Disruption Surrounds Us

Later this afternoon, I'm heading across the pond to the Blockchain/AI/IoT Expo in London.

On today's webinar with OutSystems, Mike Hughes asked me if any of these three technology trends promised to be the most disruptive in the coming years.

My answer: none of the above.

Which technology trend promises to dwarf all others with its disruptive ability?

The answer: 5G. It's time to start getting ready.

-- Jason Bloomberg

5G Wireless Network Architecture and Technologies

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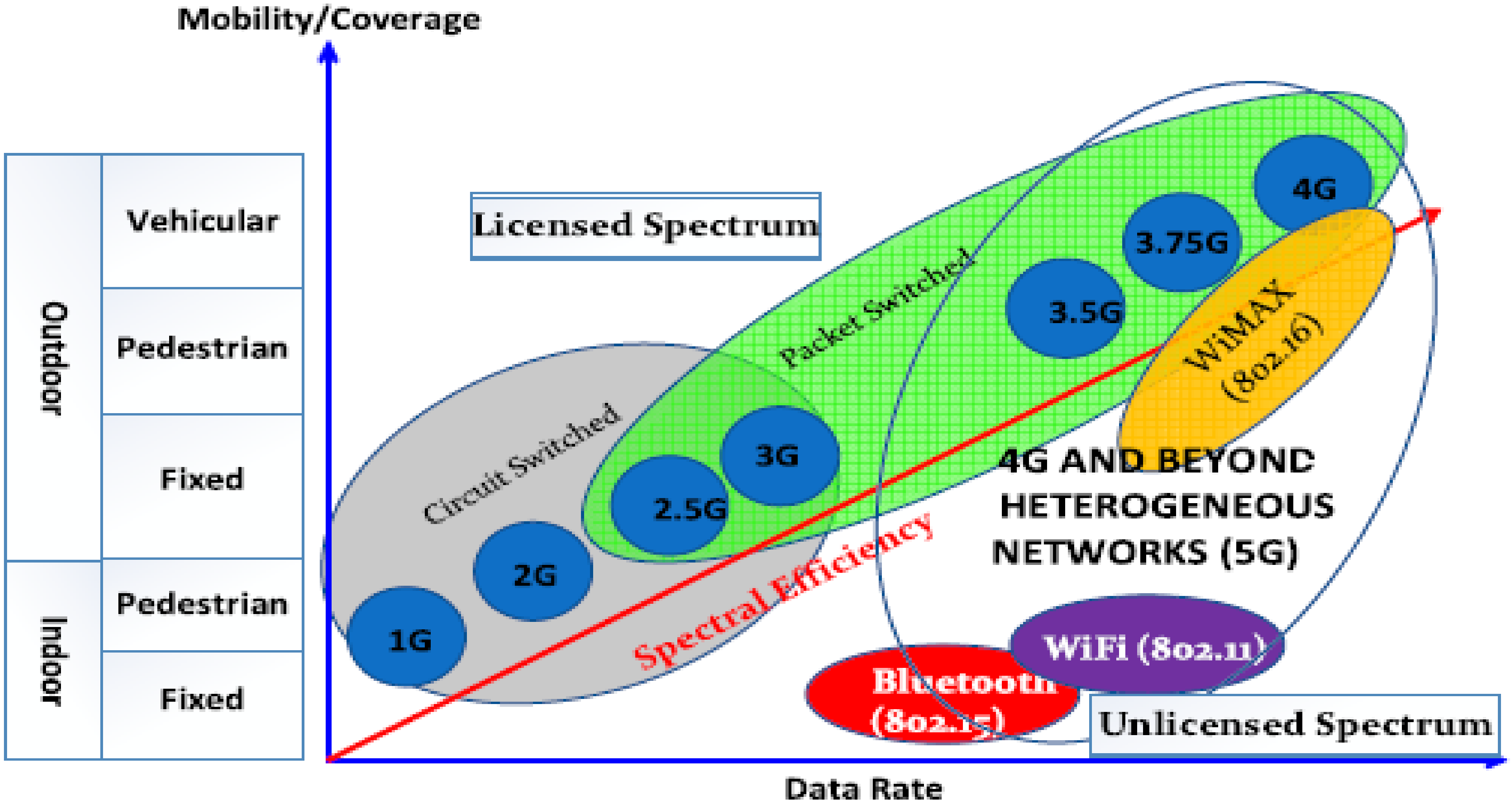


FIGURE 1. Evolution of wireless technologies.

1G – 1980’s, Data rate 2.4 kbps; major subscribers: AMPS, NMT, TACS

2G – late 1990’s, Data rate 64 kbps; GSM, SMS, CDMA (IS-95)

2.5G – 2000’s, data rate 144 kbps; use GPRS technology & 2G framework; EDGE (enhance data rate GSM), CDMA

3G – late 2000’s, data rate 2 Mbps; WCDMA, UMTS, HSUPA/HSDPA (high speed uplink packet access/high speed downlink packet access)

3.5G – early 2010’s; Evolution data optimised (EDO) between 3G-4G improved data rate 5-30Mbps.

3.75G – LTE and fixed worldwide Interoperability with Microwave access (WIMAX), better coverage and improved performance with less cost

4G – 3GPP for combined LTE and WIMAX to LTE Advanced for Multimedia messaging service (MMS), digital video broadcasting (DVB), high definition TV and mobile TV, data rate of 100 Mbps, MIMO antennas

4.5G – 2016, data rate of 500 Mbps+

5G – 2020, 1Gbps to 10Gbps and base station of 50 Gbps, Beam Division multiple Access (BDMA) and Filter Bank Multi-Carrier (FBMC); with current OFDM and massive MIMO (> 4 input and 4 output antennas)

TABLE [illegible]. Evolution of wireless technologies.

Generations	Access Technology	Data Rate	Frequency Band	Bandwidth	Forward Error Correction	Switching	Applications
1G	Advanced Mobile Phone Service (AMPS) (Frequency Division Multiple Access (FDMA))	2.4 kbps	800 MHz	30 KHz	NA	Circuit	Voice
2G	Global Systems for Mobile communications (GSM) (Time Division Multiple Access (TDMA))	10 kbps	850/900/1800/1900 MHz	200 KHz	NA	Circuit	Voice + Data
	Code Division Multiple Access (CDMA)	10 kbps		1.25 MHz			
2.5G	General Packet Radio Service (GPRS)	50 kbps		200 KHz		Circuit/ Packet	
	Enhanced Data Rate for GSM Evolution (EDGE)	200 kbps		200 KHz			
3G	Wideband Code Division Multiple Access (WCDMA) / Universal Mobile Telecommunications Systems (UMTS)	384 kbps	800/850/900/ 1800/1900/ 2100 MHz	5 MHz	Turbo Codes	Circuit/ Packet	Voice + Data + Video calling
	Code Division Multiple Access (CDMA) 2000	384 kbps		1.25 MHz		Circuit/ Packet	
3.5G	High Speed Uplink / Downlink Packet Access (HSUPA / HSDPA)	5-30 Mbps		5 MHz		Packet	
	Evolution-Data Optimized (EVDO)	5-30 Mbps		1.25 MHz		Packet	
[illegible]5G	Long Term Evolution (LTE) (Orthogonal / Single Carrier Frequency Division Multiple Access) (OFDMA / SC-FDMA)	100-200 Mbps	1.8GHz, 2.6GHz	1.4MHz to 20 MHz	Concatenated codes	Packet	Online gaming + High Definition Television
	Worldwide Interoperability for Microwave Access (WIMAX)(Scalable Orthogonal Frequency Division Multiple Access(SOFDMA)) — Fixed WIMAX	100-200 Mbps	3.5GHz and 5.8GHz initially	3.5MHz and 7MHz in 3.5GHz band; 10MHz in 5.8GHz band			
4G	Long Term Evolution Advanced (LTE-A) (Orthogonal / Single Carrier Frequency Division Multiple Access) (OFDMA / SC-FDMA)	DL 3Gbps UL 1.5Gbps	1.8GHz, 2.6GHz	1.4MHz to 20 MHz	Turbo codes	Packet	Online gaming + High Definition Television
	Worldwide Interoperability for Microwave Access (WIMAX)(Scalable Orthogonal Frequency Division Multiple Access(SOFDMA)) — Mobile WIMAX	100-200 Mbps	2.3GHz, 2.5GHz, and 3.5GHz initially	3.5MHz, 7MHz, 5MHz, 10MHz, and 8.75MHz initially			
5G	Beam Division Multiple Access (BDMA) and Non- and quasi-orthogonal or Filter Bank multi carrier (FBMC) multiple access	10-50 Gbps (expected)	1.8, 2.6 GHz and expected 30-300 GHz	60 GHz	Low Density Parity Check Codes (LDPC)	Packet	Ultra High definition video + Virtual Reality applications

Summary of comparison of all generations of Mobile cellular systems (1G-5G)

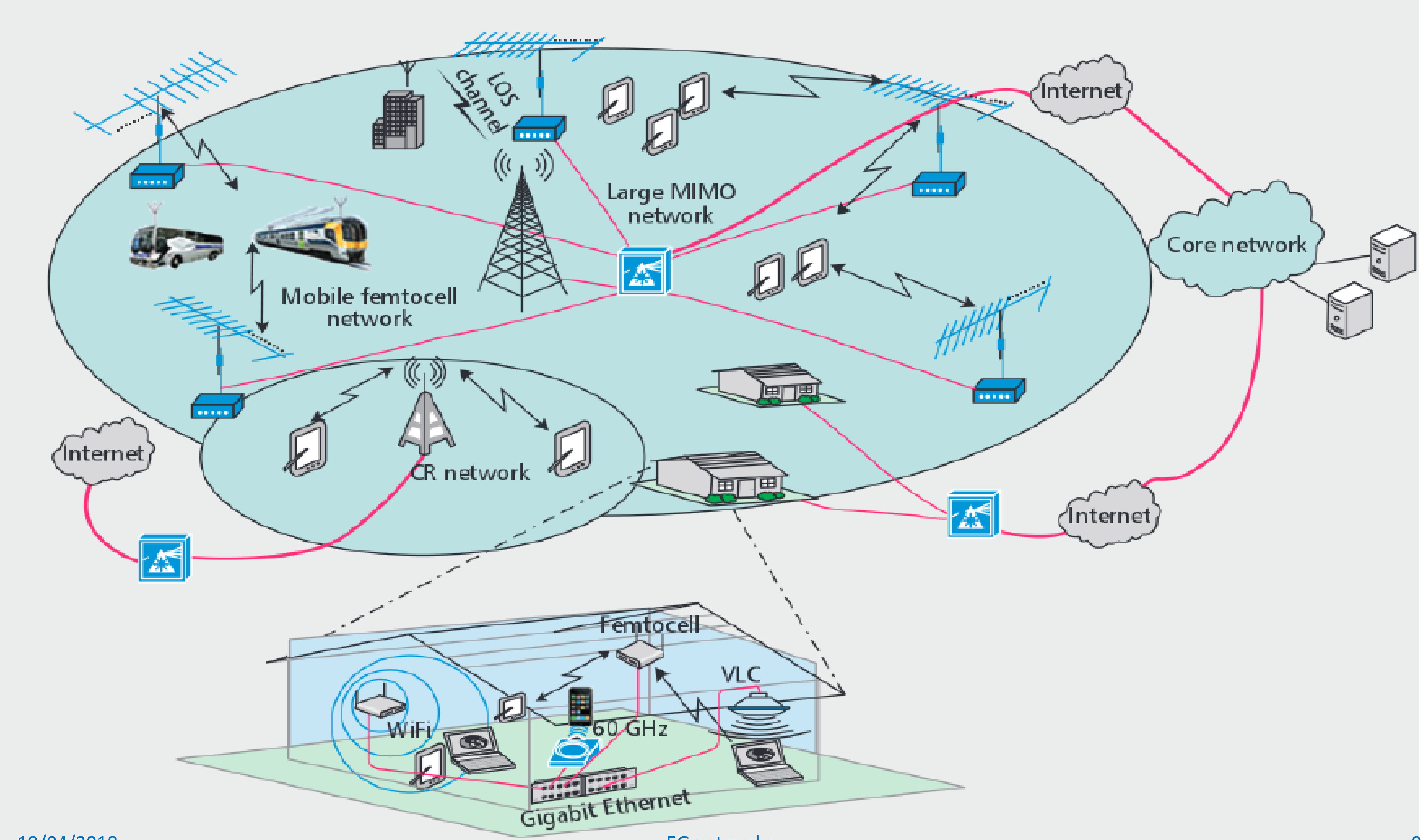
Generation	1G	2G	2.5G	3G	3.5G	4G	5G
Start	1970-1980	1990-2000	2001-2004	2004-2005	2006-2010	2011-Now	Soon (2020)
Data Bandwidth	2 Kbps	64 Kbps	144 Kbps	2 Mbps	More than 2 Mbps	1 Gbps	more than 1 Gbps
Technology	Analog Cellular	Digital Cellular	GPRS, EDGE, CDMA	CDMA 2000 (1xRT, EVDO) UMTS, EDGE	EDGE. Wi-Fi	WiMax LTE Wi-Fi	wwww
Service	Voice	Digital Voice, SMS,Higher Capacity Packet Size Data	SMS, MMS	Integrated High Quality Audio, Video & Data	Integrated High Quality Audio, Video & Data	Dynamic Information access, Wearable Devices	Dynamic Information access, Wearable Devices with AI Capabilities
Multiplexing	FDMA	TDMA, CDMA	CDMA	CDMA	CDMA	CDMA	CDMA
Switching	Circuit	Circuit, Packet	Packet	Packet	All Packet	All Packet	All Packet
Core Network	PSTN	PSTN	PSTN	Packet N/W	Internet	Internet	Internet
Handoff	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal & Vertical	Horizontal & Vertical

Talukdar R. And Saikia, M (2014), Evolution of Innovation in 5G communication systems…, arXiv1407.4335v1, 4 pages

TABLE 1. Technical comparison between recent 802.11 standards.

Technical Specifications	802.11an	802.11ac	802.11ad	802.11af
Frequency	2.4, 4.9, 5GHz	5 GHz	60 GHz	0.47-0.71 GHz
Modulation scheme	OFDM	OFDM	OFDM, single carrier, low-power single carrier	OFDM
Channel bandwidth	20, 40 MHz	20, 40, 80 MHz (160 MHz optional)	2 GHz	5, 10, 20, 40 MHz
Nominal data rate, single stream	Up to 150 Mbps (1x1, 40 MHz)	Up to 433 Mbps (1x1, 80 MHz) Up to 867 Mbps (1x1, 160 MHz)	4.6 Gbps	54 Mbps
Aggregate nominal data rate, multiple streams	Up to 600 Mbps (4x4, 40 MHz)	Up to 1.73 Gbps (4x4, 80 MHz) Up to 3.47 Gbps (4x4, 160 MHz)	7 Gbps	
Spectral Efficiency	15 bps/Hz (4x4, 40 MHz)	21.665 bps/Hz (4x4, 80 MHz)	1 bps/Hz (2GHz)	NA
EIRP	22-36 dBm	22-29 dBm	1-10dBm	16-20 dBm
Range	12-70 m indoor	12-35 m indoor	60 m indoor, 100m outdoor	< 100m indoor < 5km outdoor
Through Walls	Y	Y	Y	Y
Non-Line-of-Sight	Y	Y	Y	Y
World-Wide Availability	Y	Y (Limited in china)	Y	Y

Fig. 1. Advanced Heterogeneous Network Architecture



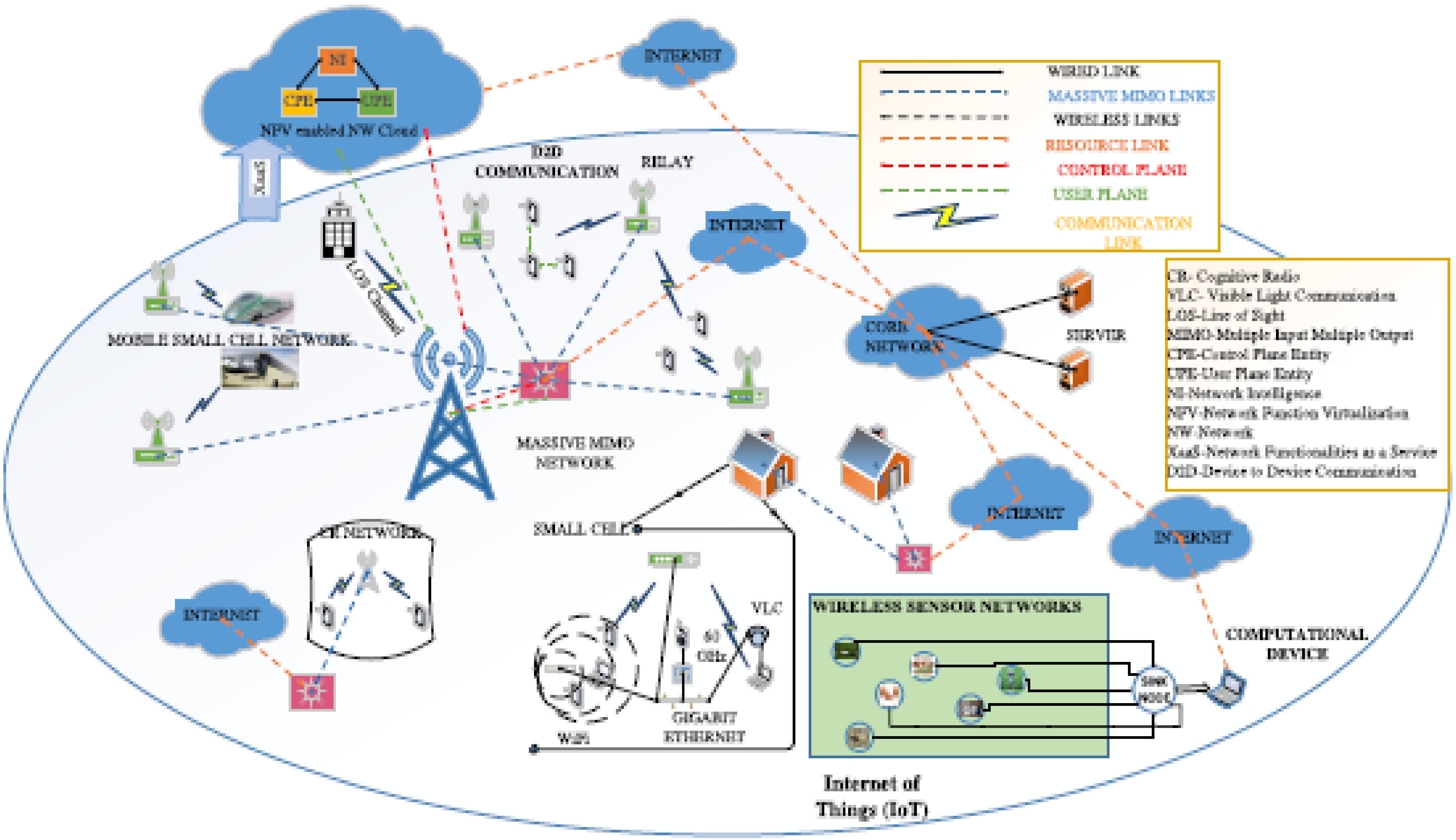


FIGURE 3. A general 5G cellular network architecture.

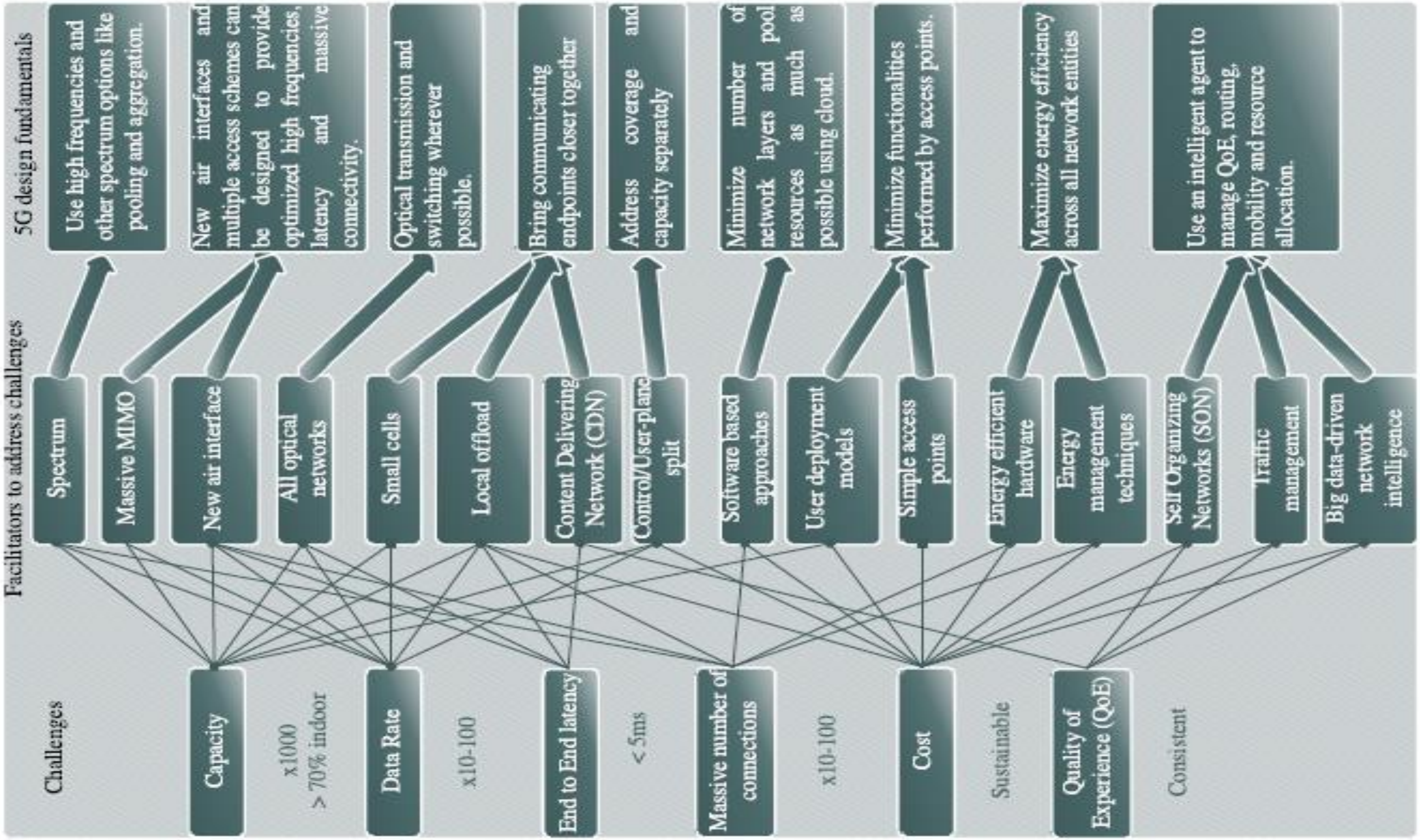


FIGURE 2. 5G challenge, facilitators, and design fundamental [20].

Concept of 5G technology (user instead of operator (3G) centric)

- The 5G terminals will have software defined radios and modulation scheme as well as new error-control schemes can be downloaded from the Internet on the run.
- The development is seen towards the user terminals as a focus of the 5G mobile networks
- The terminals will have access to different wireless technologies at the same time and the terminal should be able to combine different flows from different technologies.
- Each network will be responsible for handling user-mobility, while the terminal will make the final choice among different wireless/mobile access network providers for a given service.

Table 1
Key requirements and enabling solutions for 5G wireless networks.

Requirements	Specifications	Enabling solutions
High data rates	10 Gbps peak data rate; 100 Mbps cell edge data rate; Enhancing mobile broadband services.	Millimeter wave communications; Massive MIMO; Ultra-densification.
Reduced latency	1 ms end-to-end latency	D2D communications; Big data and mobile cloud computing.
Low energy	1000 times decrease in energy consumption per bit; Enhancing massive machine type communications.	Ultra-densification; D2D communications; Green communications.
High scalability	Accommodating 50 billion devices	Massive MIMO; Wireless software-defined networking; Mobile cloud computing.
High connectivity	Improving connectivity for cell edge users	Ultra-densification; D2D communications; Wireless software-defined networking.
High security	Standardization on authentication, authorization and accounting	Wireless software-defined networking; Big data and mobile cloud computing.

10 key enabling technologies for 5G networks

Ref: Akyildiz, I. F et al. (2016), “5G Roadmap- 10 key enabling technologies”, Computer Networks, vol 106, pp. 17-48.

TABLE 3. Small cell setup options and concern [20].

	Operator-setup	User-setup
Licensed Spectrum	*Positives* • Operator controlled Cell sites. • Easier to provide Quality of experience • Realization of advanced resource allocation (RA) techniques turn out to be easier *Negatives* • Increased cost based on equipment, setup and operation • Limited spectrum • Spectrum license fees *Concern* • Backhaul provisioning	*Positives* • Reduced cost based on equipment, setup and operation *Negatives* • For later service customer sustenance, added operational cost is required *Concern* • Monitoring issues • Public or private access control • Ensuring Quality of experience • Effect of various backhaul types on advanced resource allocation techniques • Provisioning of over the air security
Unlicensed spectrum	*Positives* • Operator controlled Cell sites • Operators have extra spectrum for exploitation *Negatives* • Increased cost based on equipment, setup and operation • Lack of Quality of experience agreements *Concern* • Mechanisms to guarantee impartial performance • Concurrence with Wi-Fi, Bluetooth, etc. • Backhaul provisioning	*Positives* • Reduced cost based on equipment, setup and operation *Negatives* • Lack of Quality of experience agreements *Concern* • Access control • Mechanisms to guarantee impartial performance • Concurrence with Wi-Fi, Bluetooth, etc. • Effect of various backhaul types on advanced resource allocation techniques • Provisioning of over-the-air security

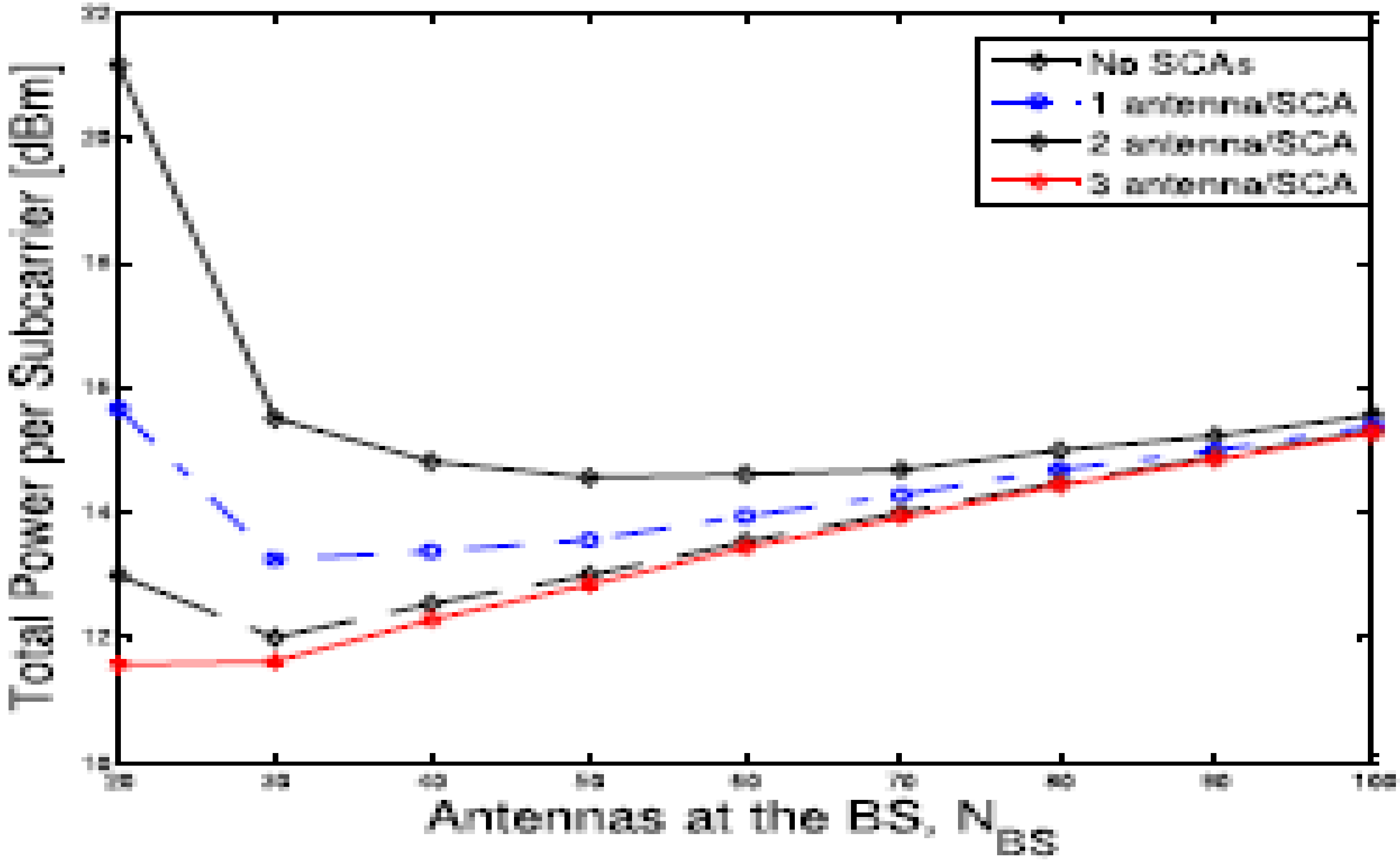


FIGURE 4. Average total power consumption in the scenario containing small cell access points.

TABLE 4. Effect of massive MIMO technology on energy efficiency of the wireless cellular network.

Reference	Objectives	Observations
[33]	Improving the cellular energy efficiency by densifying the network topology for higher spatial reuse by using two densification approaches, namely massive multiple input multiple output (MIMO) base stations and small cell access points.	By adding more hardware, power consumption can be considerably decreased, as the dynamic part is decreased, which results in less propagation losses and improved energy efficiency. Improvement in energy efficiency can be achieved by implementing a network topology combining massive MIMO and by installing a few single antenna small cell access points in areas with active users with little additional hardware
[34]	Effect on Energy Efficiency (EE) of a massive MIMO system with respect to • the number of antennas at the base station (BS) i.e. M • the number of active user equipment's (UEs) i.e. K • transmit power • area throughput For different linear processing schemes like • zero-forcing (ZF) • maximum ratio transmission /combining (MRT/MRC) • minimum mean squared error (MMSE) processing)	Energy Efficiency (EE) values for different linear processing schemes and with different values of M,K • ZF processing M = 165 and K = 104, EE = 30.7 Mbit/J. • MMSE processing M = 145 and K = 95, EE = 30.3 Mbit/J. • MRT/MRC processing M = 81 and K = 77, EE = 9.86 Mbit/J. It is observed that • For maximum energy efficiency as a function of the number of base station antennas, at high SNRs MMSE and ZF are almost equal • For all the considered processing schemes, the best energy efficient approach is to increase the radio frequency power with M • There is concurrently an 8-fold progress in area, throughput for ZF and MMSE processing as compared to MRT/MRC

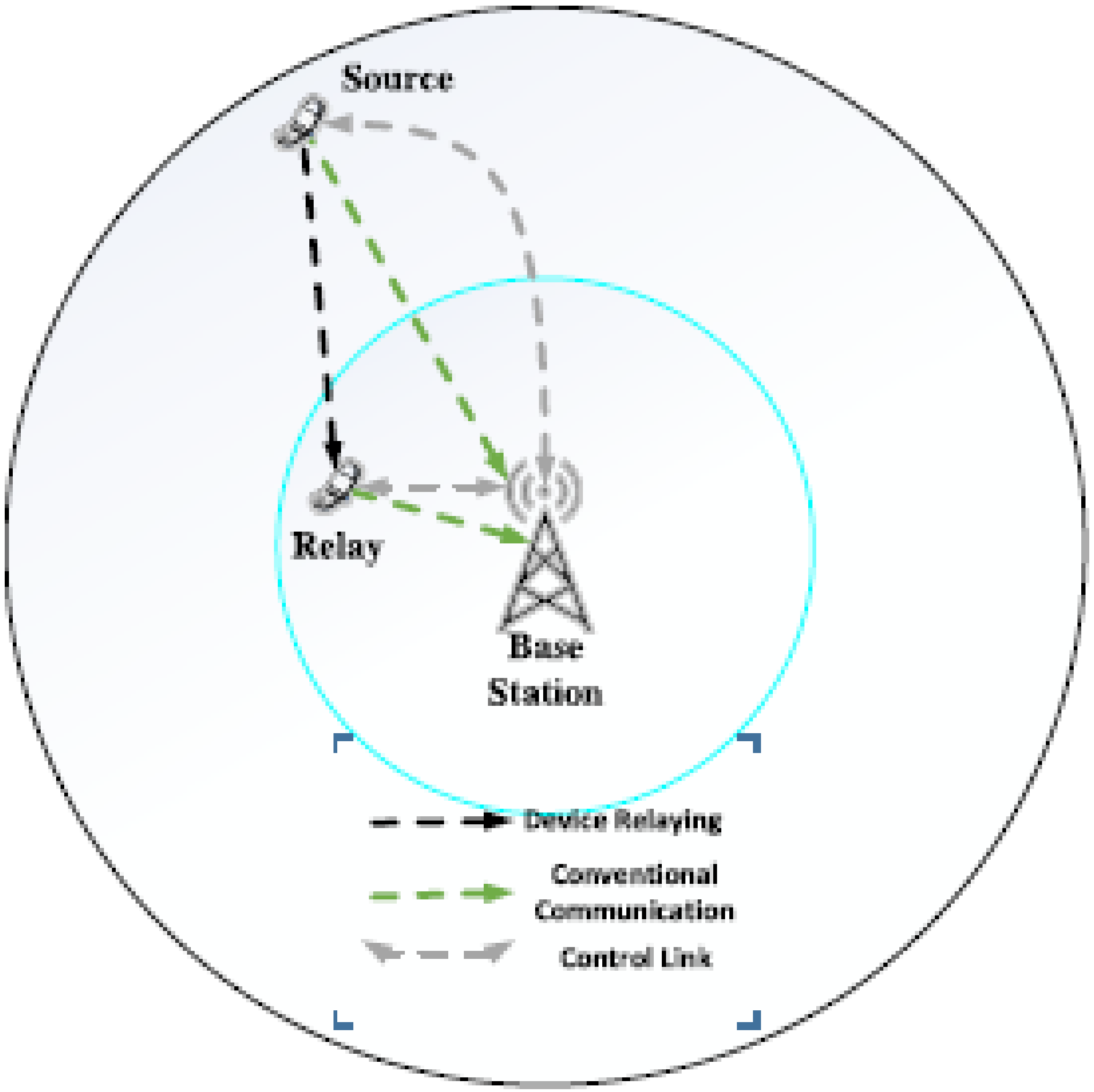


FIGURE 5. Device relaying communication with base station controlled link formation.

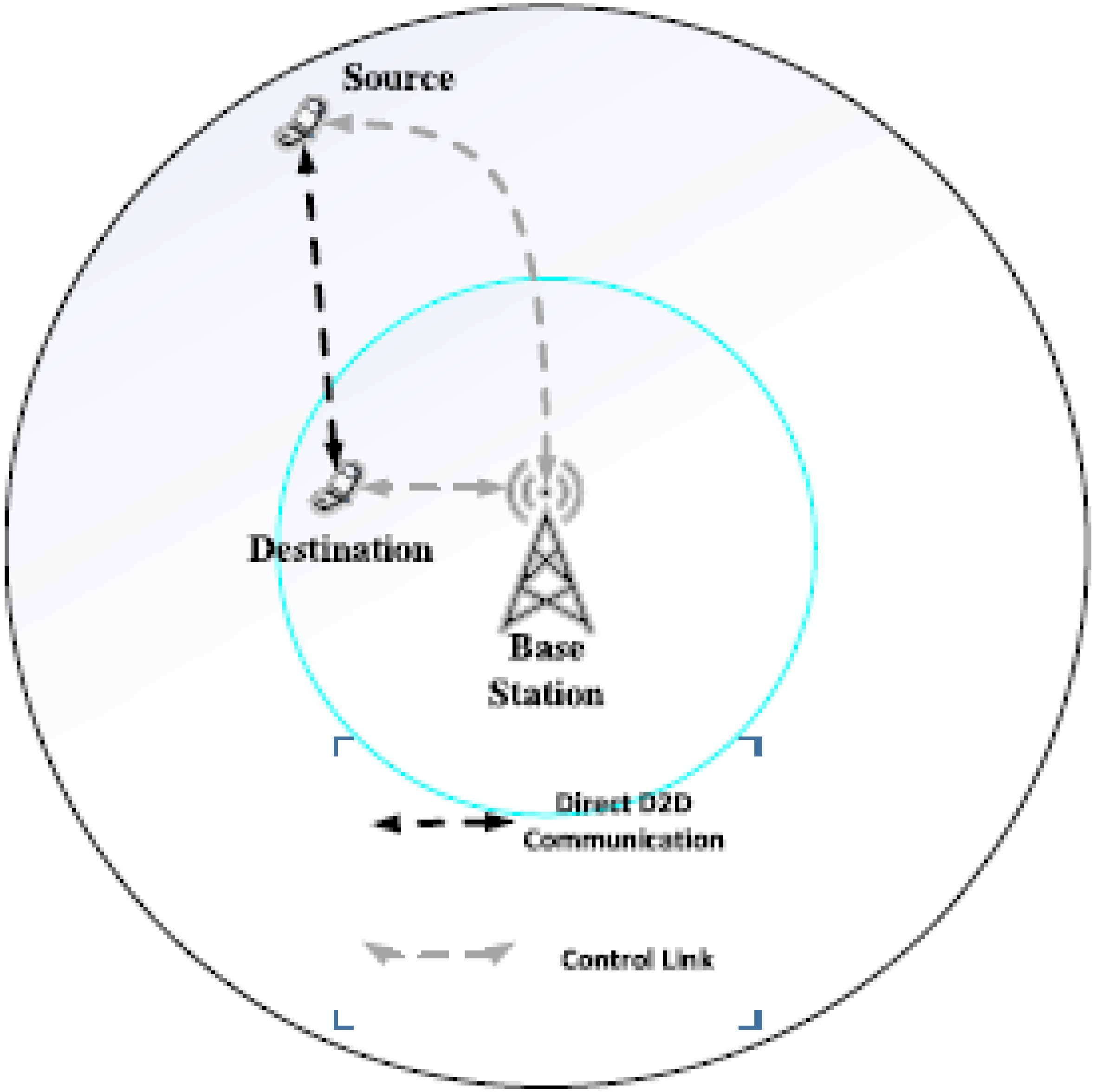


FIGURE 6. Direct device to device communication with base station controlled link formation.

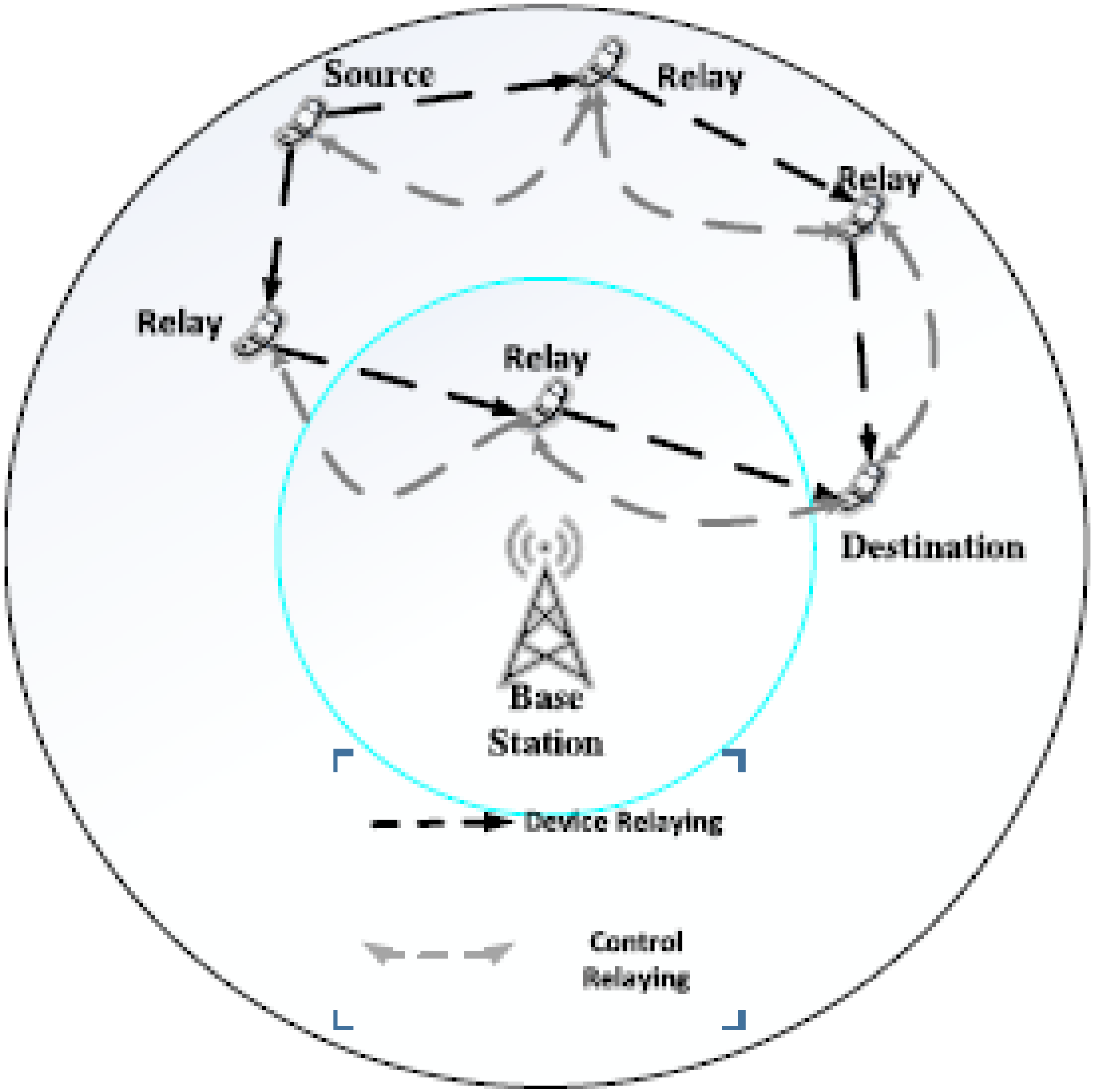


FIGURE 7. Device relaying communication with device controlled link formation.

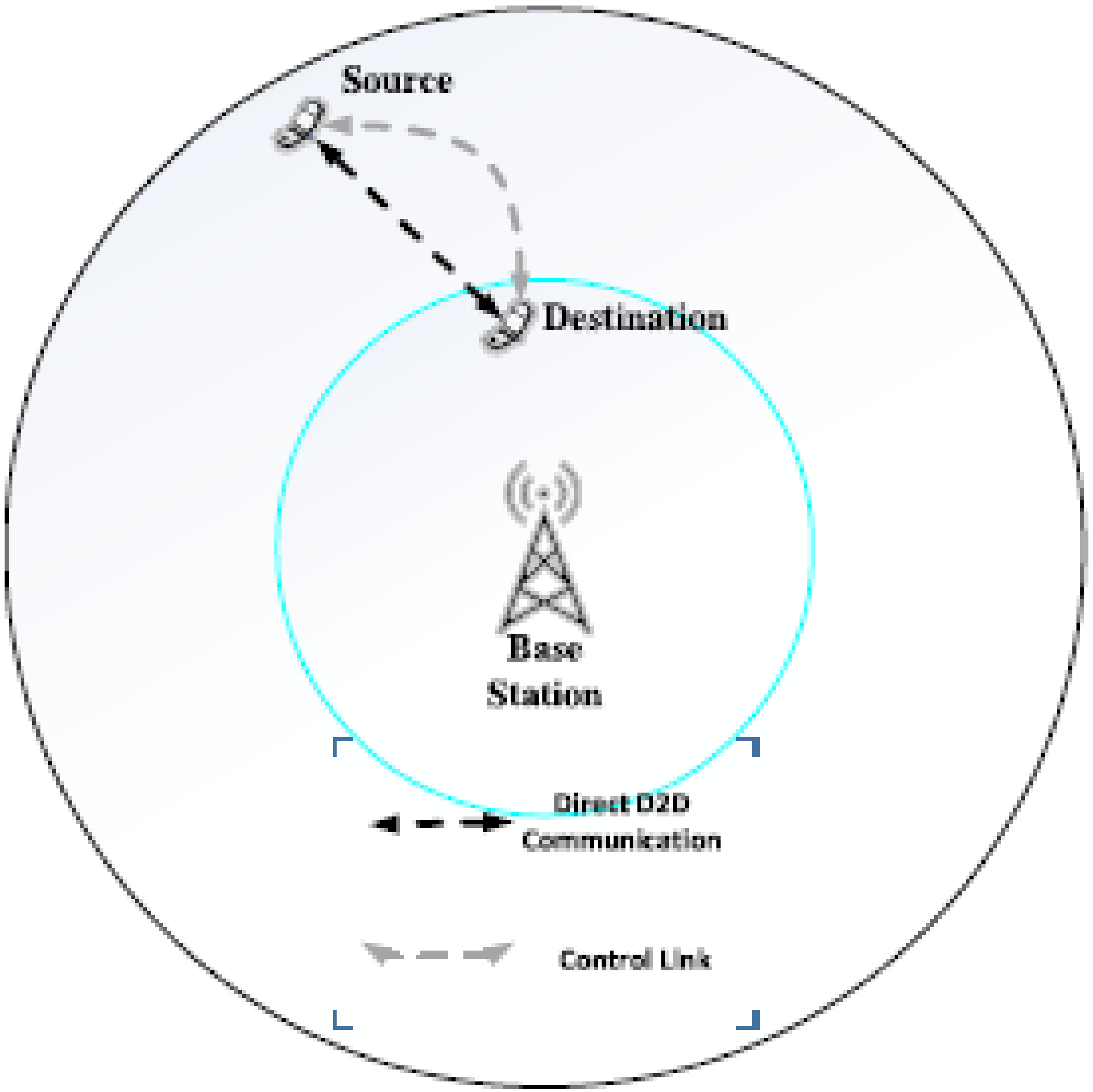


FIGURE 8. Direct device to device communication with device controlled link formation.

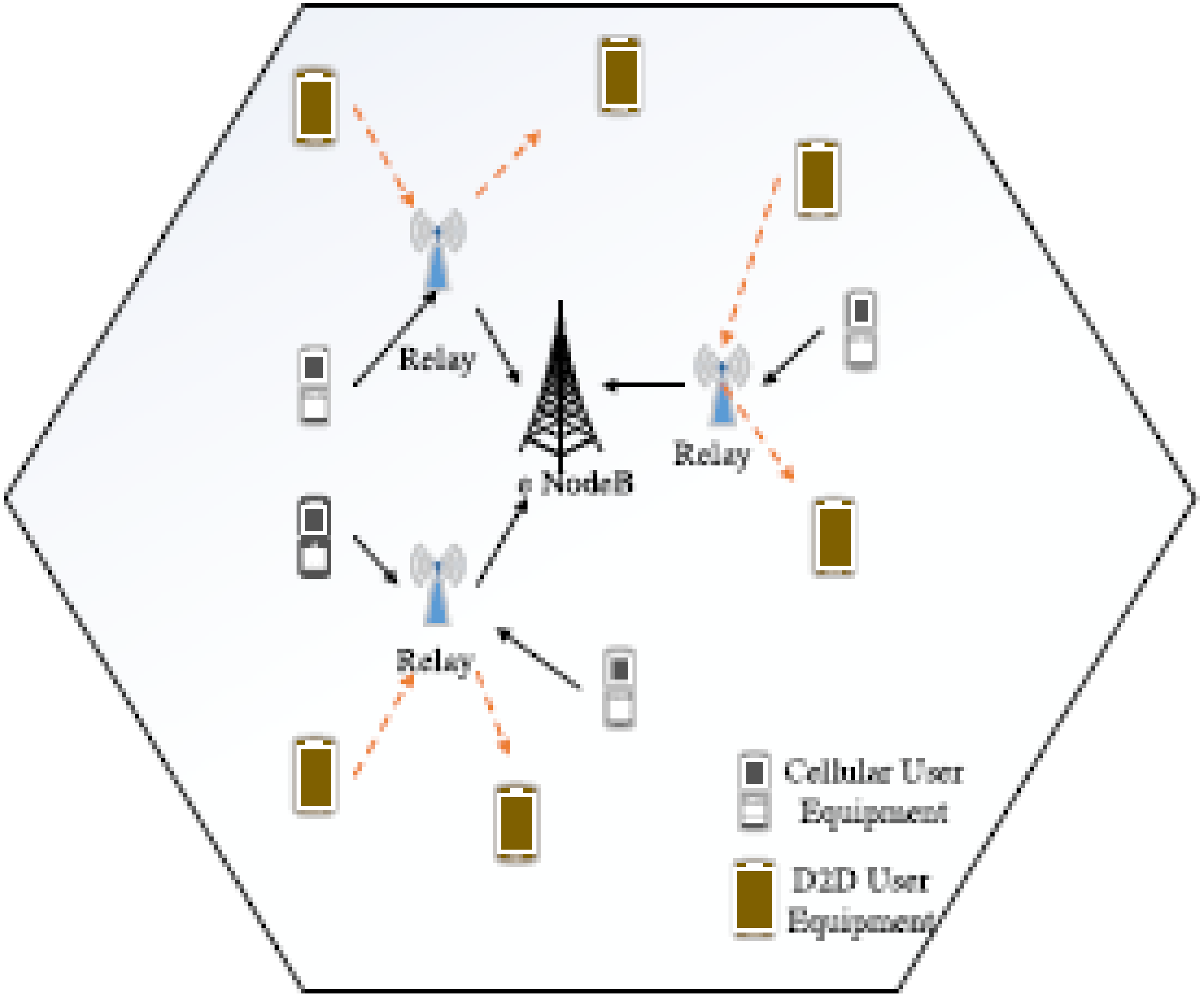


FIGURE 9. A single cell with multiple relay nodes.

TABLE 5. Summary of proposed algorithms for optimal resource allocation in device to device communication.

Reference	Algorithm	Description	Objective	Solution
[61]	Heuristic algorithm for the light load scenario	This algorithm is valid only for the cellular mode and dedicated mode with reusing of the channels of cellular users is not allowed, and thus resolve the problem in the light load scenario.	Maximization of the overall system throughput while ensuring the signal to noise and interference ratio of both devices to device and cellular links.	For maximizing throughput, low complexity algorithms are developed according to different network loads which execute very closely to the equivalent prime algorithms
[61]	Heuristic algorithm for the medium load scenario	In this algorithm, a device to device pair may choose any one among the three modes which will increase the system capacity, energy efficiency and bandwidth utilization rate.		
[62]	IPPO (Inverse Popularity Pairing Order) algorithm	This algorithm will maximize the total throughput while reducing the complexity problem for a large number of potential partners, which generally occurs in the traditional Kuhn-Munkres (KM) algorithm	Maximization of the well-defined performance metrics of all devices to device links and Cellular user equipment's after effective pairing under power and Quality of Service restraints.	An Inverse Popularity Pairing Order algorithm is proposed to reduce the computation complexity without foregoing much performance over the traditional KM algorithm
[63]	Iterative Resource Allocation Algorithm	This algorithm is for energy efficient resource allocation for device to device communications by using the properties of nonlinear fractional programming.	Observing the tradeoff between energy efficiency (EE) and spectral efficiency (SE) in device to device Communications for cellular networks with uplink channel reuse.	The tradeoff explains that the increasing transmission power beyond the power for prime energy efficiency brings little spectral efficiency improvement but with substantial energy efficiency loss.
[58]	Allocation of Resource Block and transmission power using message passing	A message passing technique is used for the resource allocation problem in which each user equipment sends and receives information messages to/from the relay node in an iterative method with an aim of attaining a prime allocation.	Examining the performance of the network supported device to device communication where device to device traffic is conceded over relay nodes	Observation about the proposed method has revealed that after a distant margin, relaying of device to device traffic improves system performance and delivers a better data rate to the device to the device user equipment's at the expense of a little increase in end to end delay.
[64]	Implementation of Distributed information theoretic link scheduling (ITLinQ)	Information theoretic link scheduling (ITLinQ), is a new spectrum sharing mechanism which at each time schedules those links that form an information theoretic independent set (ITISs), which indicates the sets of links for which simultaneous communication and treating the interference from each other as the noise is information theoretically optimal	Considering the problem of spectrum sharing in device to device communication systems.	Distributed ITLinQ outpaces similar spectrum sharing mechanisms, such as FlashLinQ, while keeping the complexity at the same level.
[65]	Coalition Formation Algorithm for the Spectrum Sharing Problem	A distributed coalition formation algorithm based on the Pareto order and the merge and split rule.	For the improvement of the energy efficiency of wireless users, a joint mode selection is modeled and spectrum sharing as a coalition formation game. A coalition formation algorithm is projected to jointly solve the mode selection and spectrum sharing in a device to device system.	The algorithm is proven to be of convergence and stability.

TABLE 6. 28 GHz antenna array configuration for 5G cellular mobile terminals and its comparison with the 4G standard.

Cellular standards	4G	5G [88]
Antenna type	Sub wavelength antennas	Phased array antennas
Radiation patterns	Omnidirectional	Directional fan-beam
Diversity and MIMO	Yes	Yes
Polarization	Single and constant	Multiple and reconfigurable

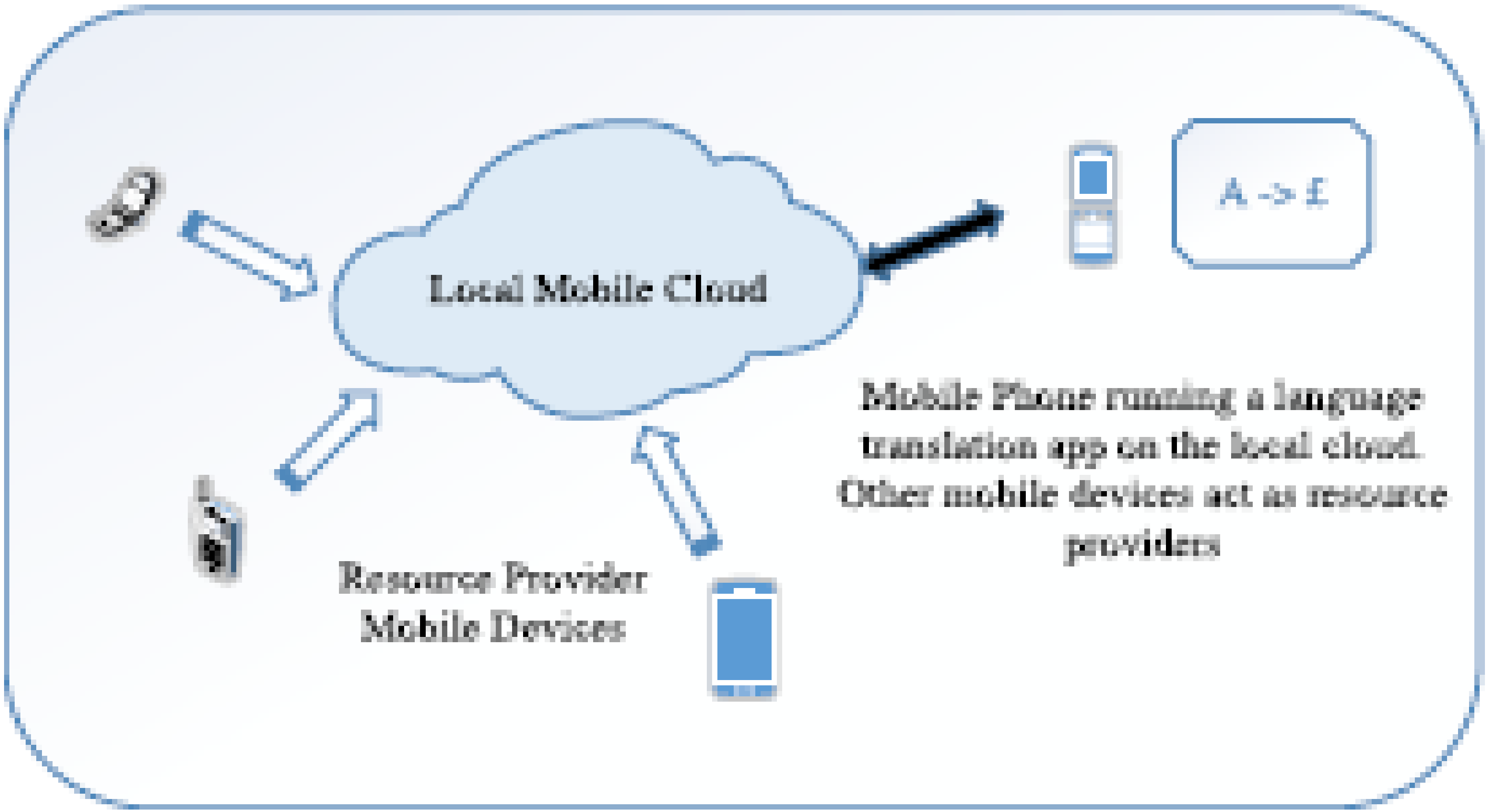


FIGURE 10. Virtual resource cloud made up of mobile devices in the vicinity.

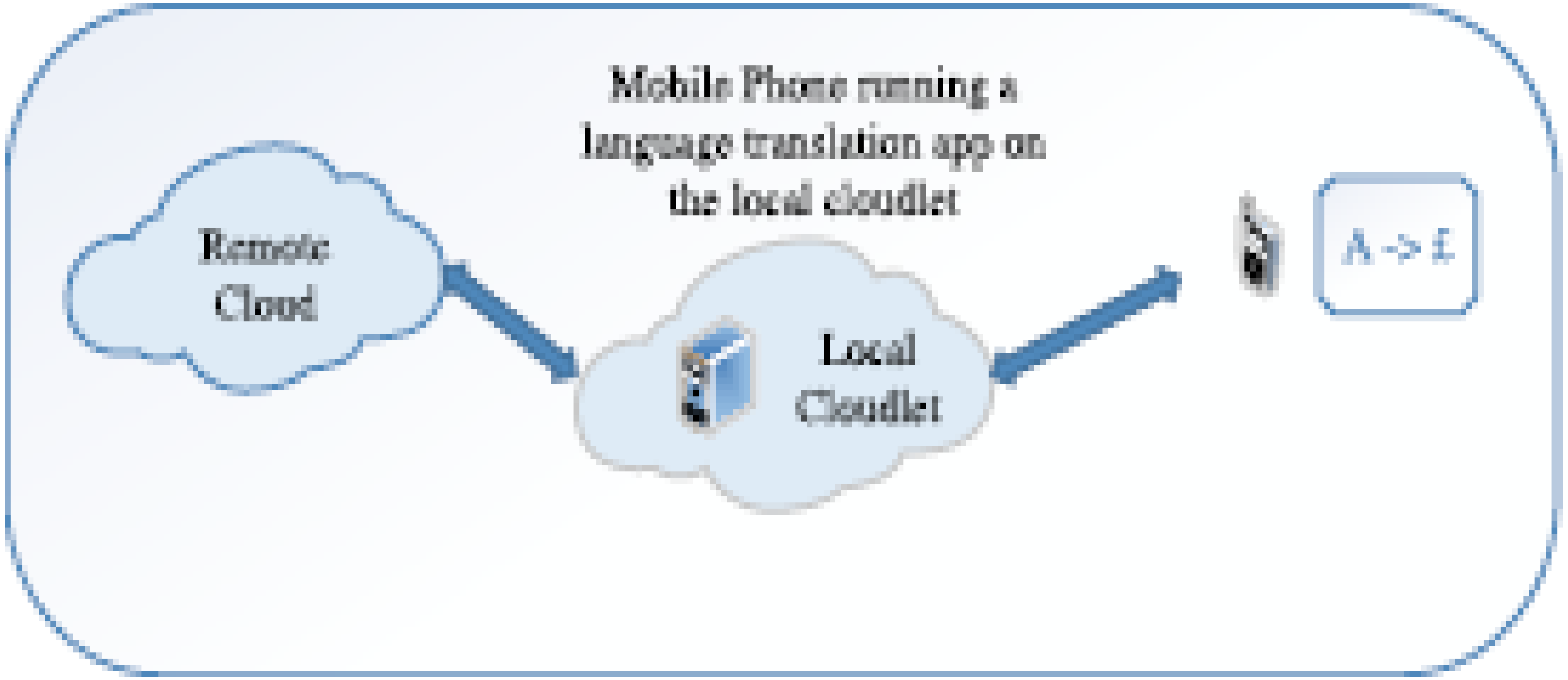


FIGURE 11. A cloudlet enabling mobile devices to bypass latency and bandwidth issues while benefitting from its resources.

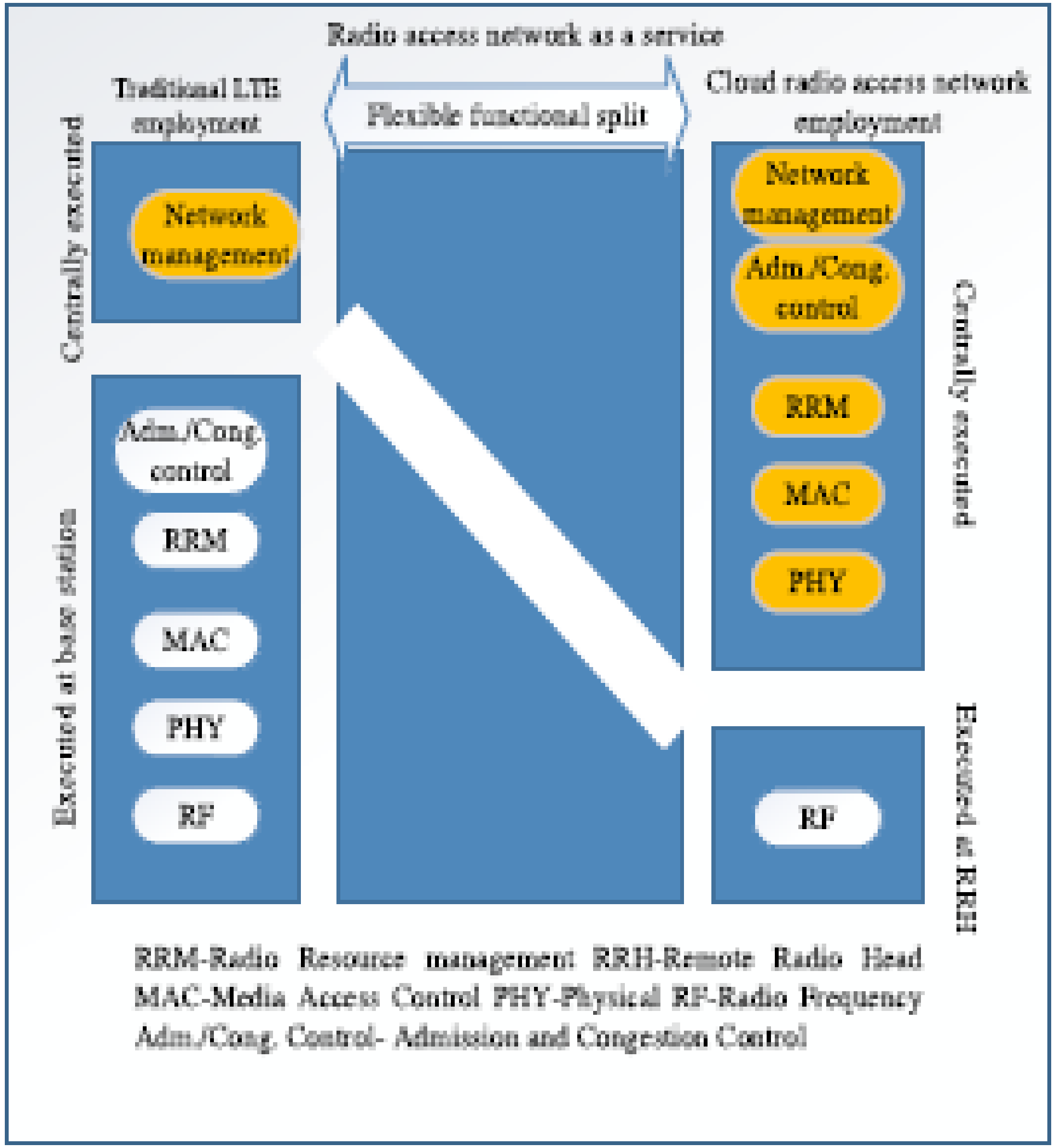


FIGURE 12. Flexible functional split [103].

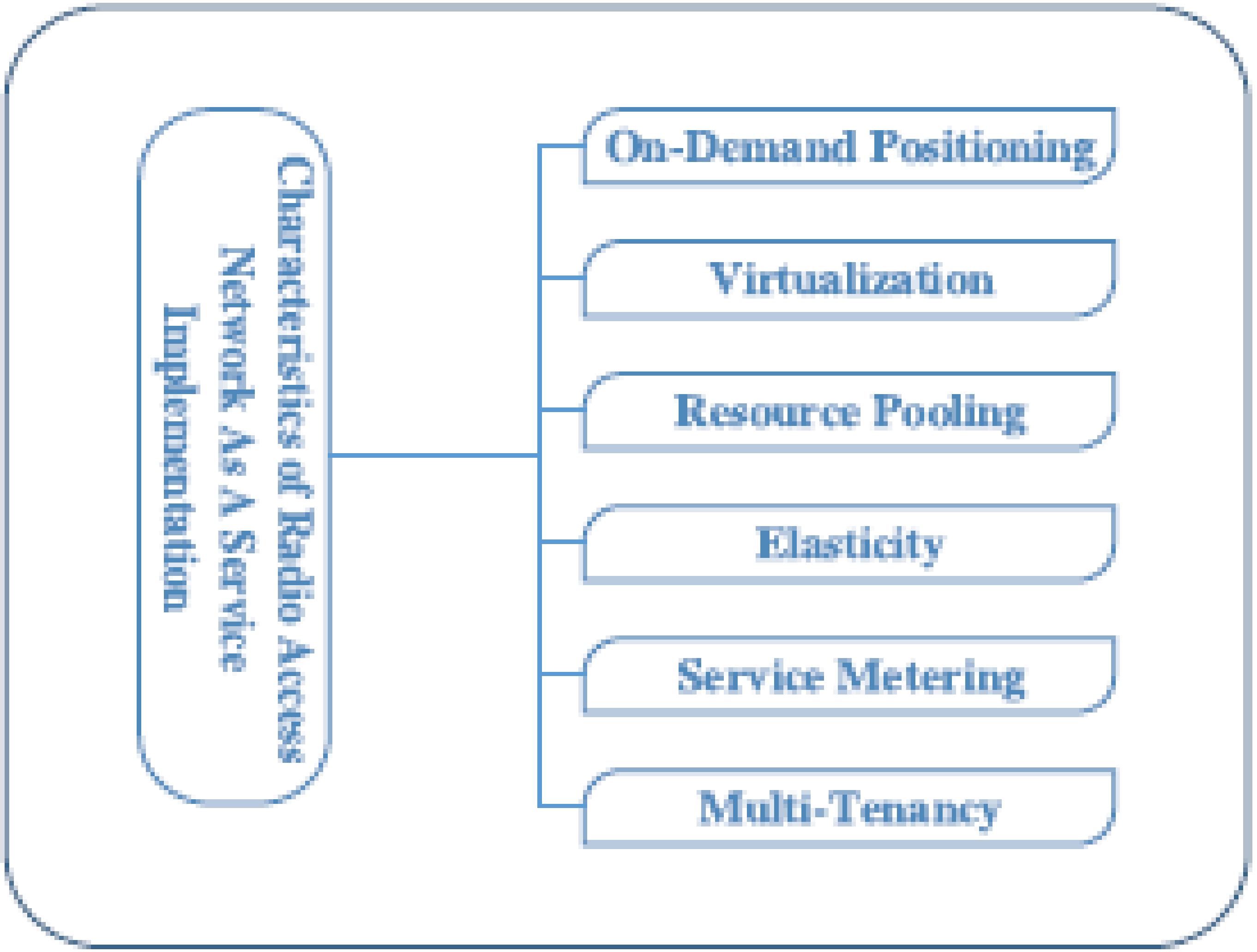


FIGURE 13. Characteristics of a radio access network as a service implementation.

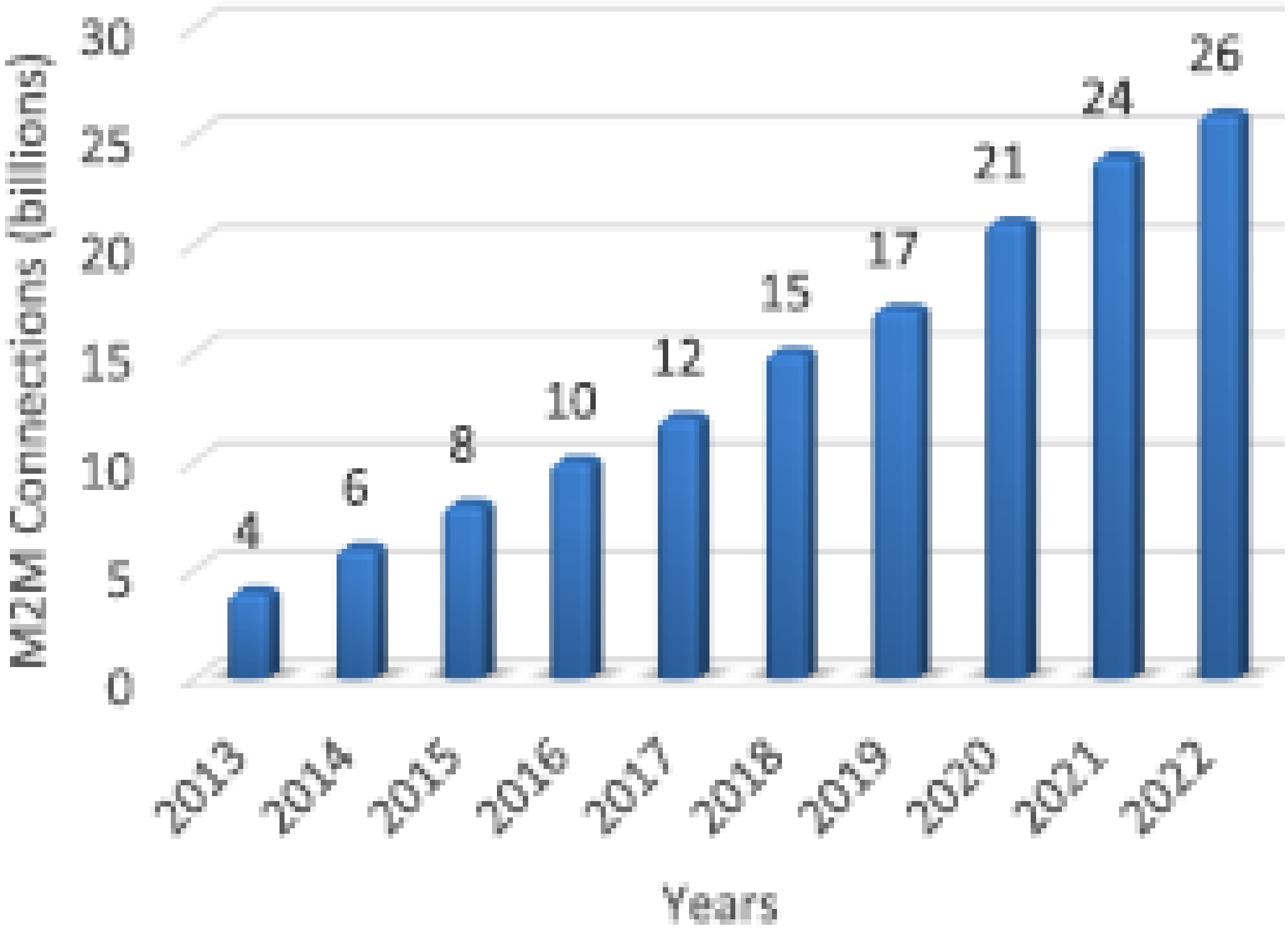


FIGURE 14. Number of Machine to Machine (M2M) connections in mobile [105]

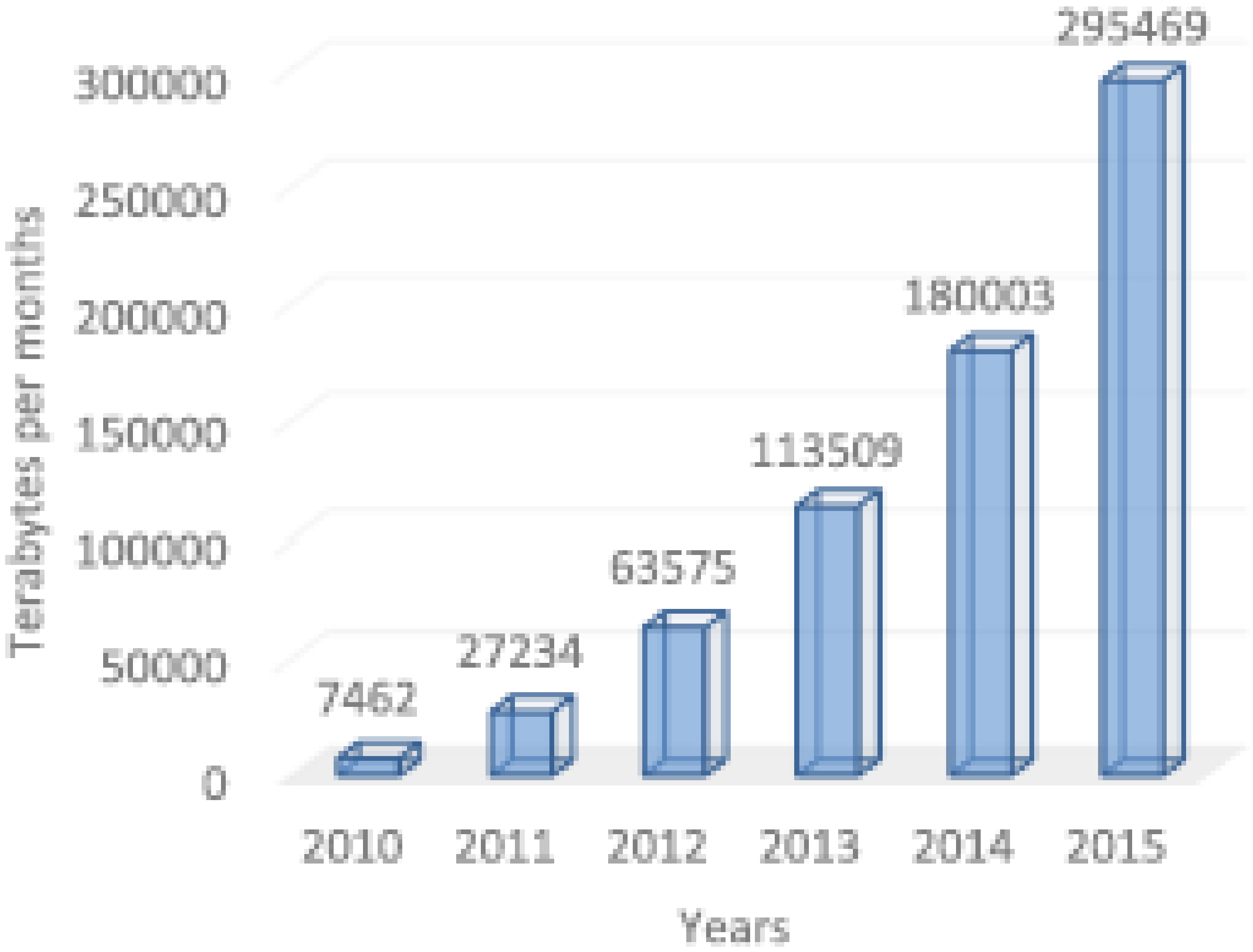


FIGURE 15. Machine to Machine traffic to increase 40-fold from 2010 to 2015.

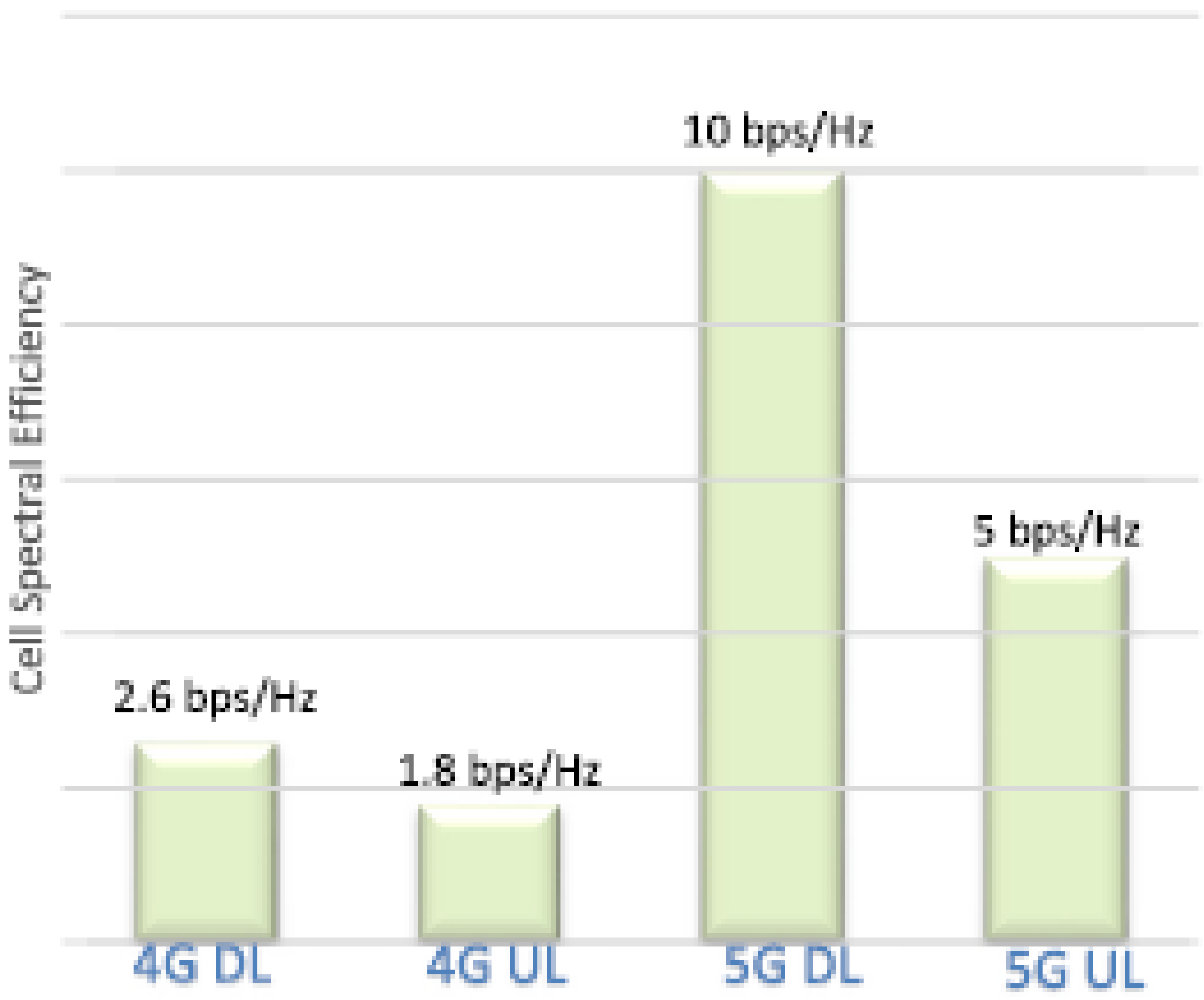


FIGURE 16. Cell spectral efficiency in 5G networks [105].

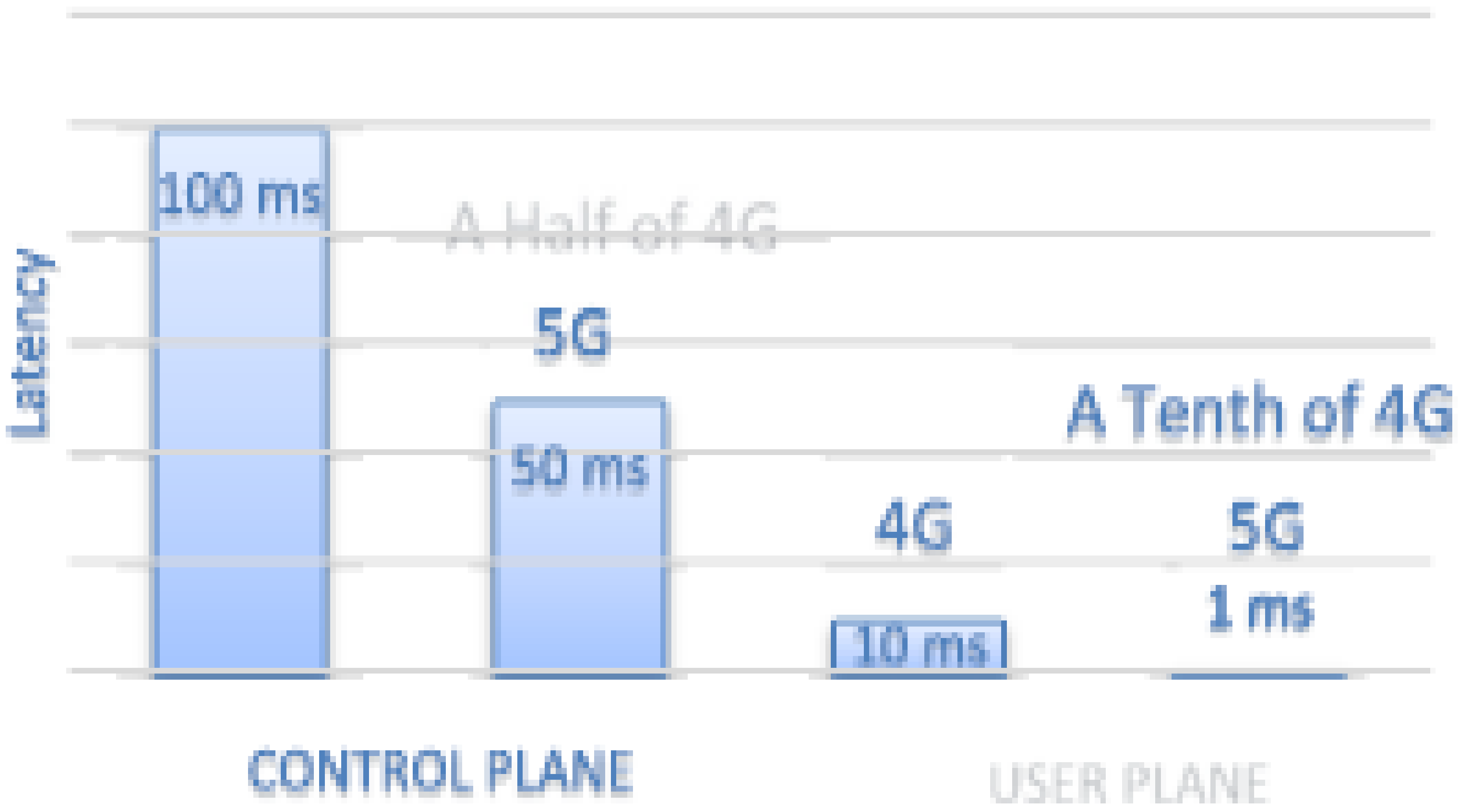


FIGURE 17. Demand to delay in control and user planes for 4G/5G networks [105].

LTE Advanced Enhancement for Vehicular Communications

V2X – Vehicle to every thing

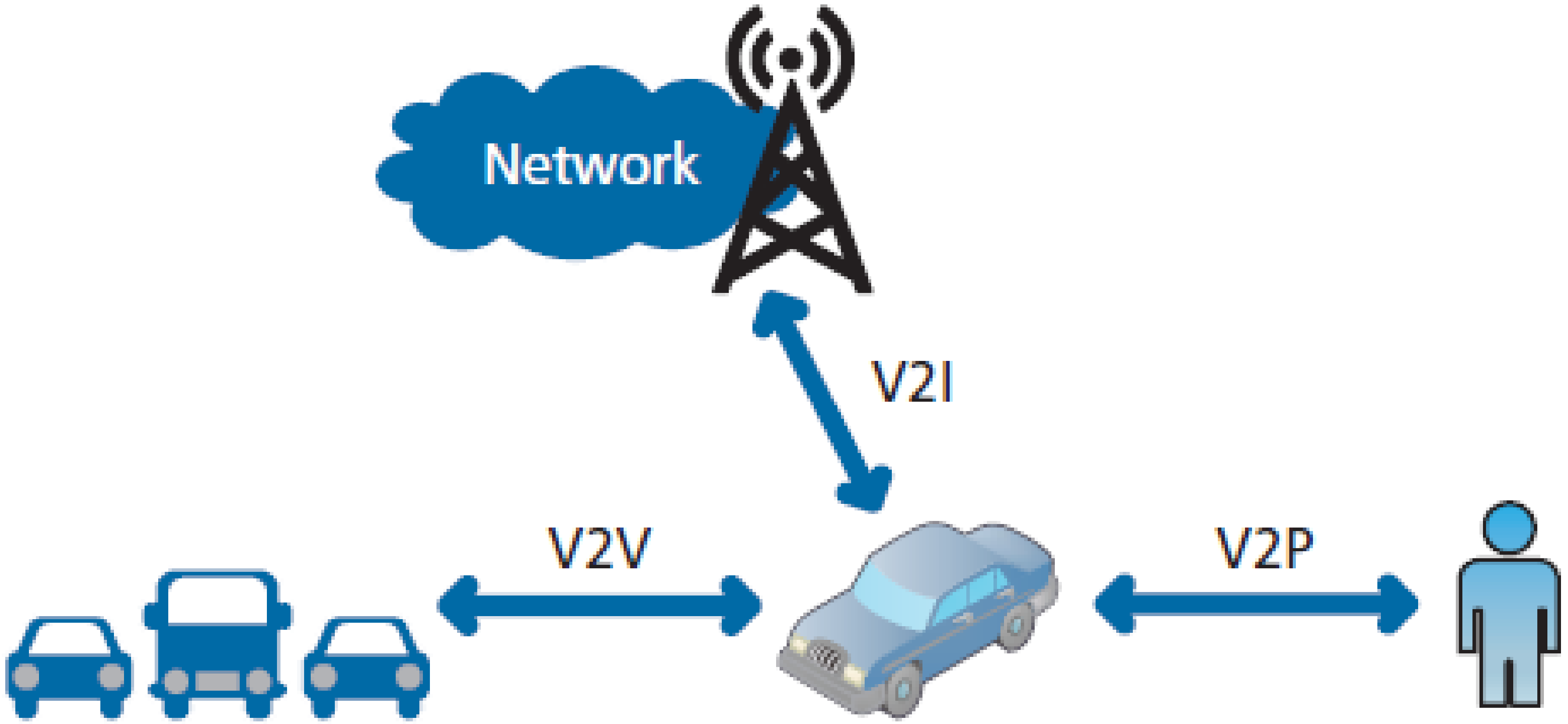


Figure 1. V2X service covers V2V, V2I, and V2P service.

Service requirements for V2X

Latency: for crucial service < 100 ms, not so critical service up 1 sec;

Message Size: generally 50-400 bytes may be up to 1200 bytes for some applications;

Mobility: max absolute velocity 160 km/h or maximum relative velocity of 280 km/h between behind 280 km/h between vehicles;

Reliability: V2X service shall be able to support periodic broadcast messages in PHY layer by UE

Response time: time to collision (TTC) = 4 sec

	Effective range	Absolute velocity of a UE supporting V2X service	Relative velocity between two UEs supporting V2X service	Maximum tolerable latency	Minimum radio layer message reception reliability	Example cumulative transmission reliability
#1 (suburban)	200 m	50 km/h	100 km/h	100 ms	90%	99%
#2 (freeway)	320 m	160 km/h	280 km/h	100 ms	80%	96%
#3 (autobahn)	320 m	280 km/h	280 km/h	100 ms	80%	96%
#4 (NLOS/ urban)	150 m	50 km/h	100 km/h	100 ms	90%	99%
#5 (urban intersection)	50 m	50 km/h	100 km/h	100 ms	95%	—
#6 (campus/ shopping area)	50 m	30 km/h	30 km/h	100 ms	90%	99%

Table 1. V2X service requirements in different scenarios.

ProSe (Proximity Services) D2D (Device to Device) Service

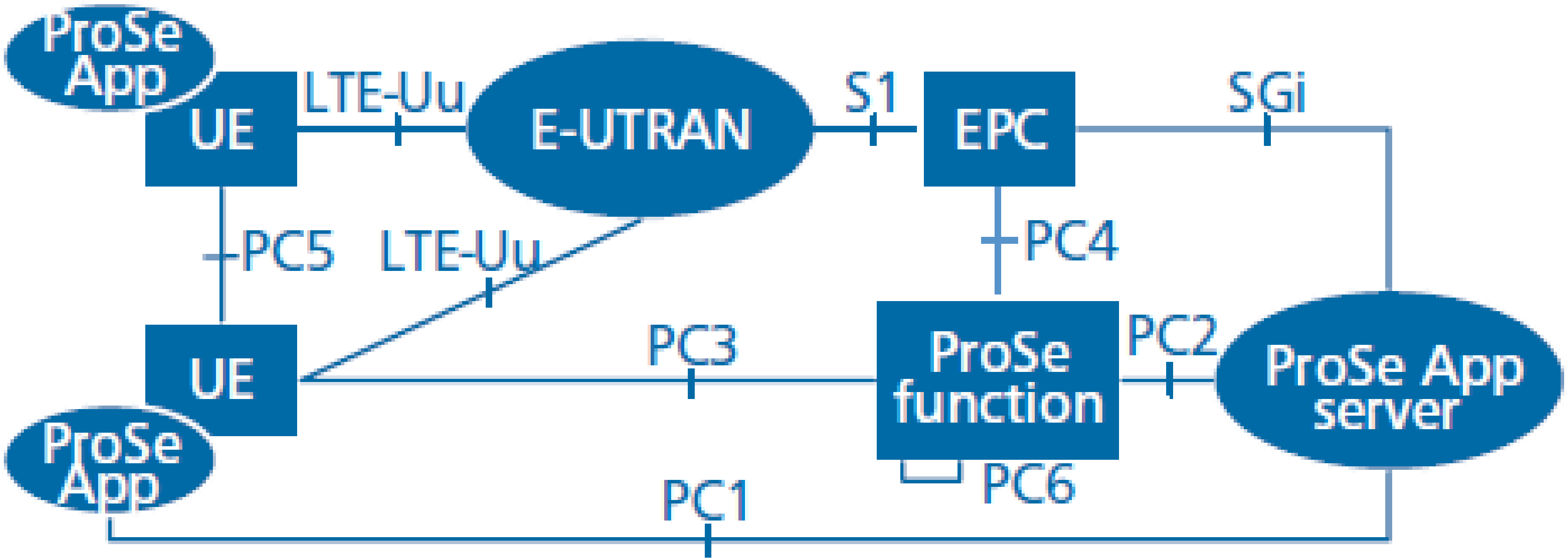


Figure 2. Reference architecture of ProSe D2D service.

The ProSe functionalities

1. Interworking via a reference point toward 3rd party applications;
2. Authorization and configuration of ProSe applications;
3. ProSe related new subscriber data and/or handing of data storage;
4. Security related functionality;
5. Provide control toward EPC for policy related functionality;
6. Charging.

Direct Communication

In release 12, direct communication is supported by in-coverage/atrial coverage/out-of-coverage scenarios

- Communication Mode (2)
- Group-based Direct Communication
- Power Allocation

DIRECT DISCOVERY

In release 12, direct discovery is supported only in the in-coverage scenario

- Fixed Payload Size
- Discovery Type
- Discovery Period
- Power Control

Issues of PC5-based V2X Service

- Radio Resource Allocation
- Message Size
- Reliability
- Priority
- Power control and communication range
- E-UTRAN Support

Emerging Technologies and Research Challenges for 5G Wireless Networks

Heterogeneous Networks

1. Small Cells
2. New Carrier Type
3. Multiple Radio Access Technologies
4. Device to Device Communications

	Energy efficiency	Capacity enhancement	Coverage
Massive/3D MIMO	✓	✓	
Dense HetNets	✓	✓	✓
Multi-RAT technologies		✓	
D2D	✓		✓

Table 1 Different enabling technologies.

Radio access	New network architecture	New applications
Massive/3D MIMO	HetNets	M2M
Multi-RAT	SDN	Localization and positioning
D2D		
Millimetre wave		

Table 2. Taxonomy of enabling technologies.

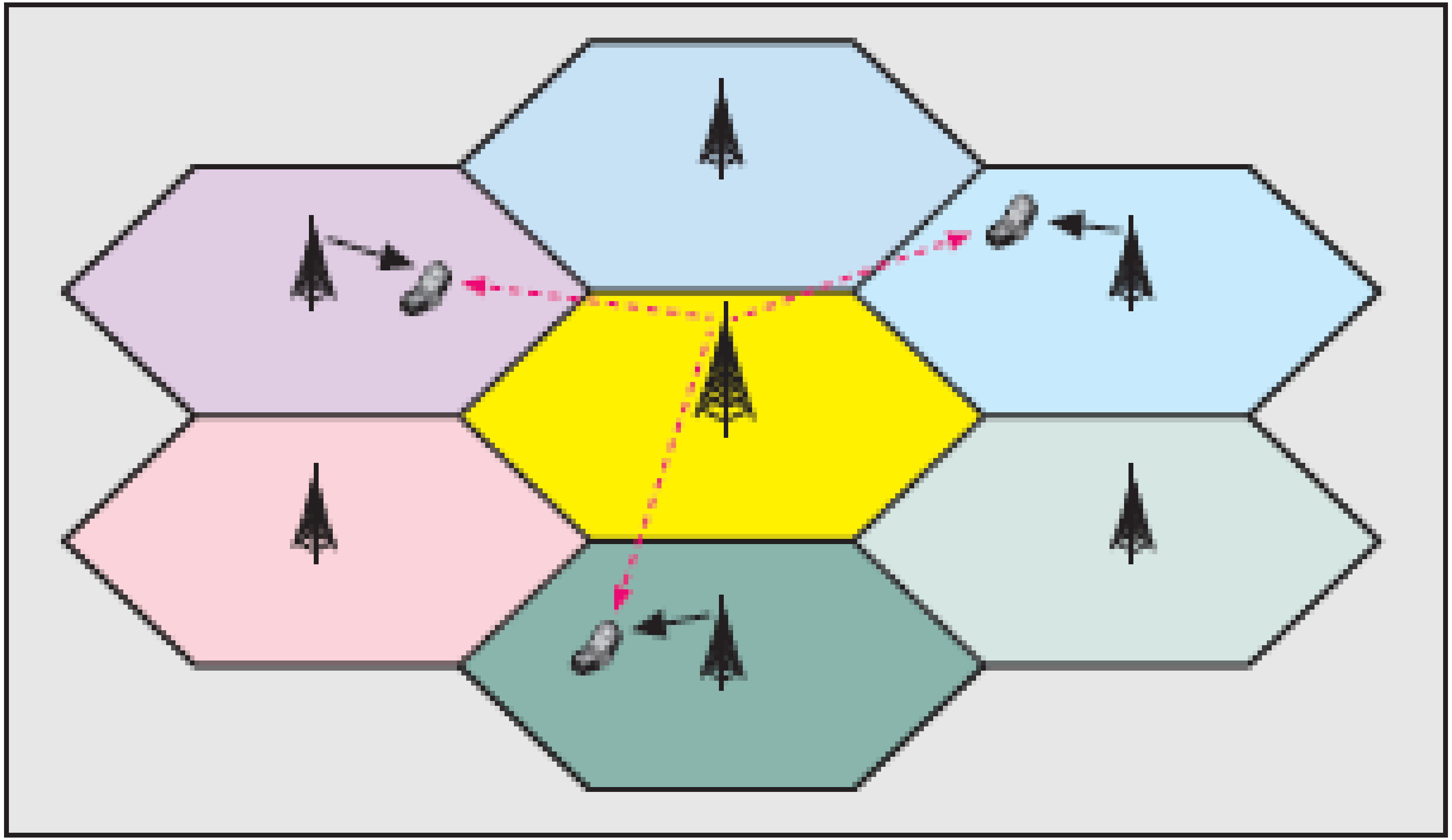


Figure 1. Separation of control and user planes.

Challenges of Heterogeneous Networks

- Inter-cell Interference
- Distributed Interference Coordination
- Efficient Medium Access Control
- Device Discovery and Link Set up

Software Defined Cellular Networks (Figure 2)

1. Directly Programmable (SDN)
2. Open
3. Agile

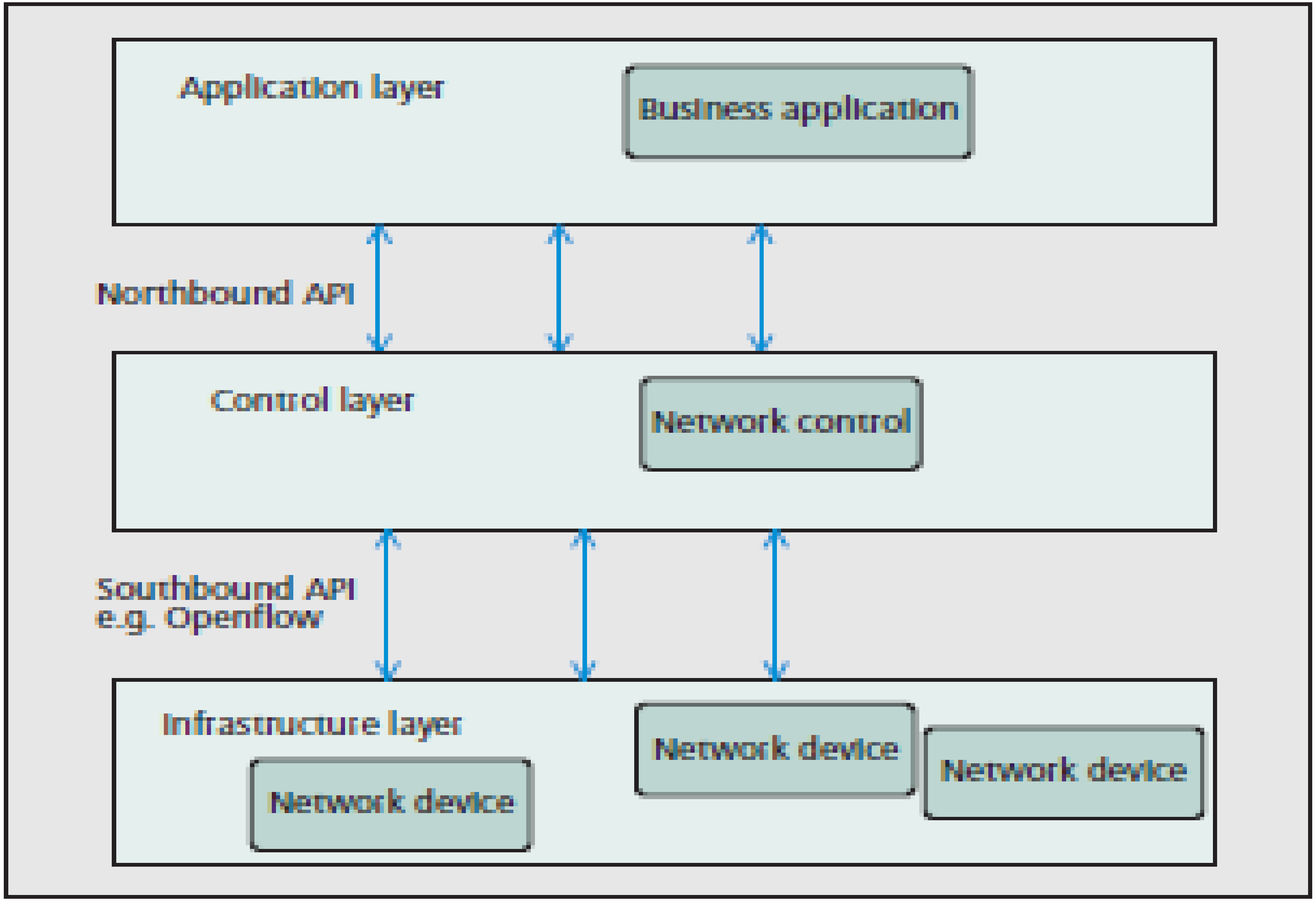


Figure 2. The SDN architecture.

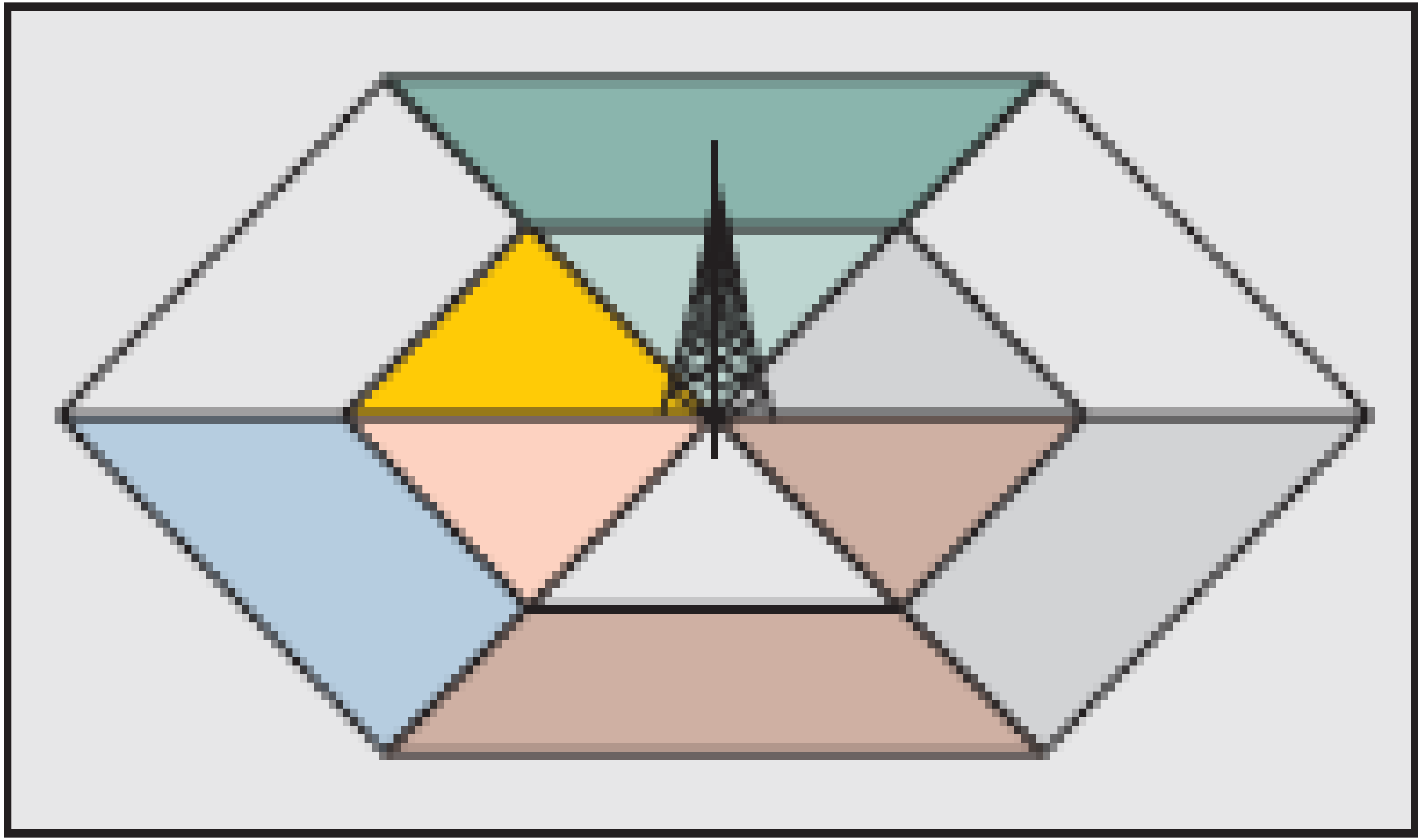


Figure 3. Possible sectorization for 3D MIMO.

5G Radio Access Architecture and Technology

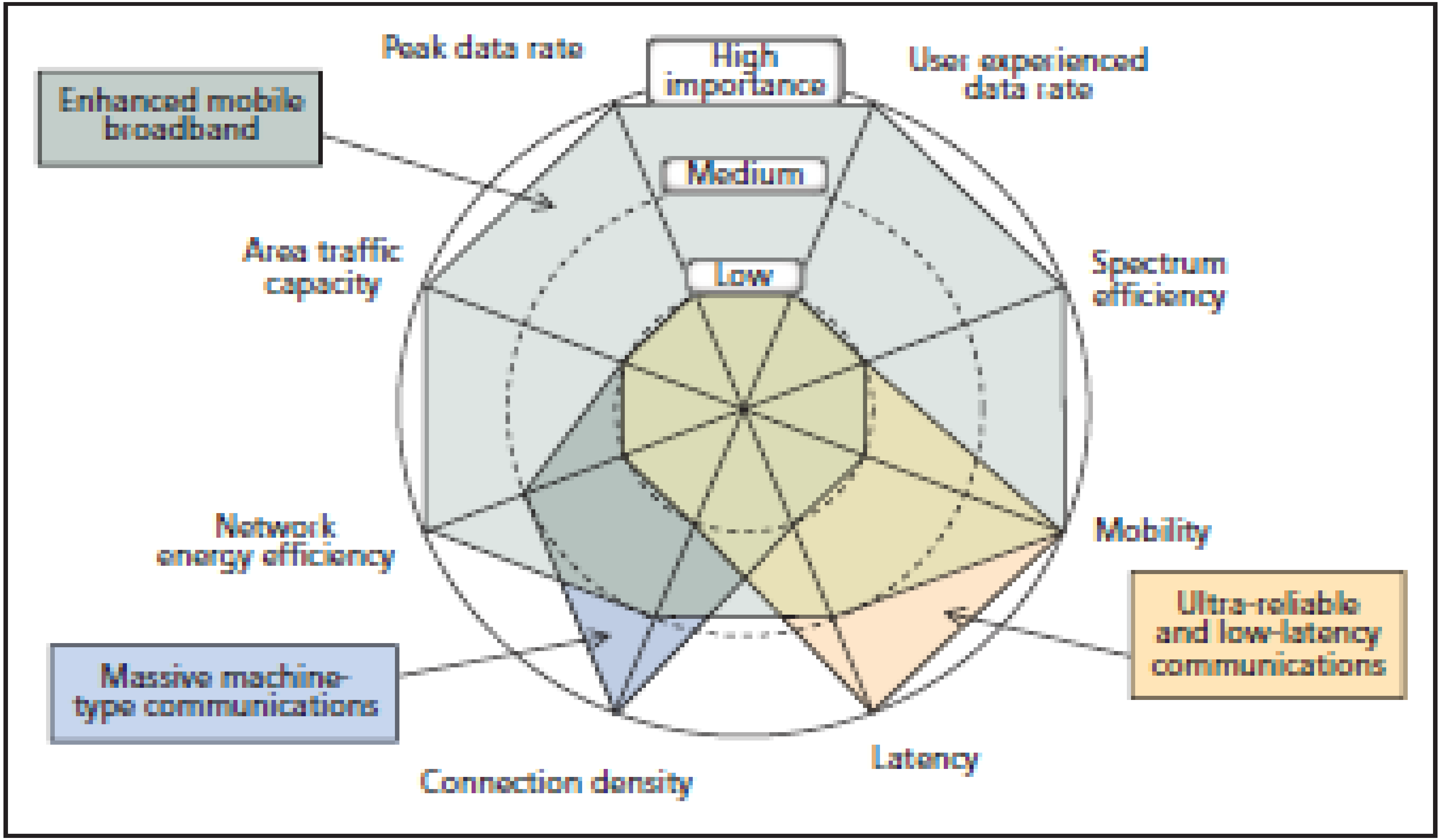


Figure 1. The importance of key capabilities in different usage scenarios [1].

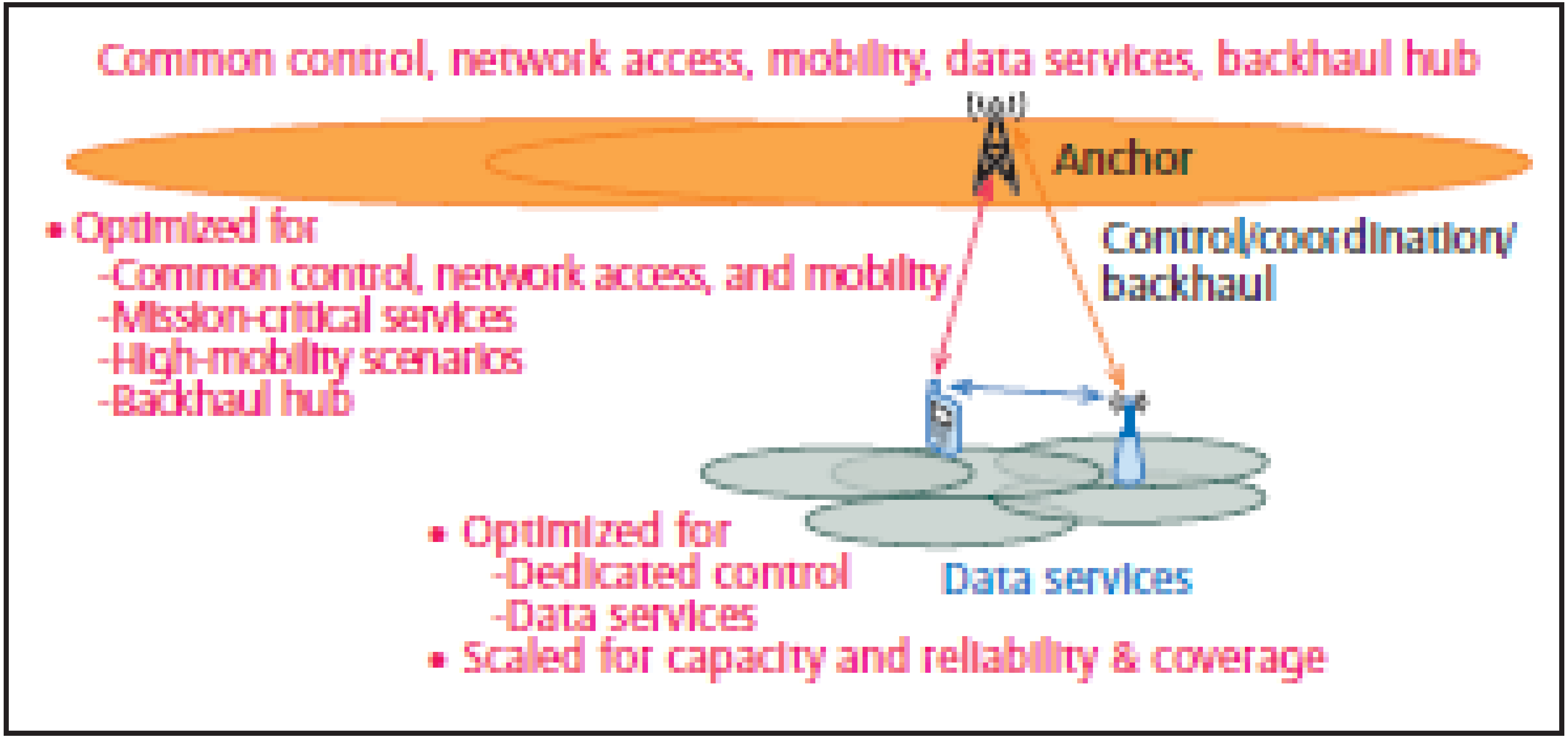


Figure 2. Specialization of macro and small cells.

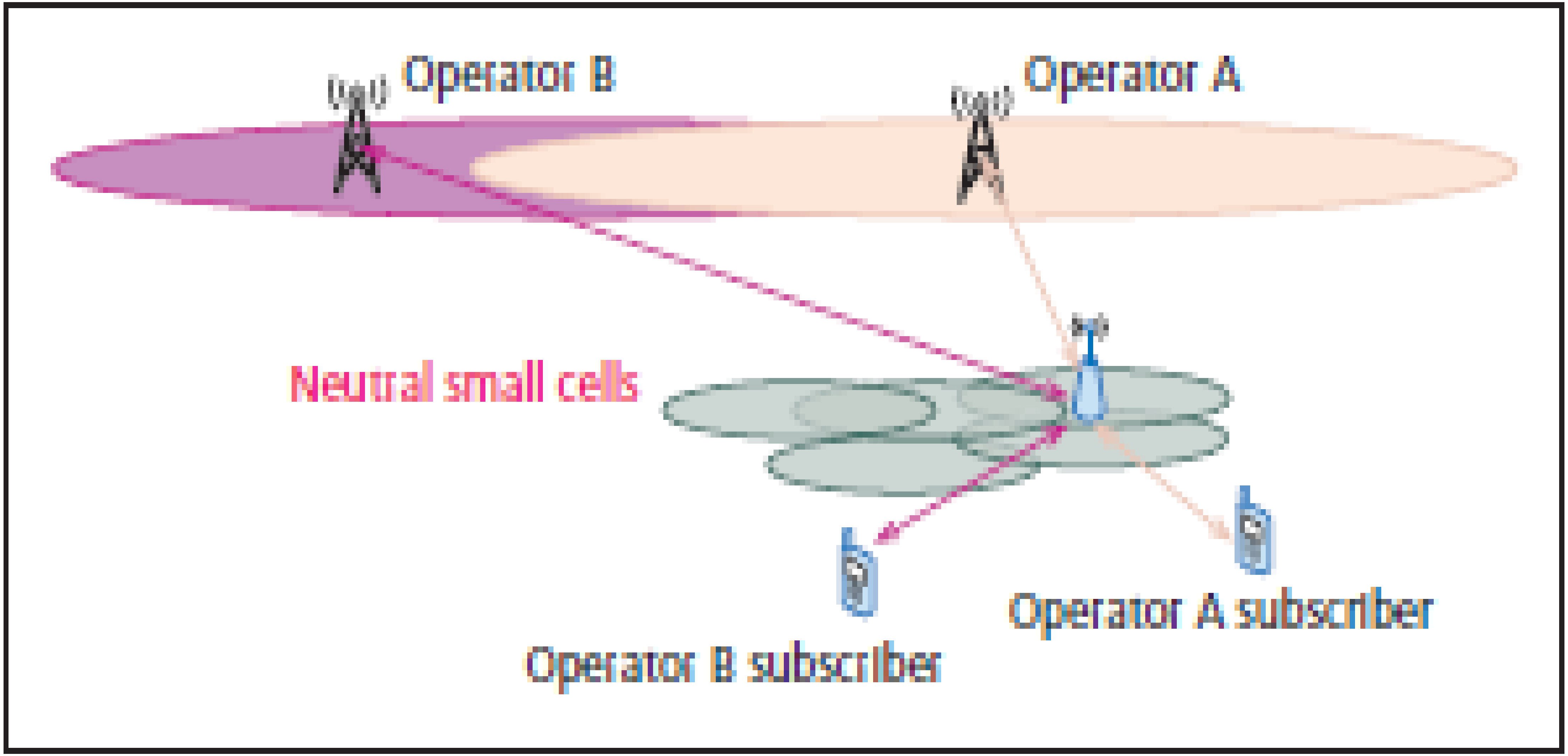


Figure 3. RAN sharing at the small cell level.

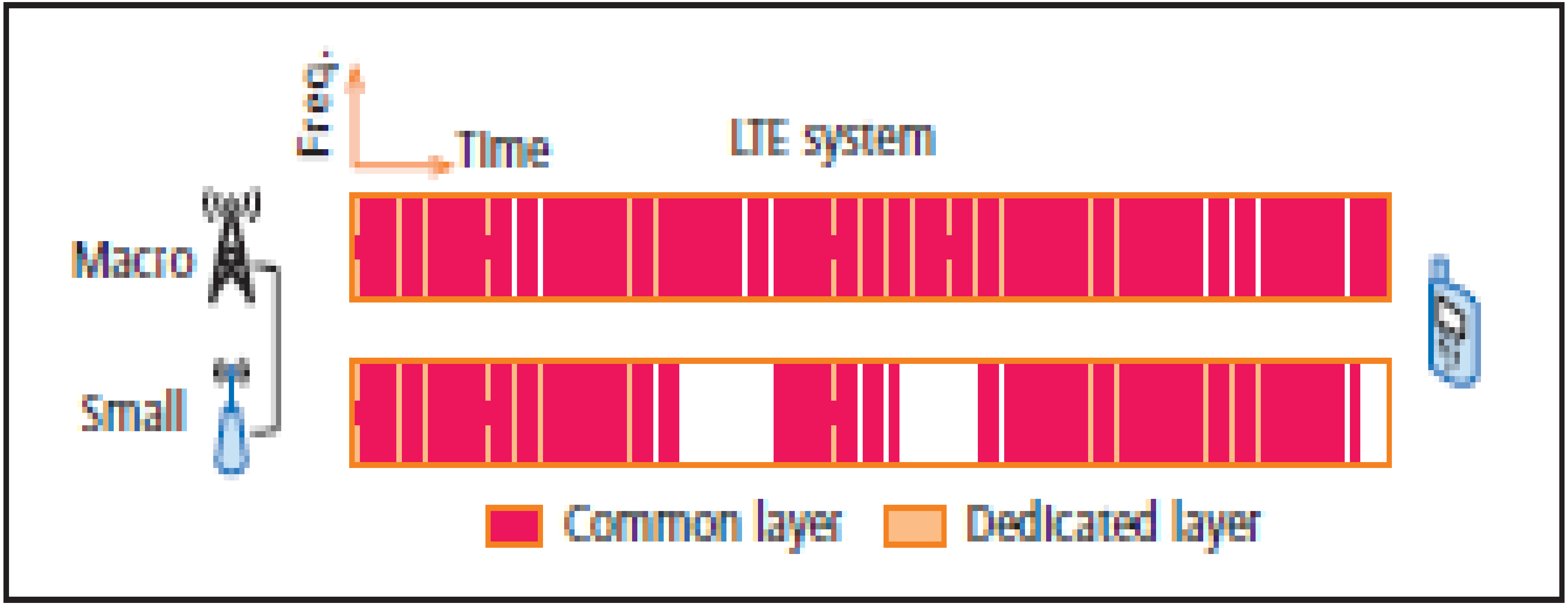


Figure 4. Common and dedicated layers in LTE.

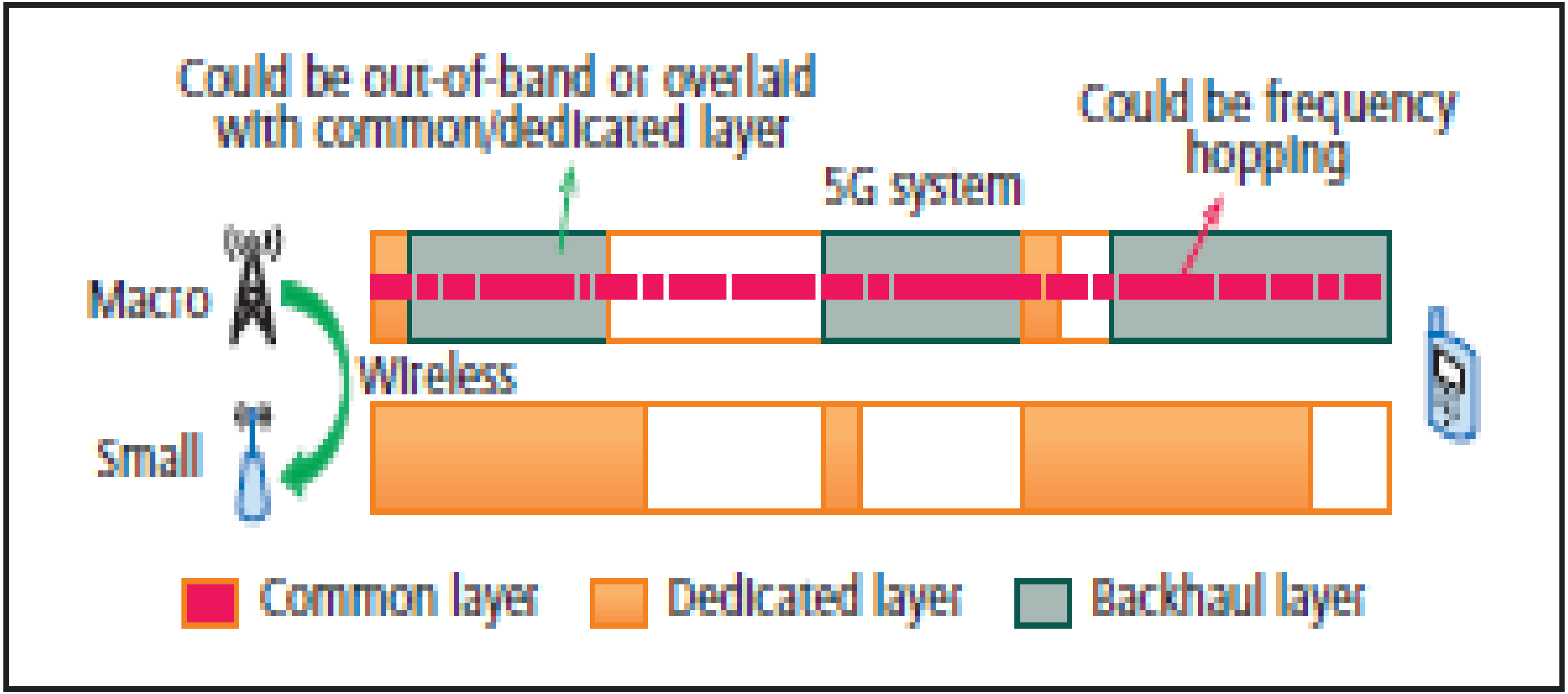


Figure 5. Physical resources providing three layers of services.

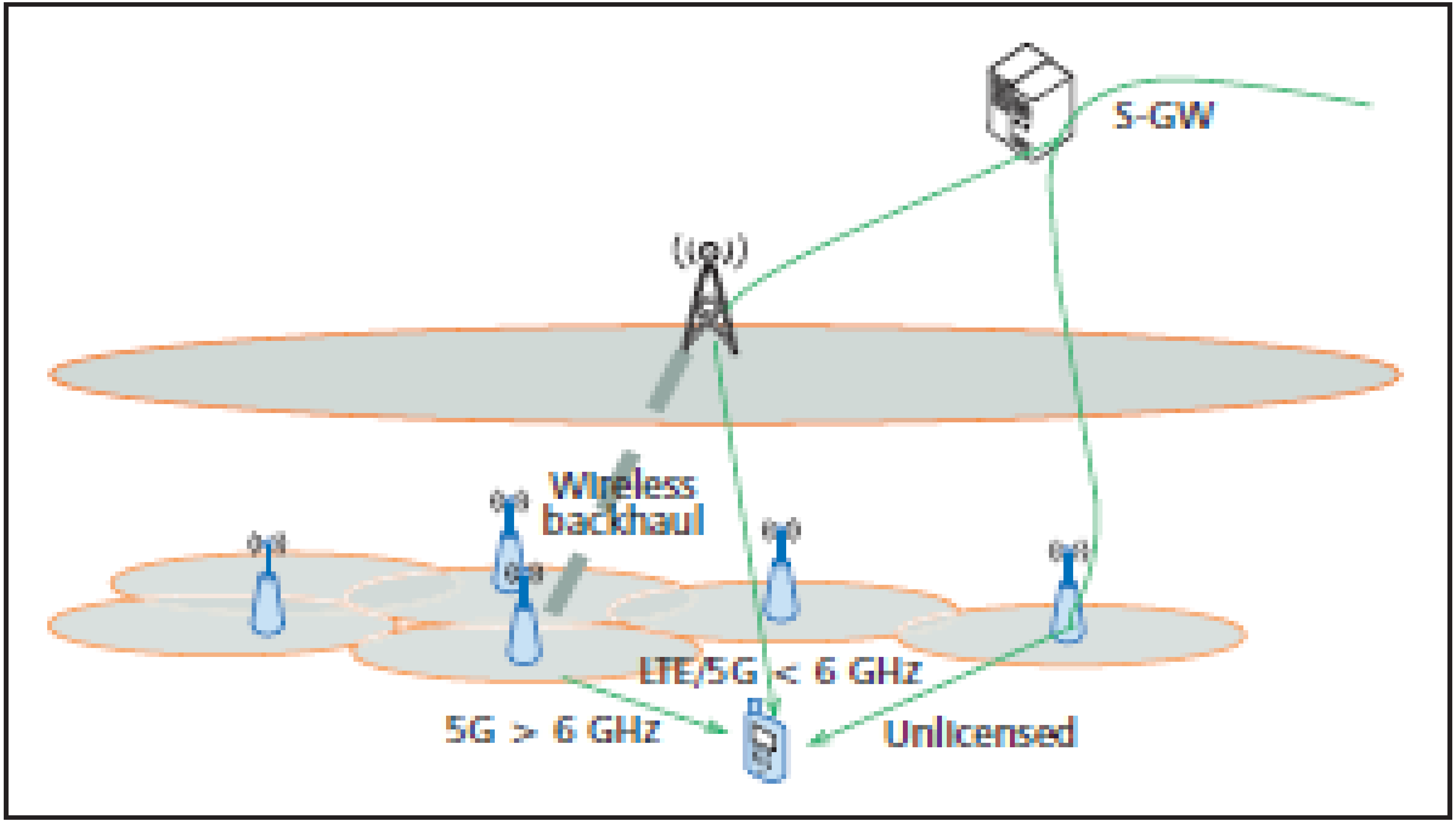


Figure 6. Example 5G mobility scenarios.

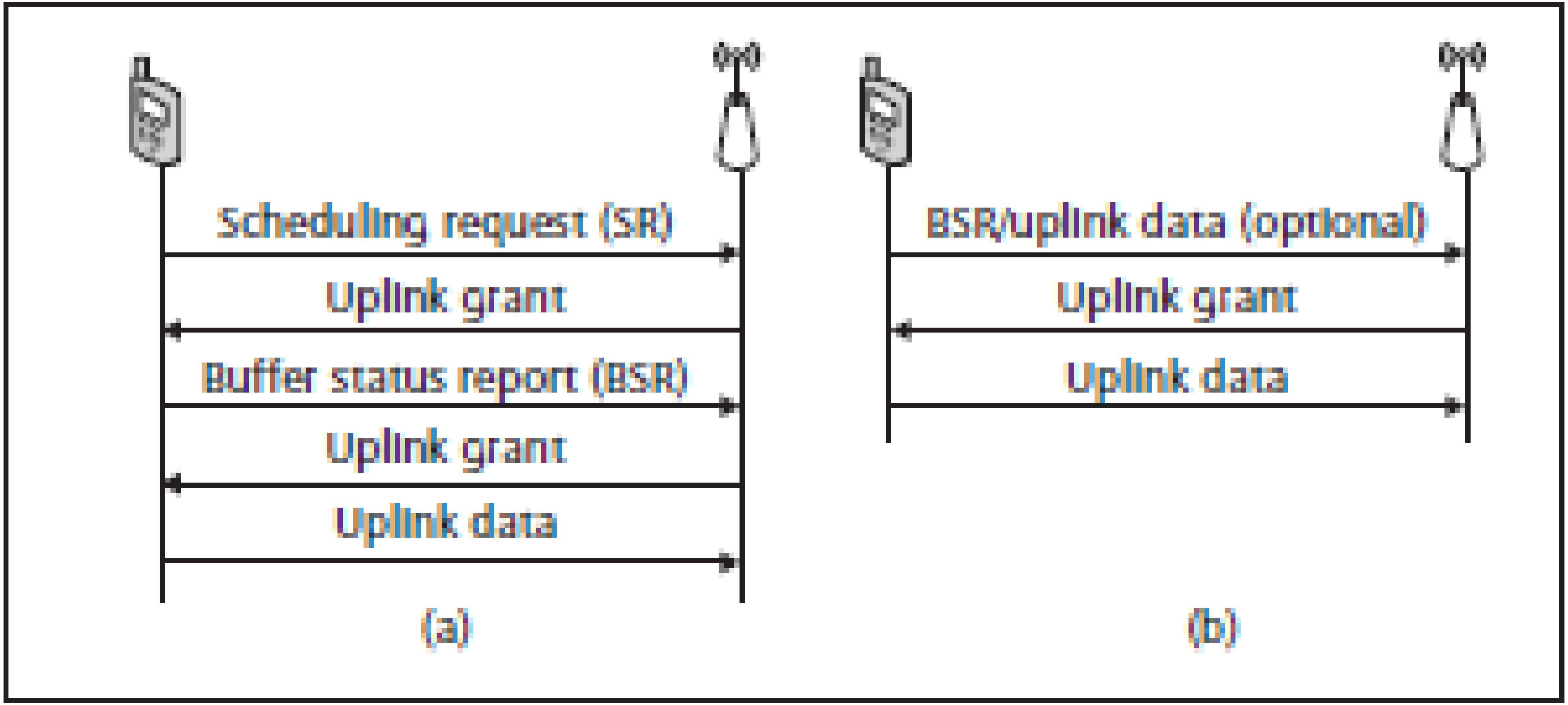


Figure 7. a) LTE request-and-grant uplink method; b) 5G contention-based uplink method.

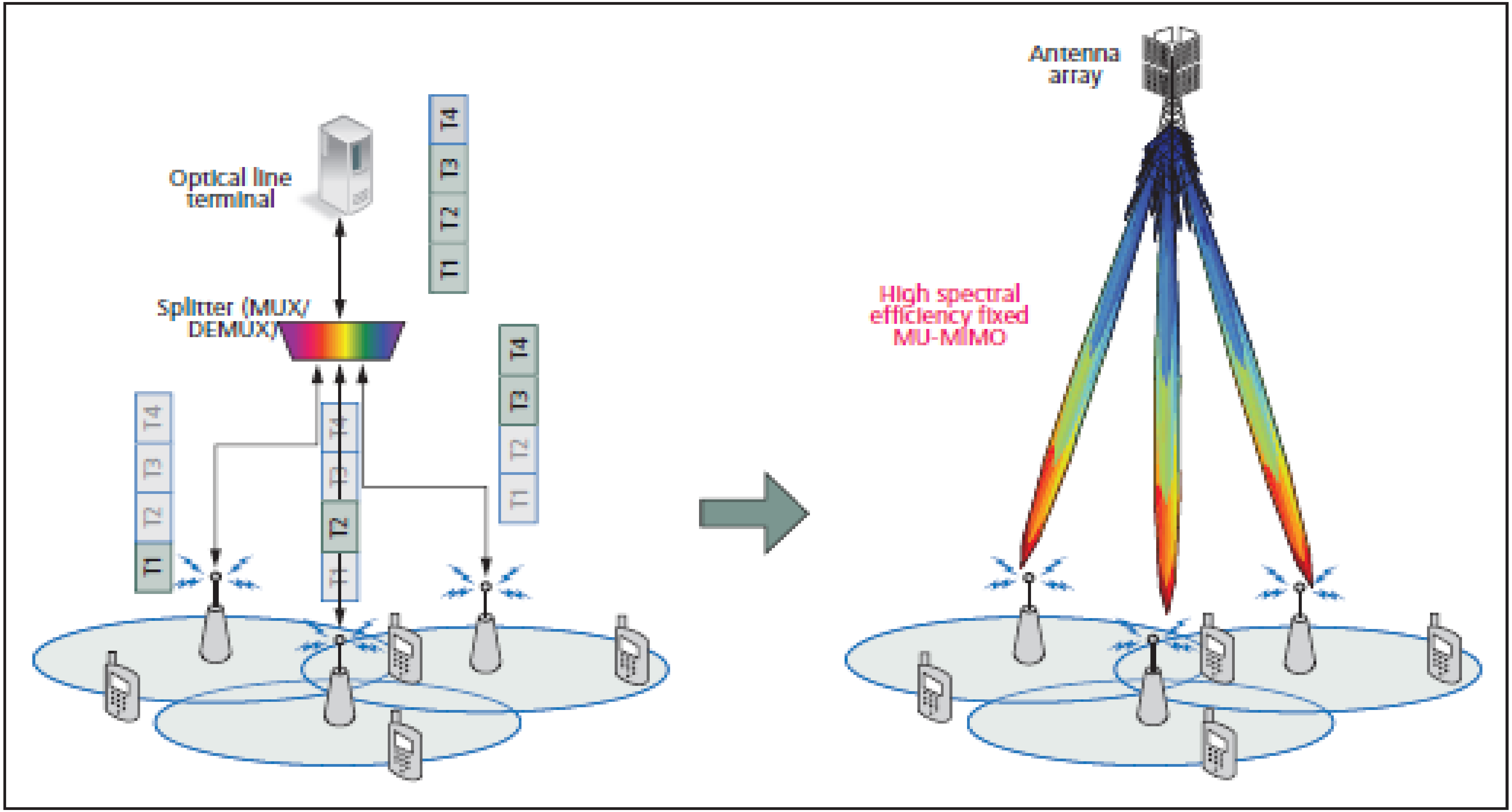


Figure 8. Point to multi-point wireless backhaul as an alternative to Passive Optical Network.

TABLE 7. 5G related activities in Europe [109].

Research Project / Institutions / Research Groups	Research area	HTTP location
5GNOW (5th Generation Non-Orthogonal Waveforms for asynchronous signaling) [110,111]	Non-orthogonal waveforms	http://www.5gnow.eu/
5G PPP (5G Infrastructure Public Private Partnership)	Next generation of communication networks, ubiquitous super-fast connectivity	http://5g-ppp.eu/
COMBO (COnvergence of fixed and Mobile BrOadband access/aggregation networks)	Fixed / Mobile Converged (FMC) broadband access / aggregation networks	http://www.ict-combo.eu/
iJOIN (Interworking and JOINt Design of an Open Access and Backhaul Network [112]	RAN-as-a-Service, radio access based upon small cells, and a heterogeneous backhaul	http://www.ict-ijoin.eu/
MAMMOET (MAssive MiMO for Efficient Transmission)	Massive MIMO	http://www.mammoet-project.eu/
METIS (Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society) [113-116]	Provide a holistic framework 5G system concept	https://www.metis2020.com/
MCN (Mobile Cloud Networking)	Mobile Network, Decentralized Computing, Smart Storage	http://www.mobile-cloud-networking.eu/site/
MOTO (Mobile Opportunistic Traffic Offloading)	traffic offloading architecture	http://www.ict-ras.eu/index.php/ras-projects/moto
PHYLAWS (PHYsical Layer Wireless Security) [115]	Security approaches for handsets and communications nodes	http://www.phylaws-ict.org/
TROPIC (Traffic Optimization by the Integration of Information and Control)	Femtocell networking and cloud computing	http://www.ict-tropic.eu/
5GrEEn [116]	Environmentally friendly 5G mobile network	https://www.eitictlabs.eu/news-events/news/article/toward-green-5g-mobile-networks-5green-new-project-launched/#allView
University of Edinburgh	Indoor wireless communications capacity	www.ed.ac.uk/
University of Surrey 5G Innovation Centre (5GIC)	Lowering network costs, Anticipating user data needs to pre-allocate resources, Dense small cells, Device-to-device communication, Spectrum sensing (for unlicensed spectrum)	http://www.surrey.ac.uk/5gic/

TABLE 8. 5G related activities in America [105].

Research Project / Institutions / Research Groups	Research area	HTTP location
Berkeley SWARM Lab	Third layer of information acquisition, synchrony to the Cloud, pervasive wireless networking, novel ultra-low power technologies	https://swarmlab.eecs.berkeley.edu/letter-executive-director#overlay-context=node/5&panel_content
Berkeley Wireless Research Centre (BWRC)	Radio Frequency (RF) and Millimeter Wave (mmWave) technology, Advanced Spectrum Utilization, Energy Efficient Systems and other Integrated Wireless Systems and Applications	http://bwrc.eecs.berkeley.edu/
Broadband Wireless Access & Applications Center (BWAC)	Opportunistic spectrum access and allocation technologies, Millimeter wave wireless, Wireless cyber security, Cognitive sensor networks of heterogeneous devices, Image and video compression technologies, IC and low-power design for broadband access/applications	https://bwac.arizona.edu/
Center for Wireless Systems and Applications (CWSA) at Purdue University	Devices and materials, Low power electronics, Communications, Networking, Multimedia traffic, Security	http://cwsaweb.ecn.purdue.edu/
ChoiceNet Project	Architectural design for the Internet of the near future	https://code.renci.org/gf/project/choicenet/
Clean Slate Project at Stanford University for research on Software-Defined Networking (SDN)	OpenFlow, Software Defined Networking, and the Programmable Open Mobile Internet	http://cleanslate.stanford.edu/
eXpressive Internet Architecture (XIA) Project	Internet Architecture	http://www.cs.cmu.edu/~xia/
Intel Strategic Research Alliance (ISRA)	Enabling new spectrum, improving spectral efficiency and spectral reuse, intelligent use of multiple radio access technologies, and use of content awareness to improve quality of service and wireless device power efficiency.	https://www.intel-university-collaboration.net/focused-research
Joint University of Texas, Austin and Stanford Research on 5G Wireless	New architecture for dense access infrastructure	http://www.ece.utexas.edu/news/profs-de-veciana-dhillon-and-collaborators-received-nsf-grant-work-5g-wireless-networks
Mobility First Project	Architecture centered on mobility	http://mobilityfirst.winlab.rutgers.edu/
Named Data Network (NDN) Project	Named Data Networking (NDN) architecture	http://named-data.net
NEBULA Project	Cloud computing data centers	http://nebula-fia.org
NSF Communications & Information Foundation (CIF)	secure and reliable communications	http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503300&org=CISE
NSF Computer & Network Systems (CNS)	enterprise, core, and optical networks; peer to peer and application-level networks; wireless, mobile, and cellular networks; networks for physical infrastructures; and sensor networks	http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503307&org=CISE
NSF Extreme Densification of Wireless Networks	Network densification	http://www.nsf.gov/awardsearch/showAward?AWD_ID=1343383&HistoricalAwards=false
NSF Future Internet Architectures (FIA) Program	Named Data Network (NDN), Mobility First, Nebula, Expressive Internet Architecture (XIA), ChoiceNet	http://www.nets-fia.net/
NSF Grant for Evaluation of 60 GHz Band Communications	Millimeter wave picocells	…………………………………………
Polytechnic Institute of New York University (NYU-Poly) Program	Smart and more cost effective wireless infrastructure	http://engineering.nyu.edu/
Qualcomm Institute	Robust wireless communication, multimedia communication systems, and devices for next-generation communication, wireless health	http://cwc.calit2.net/proposals.html
UCSD Center for Wireless Communications	Low-power circuitry, smart antennas, communication theory, communication networks, and multimedia applications	http://cwc.ucsd.edu/research/focusareas.php
Wireless@MIT Center	Spectrum and connectivity, mobile applications, security and privacy and low power systems	http://wireless.csail.mit.edu
Wireless @ Virginia Tech	Cognitive Radio Networks, Digital Signal Processing, Social Networks, Autonomous Sensor, Communication, Antennas, Very Large Scale Integration	http://wireless.vt.edu

TABLE 9. 5G related activities in Asia [109].

Research Project / Research Groups	Research area	HTTP location
IMT-2020 PROMOTION GROUP	5G research and development	http://www.imt-2020.cn/en/introduction
MOST (MINISTRY OF SCIENCE & TECHNOLOGY) 863-5G PROJECT	Radio-access-network (RAN) architecture, Massive MIMO	http://www.most.gov.cn/eng/programmes1/

Summary

- Describe a typical 5G Architecture
- Understanding the minimum requirements of 5G networks
- 10 key 5G enabling technologies for meeting minimum requirements
- Research opportunities in 5G

Today’s tutorial on Assignment 2 progress

Next lecture on emerging issues of IoT plus examination