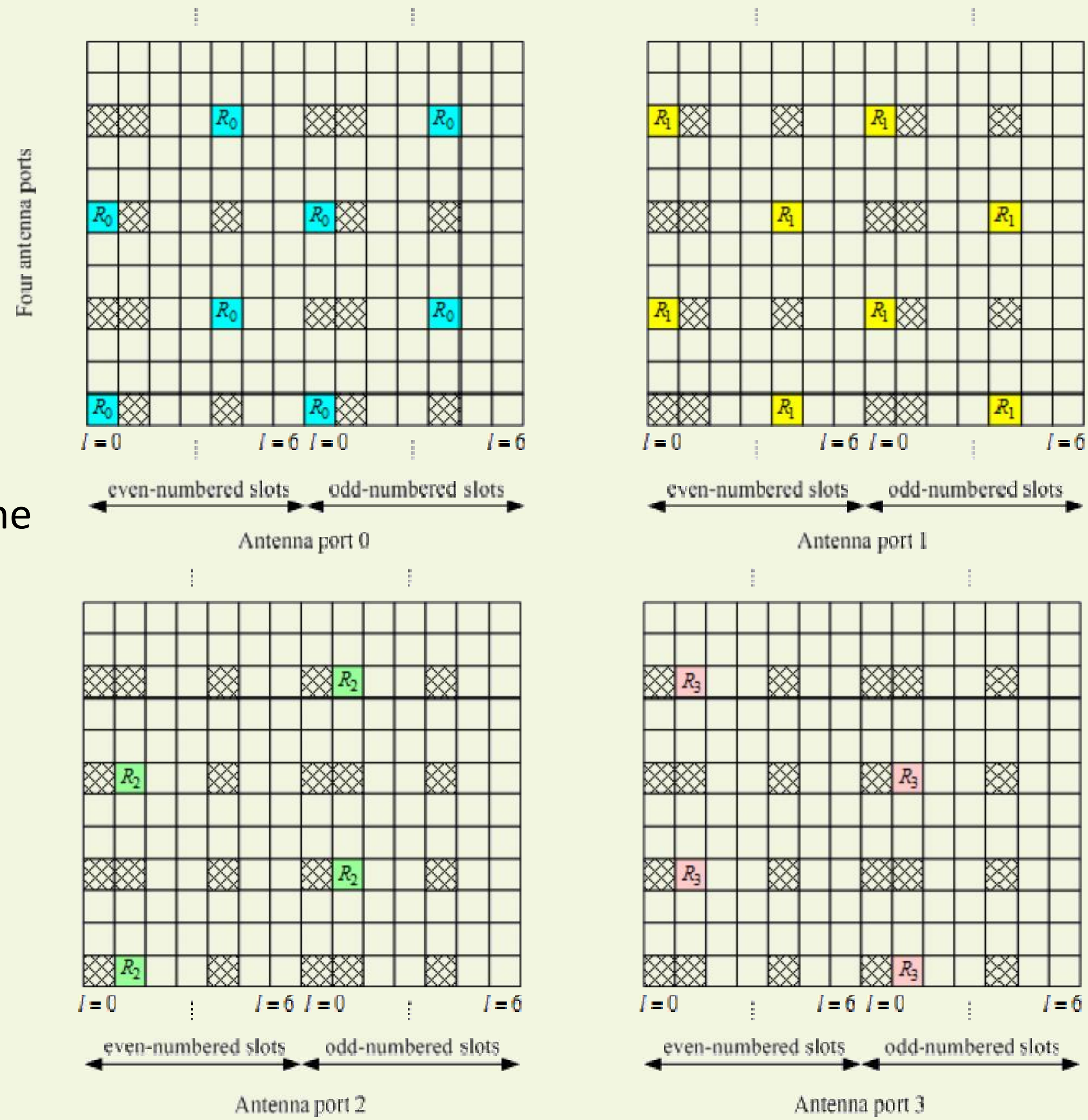
Why Separate Reference Signals

Ports 0 & 1:
8 RE/RB

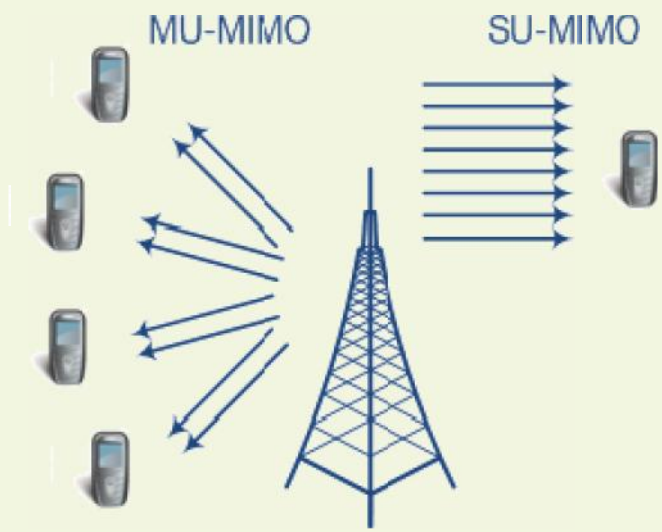
14.2% overhead,
Duty cycle: every subframe

Ports 2 & 3:
4 RE/RB

Ports 2 & 3 have a reduced set of RS pilots: Trade off between performance and efficiency



Reference Signals Separated in Rel 10



Reference Signal overhead becomes a challenge in Rel 10 with configurations of up to 8x8. The solution is to decouple CRS

Common Reference Signal (CRS) of Rel 8

Channel State Information Reference Signals (CSI-RS): 5.6% overhead /subframe*	Demodulation Reference Signals (DM-RS)
Not precoded	Precoding identical to data channel
Sparse in frequency and time	Included in every sub frame

* Duty cycle between 5 and 20 subframes

DL MIMO Transmission Modes

MIMO Transmission Mode (TM)	Data Channel Transmission	UE Feedback	Release
TM 1	Single antenna port	CQI	8
TM 2	Transmit diversity	CQI	
TM 3	Open-loop (OL) spatial multiplexing	CQI, RI	
TM 4	Closed-loop (CL) spatial multiplexing	CQI, RI, PMI	
TM 5	MU-MIMO (Space Division Multiple Access)	CQI, PMI	
TM 6	CL with Rank 1 (Precoding)	CQI, PMI	
TM 7	Beamforming with single antenna (port 5) (based on DRS open loop & non-codebook based)	CQI	
TM 8	Dual-layer beamforming	CQI, RI, PMI	9
TM 9	Seamless switching between SU-MIMO and MU-MIMO up to Rank 8	CQI, RI, PMI	10
TM10	TM9 + CoMP	CQI, RI, PMI	11

Rel 10

Rel 11

LTE-A

Transmission Mode 9 (TM9)

SK Telecom has successfully demonstrated a core LTE-Advanced technology named Transmission Mode 9 (TM-9) under partnership with Ericsson... The results of the demonstration showed that TM-9 was able to increase data transmission rate of mobile devices by **10 to 15 percent** in areas of inter-cell interference.

(January 2013)

- Seamless switching between SU-MIMO and MU-MIMO
- Up to 8 layers in SU and 4 layers in MU
- Up to 2 codewords / UE
- Backward compatible
  - Up to 2 layers / UE
- Frequency selective PMI and precoding / sub-band

SU-MIMO & MU-MIMO

- Single User MIMO – SU-MIMO:
  - The multiple antennas at the terminal side may all be within a single user's terminal
  - This single user receives multiple streams of data, nearly multiplying the obtainable peak throughput by the number of antennas

- Multi-User MIMO – MU-MIMO
  - Multiple streams destined for multiple users
  - This multiplies the aggregate cell throughput by the number of antennas
  - Requires channel state information/precoding

SU-MIMO / MU-MIMO Comparison

	SU-MIMO	MU-MIMO
Advantages	• High user throughput • High peak data rates	• High system capacity • Full exploitation of multi-user diversity
Disadvantages	• Multiple transmit antennas at the base station are not fully exploited • Multi-user diversity is not fully exploited	• Degradation of peak data rates due to inter-user interference

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