

International Telecommunication Union

ITU-R
Radiocommunication Sector of ITU

Report ITU-R M.2320-0
(11/2014)

**Future technology trends of
terrestrial IMT systems**

M Series
**Mobile, radiodetermination, amateur
and related satellite services**

15 
1865-2015

 International
Telecommunication
Union

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Annex 1 of Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from <http://www.itu.int/ITU-R/go/patents/en> where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Reports

(Also available online at <http://www.itu.int/publ/R-REP/en>)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	Mobile, radiodetermination, amateur and related satellite services
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management

Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.

Electronic Publication
Geneva, 2015

© ITU 2015

All rights reserved. No part of this publication may be reproduced, by any means whatsoever, without written permission of ITU.

REPORT ITU-R M.2320-0

Future technology trends of terrestrial IMT systems

(2014)

TABLE OF CONTENTS

	Page
1 Introduction	3
2 Scope	3
3 Related documents.....	3
3.1 ITU-R Recommendations	3
3.2 ITU-R Reports	4
3.3 ITU-R Resolutions.....	4
4 Motivation on driving factors for future technology trends	4
5 Technology Trends and Enablers	5
5.1 Technologies to enhance the radio interface.....	5
5.1.1 Advanced modulation, coding and multiple access schemes.....	5
5.1.2 Advanced antenna and multi-site technologies.....	7
5.1.3 Physical Layer Enhancements and Interference Handling for Small Cell.....	9
5.1.4 Flexible spectrum usage.....	9
5.1.5 Simultaneous transmission and reception (STR)	11
5.1.6 Other Technologies to enhance the radio interface.....	11
5.2 Technologies to support wide range of emerging services.....	12
5.2.1 Technologies to support the proximity services.....	12
5.2.2 Technologies to support M2M.....	13
5.2.3 Group Communications	14
5.3 Technologies to enhance user experience.....	14
5.3.1 Cell edge enhancement	14
5.3.2 Quality of service enhancement	14
5.3.3 Mobile video enhancement	15
5.3.4 Enhanced broadcast and multicast	15
5.3.5 Positioning enhancements.....	16
5.3.6 Low latency and high reliability technologies	16

5.3.7	RLAN Interworking	17
5.3.8	Context Aware	17
5.4	Technologies to improve network energy efficiency	18
5.4.1	Network-level power management	19
5.4.2	Energy-efficient network deployment.....	19
5.4.3	User-centric resource management and allocation	19
5.4.4	Physical Layer Enhancements and Interference Handling.....	19
5.5	Terminal Technologies	20
5.5.1	Interference cancellation and suppression	20
5.6	Network Technologies.....	21
5.6.1	Technologies to simplify management and improve network reliability	21
5.6.2	Technologies to support ease of deployment and increase network reach	21
5.6.3	Technologies to enhance network architectures	23
5.6.4	Cloud-RAN	25
5.7	Technologies to enhance privacy and security	26
6	Conclusion.....	26
7	Terminology, abbreviations.....	26
	Annex 1 – Enhanced OTDOA/E-CID	28
	Annex 2 – Advanced SON.....	29
	Annex 3 – QoE Enhancements in a multi-RAT environment	29

1 Introduction

International Mobile Telecommunications (IMT) systems are mobile broadband systems including both IMT-2000 and IMT-Advanced.

IMT-2000 provides access by means of one or more radio links to a wide range of telecommunications services supported by the fixed telecommunications networks (e.g. PSTN/Internet) and other services specific to mobile users. Since the year 2000, IMT-2000 has been continuously enhanced, and Recommendation ITU-R M.1457 providing the detailed radio interface specifications of IMT-2000, has been updated accordingly. Some new features and technologies were introduced to IMT-2000 which enhanced its capabilities.

IMT-Advanced is a mobile system that includes the new capabilities of IMT that go far beyond those of IMT-2000 and also has capabilities for high-quality multimedia applications within a wide range of services and platforms providing a significant improvement in performance and quality of the current services. IMT-Advanced systems can work in low to high mobility conditions and a wide range of data rates in accordance with user and service demands in multiple user environments. Such systems provide access to a wide range of telecommunication services including advanced mobile services, supported by mobile and fixed networks, which are generally packet-based. Recommendation ITU-R M.2012 provides the detailed radio interface specifications of IMT-Advanced.

ITU-R studied the technology trends for the preparation of development of IMT-Advanced, the results were documented in Report ITU-R M.2038. Since the approval of Report ITU-R M.2038 in 2004, there have been significant advances in IMT technologies and the deployment of IMT systems. The capabilities of IMT systems are being continuously enhanced in line with user trends and technology developments.

This Report provides information on the technology trends of terrestrial IMT systems considering the time-frame 2015-2020 and beyond. Technologies described in this Report are collections of possible technology enablers which may be applied in the future. This Report does not preclude the adoption of any other technologies that exist or appear in the future, and newly emerging technologies are expected in the future.

2 Scope

This Report provides a broad view of future technical aspects of terrestrial IMT systems considering the time-frame 2015-2020 and beyond. It includes information on technical and operational characteristics of IMT systems, including the evolution of IMT through advances in technology and spectrally-efficient techniques, and their deployment.

3 Related documents

3.1 ITU-R Recommendations

- Recommendation ITU-R M.1036 Frequency arrangements for implementation of the terrestrial component of International Mobile Telecommunications (IMT) in the bands identified for IMT in the Radio Regulations (RR)
- Recommendation ITU-R M.1224 Vocabulary of Terms for International Mobile Telecommunications (IMT)
- Recommendation ITU-R M.1457 Detailed specification of the terrestrial radio interfaces of International Mobile Telecommunications-2000 (IMT-2000)

Recommendation ITU-R M.1645	Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000
Recommendation ITU-R M.1822	Framework for services supported by IMT
Recommendation ITU-R M.2012	Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications Advanced (IMT-Advanced).

3.2 ITU-R Reports

Report ITU-R M.2038	Technology trends
Report ITU-R M.2074	Radio aspects for the terrestrial component of IMT-2000 and systems beyond IMT-2000
Report ITU-R M.2243	Assessment of the global mobile broadband deployments and forecasts for International Mobile Telecommunications
Report ITU-R M.2334	Passive and active antenna systems for base stations of IMT systems

3.3 ITU-R Resolutions

Resolution ITU-R 56-1	Naming for International Mobile Telecommunications.
-----------------------	---

4 Motivation on driving factors for future technology trends

Report ITU-R M.2243 assesses the current perspectives and future needs of mobile broadband that would be supported by IMT over the next decade (2012-2022). It also presents mobile traffic forecasts provided by a number of industry sources for the forecast up to 2015 and one source for the forecast between 2015 and 2020 taking into account the new market trends and market drivers.

In order to support these market trends and to accommodate mobile data traffic explosion, the following aspects should be considered:

- system average throughput: the average throughput of cellular systems should be dramatically increased to support the exploding traffic for example by dramatically improving the spectrum efficiency;
- user experience: the user experience should be at least maintained regardless of the user's location and network traffic conditions;
- scalability: the number of mobile terminals to be supported by a base station (BS) will be significantly increased due to the services such as machine-to-machine (M2M), Internet of Things (IoT), etc.;
- latency: users' quality of experiences can be greatly improved by reducing the latency of the packet delivery and connection establishment, etc.;
- energy efficiency: low energy consumption is an important performance metric for both the network and the mobile devices;
- cost efficiency: low capital expenditure (CAPEX) and operational expenditure (OPEX) will reduce the cost of the network, and may motivate operators to expand and improve their networks. Additionally, low cost terminals will reduce the overall cost of a mobile subscription;
- network flexibility: the ever changing network topologies coupled with the complex and evolving wireless environment and services require that the future networks have a high

degree of built-in flexibility to easily adapt to such changes as non-uniform traffic distribution in order to manage multiple generations of networks of different radio access technologies (RATs) deployed so far;

- non-traditional services: Some potential new services and applications that are emerging in the mobile arena and are expected to undergo rapid development in the near future such as high definition (HD) mobile video, M2M communication, enhanced location based service (LBS), cloud computing, which will bring new challenges in coverage, capacity and user experience to future wireless network and will consequently trigger the further improvement of wireless technologies;
- spectrum utilization: more spectrum may be required to accommodate the mobile data traffic explosion. Many frequency arrangements, spanning a wide spectrum range; and increasing requirements to share with other services has resulted in multiple complex regulatory and technical considerations. While broad based spectrum harmonization may reduce the cost of technology resources, addressing challenges such as shared use of spectrum, mobile network architecture optimization, RF component complexity, antenna efficiency and device integration are the technology trends which have the potential to improve the spectrum utilization.

5 Technology Trends and Enablers

5.1 Technologies to enhance the radio interface

5.1.1 Advanced modulation, coding and multiple access schemes

5.1.1.1 Advanced modulation and coding schemes

Advanced waveforms and modulation and coding schemes and advanced transceiver designs are being investigated as solutions having potential to improve the spectral efficiency in future IMT systems.

Deployment conditions and the different applications which are anticipated in the 2015-2020 and beyond time-frame can emphasize the importance of different performance criteria and other characteristics of transmit waveforms and modulation and coding schemes. For example, sensor category machine type communications can require a robust link budget, may be extremely cost/complexity sensitive, and may prioritize very low power operation to realize long battery life. In contrast, the scenario of small cell indoor systems providing interactive, real time virtual reality or telepresence services may prioritize high data rate and low latency. These priorities can motivate the use of wide bandwidth and short duration of time-frequency resources. Such small cell scenarios may eventually be serviced using very high frequencies.

Given the breadth of applications anticipated for future IMT systems, a relatively diverse set of performance criteria and characteristics can be relevant to the choice of transmit waveforms and modulation and coding schemes in future IMT systems. From the perspective of efficient resource utilization, it can also be appealing to support these different properties simultaneously within the same channel bandwidth and transmission time interval. Therefore, future systems may incorporate: i) definitions for time-frequency resources and for physical layer channels which are more flexible than is possible with a homogeneous application of OFDM; and ii) a broader set of modulation and coding schemes as compared to the air interfaces of previous generation systems.

Some examples of advanced waveforms, modulation and coding schemes can be found in the references listed in the footnote below¹.

5.1.1.2 Non-orthogonal multiple access

The adoption of orthogonal multiple access with the baseline linear receiver in the IMT systems was mainly motivated by the goal of limiting the complexity of signal processing by mobile devices. However, various emerging trends have revealed major shortcomings of systems which employ orthogonal multiple access. In typical cellular scenarios, these systems cannot achieve the sum capacity of multi-user systems, where multiple users are served simultaneously.

Non-orthogonal multiple access schemes, on the other hand, have an essential capability to provide increased user capacity and throughput performance by allocating the same radio resources to multiple users. Resource sharing in non-orthogonal multiple access may exploit some combination of multi-user power superposition, multi-user space diversity and codebook based multiple access. Each of these approaches affects the properties of the transmitted signals and requires the selection of an appropriate advanced non-linear detector which is capable of resolving the multiple user signals at the receiver.

One such approach is termed successive interference cancellation (SIC)-Amenable Multiple Access (SAMA)^{2, 3}. By this approach, multiple signals are transmitted simultaneously over the same radio resources using power and/or space and/or time domain multiplexing and SIC based detection in the receiver completes the implementation of the non-orthogonal multiple access concept. Recently the definition of SAMA is further evolved to pattern division multiple access (PDMA) which

¹ References for examples of advanced waveforms, modulation and coding schemes:

- Jialing Li *et al.*, “A resource block based filtered OFDM scheme and performance comparison”, Telecommunications (ICT), 2013 20th International Conference on, vol., No., pp. 1, 5, 6-8 May 2013.
- Rusek, F.; Anderson, J.B., “The two dimensional Mazo limit”, Information Theory, 2005. ISIT 2005. Proceedings. International Symposium on, vol., No., pp. 970, 974, 4-9 Sept. 2005.
- M.G. Bellanger *et al.*, “FBMC physical layer: a primer”, PHYDYAS document (Online). Available: http://www.ict-phydyas.org/teamospace/internal-folder/FBMC-Primer_06-2010.pdf.
- Nikopour, Hosein; Baligh, Hadi, “Sparse Code Multiple Access”, Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on, vol., No., pp. 332, 336, 8-11 Sept. 2013.
- Taherzadeh, Mahmoud *et al.*, “SCMA Codebook Design”, Vehicular Technology Conference (VTC Fall). 2014 IEEE 80th, 14-17 Sept. 2014.
- Xiaoming Dai, 2010, “Successive Interference Cancellation Amenable Space-Time Codes with Good Multiplexing-Diversity Tradeoffs”. *Wirel. Pers. Commun.* 55, 4 (December, 2010), 645-654.
- 3GPP TS36.211, “Evolved Universal Terrestrial Radio Access (EUTRA); Physical Channels and Modulation”.
- Saito, Y. *et al.*, “Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access”, Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th, vol., No., pp. 1, 5, 2-5 June 2013.
- METIS – Deliverable D2.2. “Novel radio link concepts and state-of-the-art analysis”.
- METIS – Deliverable D2.3. “Components of a new air interface – building blocks and performance”.

² X. Dai, R. Zou, S. Sun, and Y. Wang, “Successive Interference Cancellation Amiable Space-time Codes with Good Multiplexing-diversity Tradoff”, IEEE APCC 2009 (Invited Paper), pp. 237-240, Oct. 2009.

³ X. Dai, “Successive Interference Cancellation Amenable Space-time codes with Good Multiplexing diversity Tradeoff”, *Wireless personal commun.* Vol. 55, No. 4, pp. 645-654, 2010.

considers possible pattern level multiplexing in the transmitter, such as power pattern and/or space pattern and/or code pattern, not precluding others. Research has shown that SAMA/PDMA⁴ techniques are able to achieve significantly improved spectral efficiency and greater fairness for users in the cellular system, especially for cell edge users.

Another example of non-orthogonal multiple access is sparse code multiple access (SCMA)⁵ in which the binary domain data is mapped using code books directly to multi-dimensional complex domain sparse codewords. Multiple access is achieved by mapping the sparse codewords from multiple users onto the same block of radio resources. Considering the sparse structure of the superimposed user signals created at the transmitter, the low complexity message passing algorithm (MPA) is well-suited for the detection and separation of the multiplexed user codewords at the receiver. It has been shown that SCMA can achieve large and flexible overloading factors, resulting in large and tuneable system capacity for cellular systems. On top of the capacity gain, the robustness of the link level performance can be significantly enhanced by the shaping gain of the multi-dimensional constellation and the diversity gain of the low density codeword spreading.

These non-orthogonal access schemes employing advanced non-linear receivers aim to support the entire capacity region of the multiple-access channel. The progress on nonlinear detection techniques and semi-conductor technology (Moore's Law) has made such non-orthogonal multiple access schemes promising technologies for future IMT systems.

Non-orthogonal multiple access using different domain may also be superimposed. There are examples based on spreading code multiplexing upon the non-orthogonal plane such as interleave division multiple access (IDMA) and low density spreading (LDS).

5.1.2 Advanced antenna and multi-site technologies

Advanced antenna technologies such as 3D-beamforming (3D-BF), active antenna system (AAS), and massive MIMO will be used in addition to network MIMO for achieving better spectrum efficiency.

5.1.2.1 3D Beamforming and Multi-User MIMO (MU-MIMO)

Current MIMO schemes are typically based on two-dimensional horizontal beamforming. As the number of antenna elements increases, it becomes beneficial to exploit the vertical dimension for beamforming, especially in dense urban environments. The ability to adjust transmitted beams in the vertical dimension can improve the received signal power of terminals deep inside high-rise buildings and help to overcome some of the building penetration loss. The 3D beamforming is also advantageous in indoor deployments in high-rise buildings, where a single base station may be able to optimise its coverage over more than one floor. Such techniques will directly increase spectral efficiency. In addition, the additional control over the elevation dimension enables a variety of strategies such as sector-specific elevation beamforming (e.g. adaptive control over the vertical pattern beamwidth and/or downtilt), advanced sectorization in the vertical domain, and user-specific elevation beamforming. Vertical sectorization can improve average system performance through the higher gain of the vertical sector patterns. Terminal-specific elevation beamforming is promising in improving the signal and interference to noise ratio (SINR) statistics seen by the terminals by pointing the vertical antenna pattern to the direction of the terminal, thus causing less interference to adjacent sectors via steering the transmitted energy in elevation.

⁴ Datang Telecom Technology & Industry Group, "Spectrum-Efficiency Enhancing Techniques for 5G", IMT-2020 Promotion Group 5G Summit, Beijing, China, June 2014.

⁵ METIS, ICT-317669-METIS/D2.2, "Novel radio link concepts and state of the art analysis", 31-10-13.

5.1.2.2 Active Antenna System

Active antenna systems (AAS), where RF components such as power amplifiers and transceivers are integrated with an array of antenna elements, offer multiple benefits. Not only are feeder cable losses reduced, leading to improved performance and reduced energy consumption, but also the installation is simplified and the equipment space requirement is reduced. To fully exploit the benefits from AAS, there is an increasing focus on defining relevant RF requirements and testing methodologies.

The spatial dimension is a key aspect of AAS and needs to be carefully considered. Such issue increases the complexity of the problem and possibly calls for some limited use of over the air (OTA) testing.

Equipped with AAS technology, arrays with large numbers of antennas placed on 3D plane can possibly be deployed in future radio access networks. The extension in antenna array dimension offers the flexibility in UE-specific spatial pre-processing in both horizontal and vertical domains. In addition to the capability of matching spatial distribution of signal to 3D channel, an early orthogonal spatial channel can be provided to each group of users and consequently leading to nearly-zero inter-UE and inter-cell interference in multi-user and multi-cell operation. The imposing gains in cell-average/edge spectral efficiency over state-of-art MIMO systems are observed in many published literatures and initial field measurement results of large-scale MIMO/massive MIMO.

5.1.2.3 Massive MIMO

By using AAS technology, it is possible to deploy arrays with large numbers of antennas placed on a plane in future radio access networks. The extension in antenna array dimension offers the flexibility in terminal-specific spatial pre-processing in both horizontal and vertical domains. Due to its high beam gain, massive MIMO can be utilized to fulfil future requirements for coverage and system capacity. In addition, with reduced array size and more isolation of inter-cell interference, massive MIMO operating at higher frequency band is expected to be more suitable for pico/hotspot cell. Furthermore, in the heterogeneous network coexisting with macro and pico/hotspot cells, massive MIMO can provide a flexible way in interference coordination/avoidance. Consideration of such techniques needs to take into account practical factors such as channel estimation and control signalling overhead to support large numbers of very narrow beams. As carrier frequencies increase, so-called Massive MIMO deployments may become more feasible for high-order MU-MIMO operation (enhanced MU-MIMO scheme with non-linear precoding). Especially, massive MIMO is attracting intensive attention from both academia and the industry. Technologies like adaptive pencil-beamforming with massive antenna will enable the utilization of new higher frequency spectrum like millimetric wave bands for cellular communications.

5.1.2.4 Network MIMO

Coordinated multi-point (CoMP) transmission and reception is a family of techniques where multiple transmission points are coordinated to improve the performance of certain terminals especially for cell-edge users. CoMP schemes with almost ideal backhaul connection between the transmission/reception points are supported by LTE-Advanced, while the benefits of such schemes with arbitrary backhaul are still being studied.

Network MIMO is symbolized by the cooperation of antennas from different sites. Significant gains have been found due to a proper interference mitigation framework based on network MIMO – sometimes called joint transmission coordinated multipoint transmission (JT-CoMP). Due to the complexity further research in this area is ongoing with the goal to come up with a robust and overall-efficient solution taking latest trends like massive MIMO, higher frequency bands etc., into account. Enabling techniques like channel prediction and predictor antennas for high mobility users extend the usability of such advanced concepts to higher mobility.

5.1.3 Physical layer enhancements and interference handling for small cell

In local-area scenarios, lower mobility and potentially higher signal-to-interference ratios compared to the wide-area case may justify link-level enhancements in terms of higher-order modulation and modifications to the reference-signal structure with reduced overhead.

The deployment of the low-power nodes may not be as well planned as the macro nodes, implying that various forms of interference coordination and interference cancellation are increasingly important. Deploying the low-power nodes in a frequency band separate from the macro nodes may also be used to handle the inter-layer interference. There are on-going studies on the potential interference coordination solutions including small cell on/off with fast discovery, power control and load balancing mechanisms, as well as over-the-air synchronization.

5.1.4 Flexible spectrum usage

Flexible spectrum usage can provide technical solutions to address the growing traffic demand in the future and allow more efficient use of radio resources including the limited spectrum resources.

Flexible spectrum usage can improve the frequency efficiency, which includes the following aspects:

- Cognitive radio techniques: cognitive radio systems could enhance spectral efficiency. Cognitive capabilities such as database access and spectrum sensing could be used to monitor the radio environment.
- Authorized shared access (ASA): when allocated spectrum is authorized as shared access, under appropriate coordination and related rules. For example, through the use of cognitive radio systems. Another possible example is that spectrum may be shared by several operators to deploy systems in same geographic area with coordination.
- Joint management of multiple RATs: in heterogeneous network, spectrum can be adjusted flexibly according to load of each RAT so that network can use the allocated spectrum more efficiently. Furthermore, flexible time resource usages among multiple RATs in the same band are possible to improve spectral efficiency.
- Flexible resource allocation: Asymmetric resource allocation between uplink and downlink as well as Carrier Aggregation (CA) between discontinuous bands can be promising technologies to utilize wider bandwidth for enhanced system performance. In time division duplex (TDD) systems, flexible uplink/downlink transmission is achievable by using dynamic allocation of time resources. In frequency division duplex (FDD) systems, asymmetric spectrum allocation between uplink and downlink is possible to increase downlink bandwidth in order to accommodate traffic asymmetry with higher spectral efficiency in both uplink and downlink. Carrier Aggregation of discontinuous bands including inter-band carrier aggregation could allow wider bandwidth to be used. Heterogeneous carrier aggregation which combines different carriers such as TDD and FDD could be considered.

5.1.4.1 TDD-FDD joint operation

To further enhance the spectrum flexibility, various forms of joint TDD-FDD operation, for example higher-layer or physical-layer aggregation between TDD and FDD carriers, is a promising technology. Such joint TDD-FDD operation could be envisioned when the two duplex schemes operate from the same network node, as well as in a heterogeneous deployment when one duplex scheme is used by the macro nodes and the other duplex scheme by the low-power nodes.

5.1.4.2 Open Carrier for Service Orientation

The future communication network is foreseen as a fully integrated and highly-efficient platform with huge volume of diversified and non-traditional services, e.g. machine-type communication (MTC),

device-to-device (D2D), eMBMS, small cell on high frequency band and so on. Evolution in IMT systems is needed to better support other services to compete with dedicated carrier solutions. It is possible to further improve the spectral efficiency of some component carriers with flexible bandwidth utilization and on-demand usage of common channels/signals for lower IMT terminal capabilities. The adaptation, multiplexing and sharing between services can be enabled by the flexible spectrum utilization methodology.

5.1.4.3 Dual Connectivity and Multi-Stream Aggregation

In scenarios where basic coverage is already available from the wide-area macro layer, operating the wide-area and local-area layers in a more integrated manner may prove beneficial. In particular, dual connectivity with split control-plane and user-plane, where the terminal is simultaneously connected to two network nodes, may provide multiple benefits such as:

- mobility robustness – that is, vital control-plane information such as handover commands can be transmitted from an overlaid macro node even if the user data is provided by a low-power node. A terminal being connected to a single node only may lose the connection if it has moved outside of the coverage area of the low-power node before the handover procedure is completed, a problem that can be avoided if the overlaid wide-area macro layer is responsible for transmitting handover commands. Alternatively, the handover commands can be transmitted from both the source and the destination nodes;
- user throughput enhancement: by aggregating data streams from different sites, a higher user throughput can be achieved. This can be seen as an extension of carrier aggregation or CoMP. Different nodes can also be used for different data flows depending on QoS needs;
- signalling reduction: depending on realization of inter-node radio resource aggregation, signalling overhead towards the core network can potentially be saved by keeping the mobility anchor in an overlaid macro node;
- uplink-downlink separation: that is, uplink reception may occur in a network node different from that used for downlink transmissions. Uplink-downlink separation is particularly advantageous in a heterogeneous deployment where the node with the strongest received signal at the terminal (and thus typically used for downlink transmissions) may not be the node with the lowest pathloss to the terminal (and thus not the best node for uplink reception) as the difference in transmission power and/or load between a macro node and a low-power node can be substantial;
- interference reduction: that is, minimizing unnecessary transmissions from the low-power nodes. As terminals can obtain essential system information from the overlaid macro layer, there is no need to broadcast this information also from the low-power nodes. This can also help in reducing the overall energy consumption as a low-power node only need to transmit when there is a terminal to serve in its coverage area.

5.1.4.4 Dynamic TDD

Both FDD and TDD are relevant duplex schemes in the low-power layer as they are in the overlaid macro layer. Traditionally, TDD in the macro layer uses a fixed and relatively static split between uplink and downlink resources on the carrier, such partition typically has to be identical across multiple macro nodes in order to avoid downlink-to-uplink and uplink-to-downlink interference. This is a suitable approach in a macro setting as there typically are multiple terminals in each macro cell and the aggregated traffic dynamics therefore are fairly constant over time. However, the number of terminals served by a specific low-power node can be very small, resulting in a higher per-node traffic dynamics.

Dynamic TDD is a candidate approach to better handle the high traffic dynamics in a low-power node. In dynamic TDD, the network can dynamically use resources for either uplink or downlink

transmissions to match the instantaneous traffic situation, which leads to end-user performance improvement compared to the conventional static resource split between uplink and downlink. At the same time, interference mitigation needs to be considered when nearby low-power nodes use different DL/UL configuration.

5.1.5 Simultaneous transmission and reception (STR)

Simultaneous transmission and reception (STR) in the same frequency band with self-interference cancellation a.k.a. full-duplex radio, is a novel spectrally efficient technique which can theoretically provide doubling capacity of cellular networks.

The typical scenarios for full-duplex radio include wireless backhaul (e.g. relay to eNB) and wireless access (i.e. one full duplex eNB and two half duplex terminal).

STR improves the physical layer capacity and provides other important benefits in layers beyond physical layer. For example, STR can reduce significantly end-to-end delay in multi-hop networks. In non STR systems, each node can start transmission of a packet to the next node only when it is fully received from the prior node in network. Therefore, the end-to-end delay is equal to packet duration multiplied by the number of hops. However, when STR is employed, a node can forward a packet while receiving it, and consequently the end-to-end delay in STR systems can be just a bit longer than the packet duration. This can be a huge advantage over non-STR systems especially as the number of hops grows. Meanwhile, the forwarded packet to next node can play a role of implicit acknowledgement to previous node as well.

In cognitive radio networks, active secondary users have to release the spectrum when primary users start their transmissions in general. Without STR capability, it is a challenge for secondary users to detect activity of primary users while they are using the spectrum for their own communication. However, STR-enabled secondary users may frequently scan the activities of primary users (even as they transmit) and stop their transmissions immediately once they detect primary users' transmissions.

Likewise, STR may make device discovery easier in D2D systems. This is due to the fact that in D2D systems, when user terminal has STR capability, it can discover neighbouring terminals easily by monitoring UL signals from proximate terminals without stopping UL transmission.

The key issues of STR are as follows:

- self-interference cancellation: antenna/RF/baseband;
- physical frame format;
- channel measurement mechanism and RS design;
- RRM mechanism and scheduling algorithms;
- networking;
- combination with other technologies.

5.1.6 Other technologies to enhance the radio interface

5.1.6.1 Flexible backhaul

The technologies for higher spectrum efficiency should also be applicable for wireless backhaul to provide better end-to-end performance while enabling clean and flexible solutions for backhaul in complex deployments. Besides, joint optimization of both backhaul and access links is expected to achieve further spectrum efficiency gain.

Flexible backhaul network, which is expected to satisfy various requirements for point-to-point, and point-to-multipoint connection systems, can be employed for industry application. Key features of flexible backhaul are characterized as follows:

- flexible system resources: utilizing flexible system resources including wired lines such as optical fibre, wireless resources of radio link, or those hybrid resources;
- dynamic network topology: adjusting network topology including backhaul transmission nodes appropriately in order to accommodate the varying traffic and to adjust the transmission capability. The plug-and-play capability is an attractive feature of the backhaul node deployment where spectrum bands can be self-organized for both access and backhaul nodes;
- efficient resource scheduling: efficient use of network resources such as frequency, space, power, and time, while maximizing the transmission capability of access network aggregated to the backhaul under control platform in the hierarchical structure.

Furthermore, in the case of wireless backhaul, it is a well-fit solution to improve transmission capacity, capability of mobile backhaul with more flexible and scalable network topology by utilizing available system resources and dynamic resource allocation to meet the network transmission requirement with affordable cost.

5.1.6.2 Dynamic Radio Access Configuration

Radio access configuration comprises the provisioning of different interworking RAT and the configuration of physical channels which may be defined as part of a future IMT air interface. The radio access configuration would be a dynamic process that would respond to the different environments, application and user characteristics, including the composition of the user population. Dynamic radio access configuration measures can ensure efficient use of resources such as radio spectrum resources, transmission power, and utility power needed to run the system. This approach also contributes to reduce the interference to neighbour cells and coexisting systems, while maintaining the desired quality of service for users.

The physical channels of the future IMT may differ in terms of a number of different system elements such as the waveform, modulation and coding schemes, frame (resource grid) structure, re-transmission scheme, and access scheme.

Radio access configuration may be supported by an adaptation mechanism that employs signalling exchange between UEs and the radio access configuration entity in the network, working on the PHY, MAC, RRM and IP layer. During initial access procedures, the UE capability information is sent to the network side, and the selection of radio access channels is ordered to the UEs from the network side based on some measurement metrics (e.g. CQI, QoS, QoE). The dimensioning of radio access channels may be explicitly controlled by signalling exchanges, while supplemental attributes and the associated parameters may be implicitly invoked.

5.2 Technologies to support wide range of emerging services

5.2.1 Technologies to support the proximity services

Proximity-based techniques can provide applications with information whether two devices are in close proximity of each other, as well as enable direct D2D communication.

D2D technique is a promising concept both for commercial and for public purposes. It may enable new service models such as local advertisement, finding friends and sharing data, network traffic offloading, and public safety. Beyond these usages, D2D communication may confer many additional benefits, improved cellular coverage, reduced end-to-end latency and reduced power consumption.

In general, D2D technique deployment includes the following aspects:

- discovery of proximity: it allows devices/users discover each other from requirement of range, with the help or under the network control of operators;

- direct communication between devices: network control and resource management is also needed to assist;
- integration of current infrastructure services: user experience can be kept consistently with respect to range and mobility;
- service requirements: it includes network operator control, authentication, authorization, and accounting.

Technologies that incorporate the benefits of D2D communication may be considered for future IMT systems. Of particular importance can be the use of D2D communication to potentially increase network capacity. However interference can increase in the different levels i.e. between D2D links and significantly between D2D and device-to-BS links (so called intra- and inter-tier interference) hence dedicated interference management mechanisms will be needed in order to not harm traditional network-based services.

5.2.2 Technologies to support M2M

The IMT-Advanced family of technologies has primarily been designed with data services in mind and much effort has been put into developing techniques for providing high data rates and low latencies for services such as file downloading and web browsing. However, with the increased availability of mobile broadband, connectivity has also become a realistic issue for machine-to-machine (M2M). In the long term, it is expected that all devices that benefit from network connectivity eventually will become connected, and the number of connected devices will by far outnumber the human-centric communication devices.

Clearly, there are a large number of very different scenarios and use cases for M2M and it is difficult, if not impossible, to define a single set of requirements. Nevertheless, the following technologies have recently been discussed in the research and standardization community:

- further improve the support of low-cost and low-complexity device types to match low performance requirements (for example in peak data rates and delay) of certain M2M applications;
- allow for very low energy consumptions for data transfers to ensure long battery life;
- provide extended coverage options for M2M devices in challenging locations;
- handle very large numbers of devices per cell.

For low-end M2M applications requiring very low cost with maintained coverage and spectral efficiency, bandwidth and peak rate reductions, the usage of a single receive RF chain, can be considered.

In order to enable long battery life, the energy consumptions of every data transfer of a device need to be reduced to a minimum. For devices with infrequent data transmission, energy consumption can be further reduced if the DRX cycles are significantly extended. This enables a device to make use of extended sleep times when not transmitting data, which minimizes reading of control channels and mobility-related measurements. Furthermore, infrequent transmissions of small amounts of user data are typically associated with signalling procedures, for example to establish radio bearers. These signalling procedures are sometimes more expensive from a power-consumption perspective than the data transfer itself. Simplifying these procedures for infrequent small data transfers can therefore provide significant benefits.

In some use cases M2M devices may be located in challenging locations where wide-area coverage is not available with existing network deployments. One example hereof is smart meters in the basements of buildings. Options for coverage extensions are primarily repetition and energy accumulation of the appropriate signals, possibly complemented by directional antennas and/or a further densified network.

Since the number of connected machines is expected to grow to very large numbers, mechanisms are needed to handle a large number of devices within a given area. Lightweight signalling procedures are therefore desirable to reduce the signalling load per device. Note that a lightweight signalling scheme may at the same time improve device battery consumptions as described above.

The application of M2M communication is proliferating and will play more and more important role in the daily life. It is required the technology development to better serve the M2M applications and support a high volume of M2M applications.

The technology varies greatly for different types of M2M applications. A simple classification of M2M applications could be small data/long delay, small data/short delay, and large data M2M. The former includes the smart metering, mobile tracking, and eHealth, etc. The second refers to the vehicle to vehicle communication. The third refers to the video surveillance. For the first type of applications, low cost, low power and large coverage are the common requirements. For the second type of applications, the short delay and high reliability are the key requirements. As for the third type, high data rate is the key requirement. The appropriate air interface design may not be the same due to the large variance in the requirements of different types of M2M applications.

For the first type of applications, the narrow band technology may be a good choice due to its excellent coverage performance and low processing complexity. For the second type of applications, the network controlled D2D communication can be considered as it allows sending a packet to another terminal in a very short time through the direct path.

Existing air-interfaces, such as cdma2000, can also be enhanced to provide better link budgets, lower power consumption, and increased capacity and reduced overhead. These techniques include reduction of overhead, restructuring of control channels, supporting lower data rates and the management of channel usage.

5.2.3 Group Communications

Group communication, including push-to-talk type of communication, is highly desirable for public safety, for example when a dispatcher needs to address multiple officers working in an emergency situation. Support for group communication for LTE is worked on in 3GPP.

5.3 Technologies to enhance user experience

5.3.1 Cell edge enhancement

Relay based multi-hop network architecture can reduce the shadow area and greatly enhance QoS of cell edge users especially in low traffic regions, and can reduce optic backhaul cost between the digital unit (DU) and radio unit (RU) in DU-RU separated architecture. In addition, cooperative communication such as advanced CoMP can greatly improve the QoS of cell edge users in high traffic regions. A very sharp beamforming using large-scale antenna can also enhance the cell edge users' experience.

5.3.2 Quality of service enhancement

Small-cell deployment can improve the QoS of users by decreasing the number of users in a cell and user experience can be enhanced.

A large number of services, including emerging novel services, will enable users to exploit the high capacity and low latency features of the network. Those services have different QoS requirements and traffic characteristics. If the network is aware of traffic types and differentiates traffic according to the traffic types, it will enable traffic-specific or service-specific enhancements for transmission efficiency and power efficiency, which finally leads to network efficiency optimization and Quality of Experience (QoE) enhancement.

Moreover, if the network is aware of the user's subjective quality of perception (e.g. user's satisfaction level on tariff, battery life-time, and display resolution) as well as objective quality of services (e.g. data rate, BER), the network can provide better quality of experience to users by utilizing their satisfaction level as one of scheduling parameters for efficient allocation of network resources. This approach to QoE enhancement requires cooperation between terminals and wireless networks. Annex 3 introduces a QoE enhancement framework in a multi-RAT environment.

5.3.3 Mobile video enhancement

The higher QoE required due to the increasing trend from VoIP call to Video call will present considerable challenge to the capacity constrained mobile network. The transportation of streaming service with HD support is driven by market shift towards smart phone/tablet, and over the top (OTT) players provides more streaming service with low monthly payment and legacy TV players are streaming their content too.

In terms of transmission technology, dynamic adaptive streaming over HTTP (DASH) allows the network to trade off among user perceived streaming quality, network condition and achieved QoS. Considering the massive streaming content delivered over network, the converged broadcast and unicast is one prominent solution. DASH enhancement and evolved multimedia broadcast multicast service (eMBMS) enhancement are studied to improve user experience and accommodate more streaming content in existing infrastructure.

In terms of source coding technology, high efficiency video coding (HEVC), also known as H.265, is the next generation of video coding technology supporting up to 4K ultra HD video service. 3D coding is another important technology for virtual reality and immersive display. H.264/AVC extension and H.265/HEVC extension are studied to support 3D coding, which places a significantly high requirement for bandwidth.

Further research on mobile video enhancement will focus on end-to-end system performance improvement from the perspective of video transmission efficiency and QoE of the video service.

The trend towards mobile computing including the anticipated wide spread acceptance of social mobile video becomes more and more popular, and drives the dramatic increasing of wireless network traffic in the coming years.

Mobile network should be able to support diverse video services with good end-to-end experience, such as SD and HD HTTP streaming and especially DASH, video call, gaming, etc., each of which has different QoE requirement.

5.3.4 Enhanced broadcast and multicast

Bandwidth Saving and transmission efficiency improvement is an evolving trend for evolved multimedia broadcast multicast service (eMBMS). It neatly offloads the mobile network operator's network by enhancing eMBMS mechanism to support diverse services. Flexible broadcasting should be supported for dynamically delivering event-triggered services, such as push type service (e.g. twitter) and other grouping services (e.g. trunking, IPTV broadcasting, and video clips sharing) etc. Considering more and more virtual operators in the future, sharing of MBMS services across public land mobile networks (PLMNs) is also considered as an expected trend. And combination of unicast/multicast should also be considered for optimizing the transmission of concurrent demand service/content that otherwise has been delivered via unicast separately by multiple subscribers.

The dramatic capacity due to video traffic boosting is a big challenge to the mobile network transmission capability, where the multimedia broadcast and multicast transmission can provide an efficient solution to accommodate more streaming content in existing infrastructure. To provide acceptable end user experience of multimedia service, dynamic switching between unicast and multicast transmission can be beneficial.

5.3.5 Positioning enhancements

Some of the technologies that are currently used for positioning are GPS, observed time difference of arrival (OTDOA), uplink time difference of arrival (UTDOA), and radio frequency pattern match (RFPM). GPS is used only in outdoor and its application is limited, especially in the scenarios of indoor, and UTDOA needs to deploy additional equipment to currently deployed base stations, while RFPM is a positioning technology based on RF signal strength measurement and needs large numbers of measurements.

With the introduction of new features in the future wireless network such as carrier aggregation, heterogeneous network (HetNet) and small cell, positioning technologies should be enhanced accordingly, e.g. enhanced OTDOA (EOTDOA), further enhancement of enhanced cell ID (E-CID) and etc.

Annex 1 provides additional information on EOTDOA/E-CID.

5.3.6 Low latency and high reliability technologies

The reliability and latency in today's communication systems have been designed with the human user in mind. It is envisioned that future wireless systems will to a larger extent also be applied in the context of M2M communications, for instance in the field of traffic safety, traffic efficiency, smart grid, e-health, wireless industry automation, augmented reality, remote tactile control and teleprotection. These applications may require an end-to-end latency by the order of a few ms, and/or with ultra-high reliability (e.g. transmission failure rates down to the order of 10^{-9}). All these applications and services will bring forward great challenges to the present IMT network. For instance, in vehicular communication the safety related information is expected to be distributed to the proximal vehicles and infrastructures in very short delay. In critical communication for public safety, the end-to-end group session setup latency is required to be fewer than hundred milliseconds with or without infrastructure support.

In case a new solution from upper layers does not become timely widespread, the other path is to make the future system display a wire-like behaviour in terms of latency and reliability. Here an important trade off appears. Link layer retransmissions can mask errors occurring in the physical layer but lead to further packet delay variation. The only way to mask errors without exacerbating jitter is to have shorter transmission cycles and timely retransmissions.

To obtain such ultra-low latencies on data and control planes may require significant enhancements and new technical solutions as compared to current IMT standards, both on the air interface and network architecture.

Basically 6 aspects can be considered to provide low latency and/or high reliability as follows:

- Air interface optimization: The air interface needs to be modified to accommodate for low latency and high reliability. For low latency, key components like frame structure, control signal timing, and HARQ procedure and settings should be reconsidered to decrease the TTI length as well as the RTT of the air interface and ensure low latency transmission. High reliability communication could include more coding on the air interface but the level of coding may compromise the low latency.
- Latency- and reliability-aware radio resource management: Further, latency and reliability guarantees may be provided from a system perspective by taking these requirements into consideration in radio resource allocation, i.e. giving priority to delay-critical transmissions while postponing delay-tolerant ones. Future networks may in particular use a prediction of user movement and application behaviour in order to proactively allocate resources in a forward-looking way according to QoS constraints instead of solely reacting to current channel conditions and application needs.

- Direct device-to-device transmission: Clearly, lowest latency in the communication – between two devices in proximity can be achieved via direct D2D communication. Also, due to the better link budget between devices in proximity, it is possible to provide a link at higher reliability than in classical device-infrastructure-device communications.
- Edge computing: For some future applications, the maximum allowed end-to-end latency will be so limited that the application basically has to be moved from the cloud to the edge, i.e. an infrastructure node which is located as close as possible to the devices utilizing the application. An option would for instance be to have applications hosted directly on, e.g. cellular base stations. A use case where this would be required is for example augmented reality, where video information from AR glasses would be processed in real-time on the edge, before the augmented video information is sent back to the AR glasses.
- Access procedure optimization: The access procedures like random access, connection setup, handover and authentication need reconsideration to leverage the performance of low latency and high reliability.
- User plane path optimization: Many new communication use cases are related to the proximity of end users, and thus the user plane transmission path is required to switch dynamically and seamlessly to optimize the latency performance.

5.3.7 RLAN Interworking

Radio local area networks (RLANs) based on the 802.11 family of standards are already used by many operators for offloading cellular networks and embracing capacity expansion into license-exempt spectrum bands. The LTE specifications provide support for RLAN interworking, including seamless as well as non-seamless mobility, at the core network level.

The selection whether to use RLAN or 3GPP access currently resides in the terminal and is implementation-specific. Existing terminals have no information about the network load and typically connect to the RLAN whenever such a network is found, irrespective of which technology would be preferable from an end-user perspective in a particular scenario. Hence, existing terminals may switch to an RLAN even if it is heavily loaded and the LTE connection would provide significantly better end-user experience. Providing the system with mechanisms to support control by the network over the radio-access technology used by the terminal can remedy this situation.

5.3.8 Context Aware

Future IMT systems need to be context-aware allowing context information in real-time manner on the network, devices, applications and the user and his environment. This allows improving the efficiency of existing services and providing more user-centric and personalized services while ensuring high QoE for those services and proactively adapting to the changing context. For example, networks will need to be more aware of the application requirements, QoE metrics, and specific ways to adapt the application flows to meet those QoE needs of the user and the application needs. For video content, for example, the network will need to be aware of the rate-distortion characteristics of the video flow and the priority of the video frames to make better multi-user resource allocation decisions when managing congestion. There will need to be new interfaces between the application layers and network layers to efficiently adapt both the application source and networking resources to deliver the best QoE for the most users (capacity) considering a trade-off between the best QoE to offer and the resources cost “for the network and devices”. The network will also need to be aware of the users’ location to be able to take a cost-effective decision on the video delivery, for example on multicast delivery instead of unicast to users within the same region (this could be especially beneficial for live sport and political events that attract real-time audience). Context-aware network design will help lower device power consumption, an important consideration for enhanced user experience, by taking into account user context, device implementation, and modes

of wireless connectivity available. For example, user may choose to select a particular RAT or choose between using cloud or local services based on energy efficiency considerations.

The context-based adaptations discussed above take into account device level context (battery state, CPU load, device characteristics such as display size, multi-comm capability), user context (user specific preferences on quality, user activity, user location, user level of distraction), environment context (motion, lighting conditions, proximate devices, background activity), and network context (congestion/load, available timely throughputs, alternative network/spectrum availability). New ways to abstract and efficiently generate the context information through collaboration between the device and cloud-based services will be needed, and new ways to share the context information between the application, network, and devices will also be needed. Privacy means for sensitive context information, “especially user context information, need to be present to guarantee services acceptability by users.

5.4 Technologies to improve network energy efficiency

Energy efficiency has become an important issue for wireless communication systems, where specific performance metrics, requirement and technologies to improve energy efficiency must be taken into consideration. It is shown that bit per Joule is a suitable performance metric to measure the energy efficiency for a specific network, which denotes how many data bits can be reliably conveyed by the network with unit energy provided. In order to enhance energy efficiency, energy consumption should be incorporated in protocol design including scheduling scheme system development. For example, bps/Joule can be an excellent performance metric.

In addition to the general quest for a more sustainable world, there are clear practical benefits from improved network energy efficiency:

- for many operators, the cost of the energy to operate the networks contributes a major part of the overall operational expenses. High energy efficiency is thus important in order to limit the operational cost, especially taking into account the expectations of energy prices increasing in the future;
- the possibility for reduced base-station energy consumption may open up for new deployment scenarios, for example solar-powered base stations with reasonably sized solar panels in areas with no access to the electrical grid. This is of particular interest for spreading mobile broadband services in rural areas within the developing world.

Heterogeneous network including various types of base stations such as macro, micro, pico, and femtocells can enhance network scalability and flexibility. When or where mobile data traffic is very bursty, especially distributed antenna system (DAS) can be another promising technology to reduce total power consumption because a single antenna radiating high power can be replaced with many low power elements to serve the same area.

Since mobile data traffic typically varies dramatically in time and/or geography, network adaptation to re-assign radio and power resources among isolated network nodes in order to align the fluctuation of traffic may lead to higher energy efficiency. Besides, advanced resource allocation for both access and backhaul links should be considered to improve the overall energy efficiency of the whole network.

In addition, technologies to improve the energy efficiency of hardware, e.g. advanced power amplifier must be taken into consideration.

From the user’s perspective, energy saving is also important to increase user battery life. For example, communication between users or a small cell and a mobile terminal in proximity directly can reduce user’s transmission power due to high possibility of good channel characteristics and interference management.

Also, in specific application, such as mobile relay for high speed train, with mobile terminals connected to a close by relay node on board, the required transmit power of the mobile terminals is much less, leading to significant mobile terminal power saving and increased mobile terminal battery life.

Energy efficiency has been recognized as an issue, which should be jointly considered with spectral efficiency for future network design. Traditional spectral efficiency oriented design only concerns about the air interface issues, which means that only transmit power consumption is considered. From Shannon theory, a trade-off between energy efficiency and spectral efficiency exists, i.e. increasing spectral efficiency will cause energy efficiency reduction. However, in the realistic network operation, besides the transmit power, circuit power also exists and takes an important part. For example, after considering circuit power, energy efficiency will first increase and then decrease with spectral efficiency in additive white Gaussian noise (AWGN) channels.

5.4.1 Network-level power management

Energy efficiency of a network can be improved from both saving transmit power and circuit power. Naturally, if a technique can improve channel capacity, less transmit power is needed to achieve the same data rate. Therefore, the energy efficiency is improved in the condition that no additional circuit power is introduced. If circuit power can be reduced without affecting the data rate, the energy efficiency can also be improved. In practical networks, circuit power may be affected by many factors, such as the chip processing capability, efficiency of power amplifiers, the number of base stations, the number of antennas, the frequency bandwidth, etc. Furthermore, the factors related to wireless resources also affect the data rate. Therefore, the whole network power consumption on air interface and devices should be cooperatively managed to enhance energy efficiency.

5.4.2 Energy-efficient network deployment

Nowadays, traffic volumes are becoming more diverse both temporally and spatially. Network deployment should be optimized to accord with traffic variation. Traffic balancing among multiple RATs is a good way to enhance energy efficiency. Heterogeneous networks including various types of base stations such as macro, micro, pico, and femtocells can enhance network scalability, flexibility and energy efficiency. The density of small cells in heterogeneous networks should be optimized by jointly considering the circuit and transmit power consumption. Distributed antenna system (DAS) can reduce transmit power consumption by moving the antennas closer to users.

5.4.3 User-centric resource management and allocation

To well enhance energy efficiency, the traffic variation characteristic of different users should be well exploited for adaptive resource management. Good examples include discontinuous transmission (DTX), base station and antenna muting. Various resources, such as transmit power, base stations, antennas, and frequency bandwidth, are expected to be jointly optimized. Based on different realistic power models, different resources may be used with high priority.

By exploiting different service quality requirements from multiple users, new scheduling and resource allocation schemes can be re-designed from the perspective of energy efficiency. The resource allocation among multiple RATs is also a possible way to further save energy.

5.4.4 Physical layer enhancements and interference handling

Low energy consumption is an important characteristic in general but further emphasized with the increasing number of network nodes in a heterogeneous deployment and the typically low average load/usage per node. Furthermore, it is reducing the average interference generated by minimizing transmission of signals when no users are actively receiving from or transmitting to a local-area node can be beneficial. Fulfilling these design targets may require modifications to existing transmission

structures such as reducing or completely switch off transmissions from a network node when there is no data to transmit.

5.5 Terminal technologies

Mobile terminal will become more human friendly companion as a multi-purpose ICT device for personal office and entertainment, and will evolve from hand-held smart phone to wearable smart devices such as smart watch and smart glasses. Future mobile devices might be flexible and stretchable, allowing the user to transform their mobile device into different shapes. It will be self-powered from the sun, water, or air, sense the environment, and be composed of flexible material and self-cleaning surface that nanotechnology might be capable of delivering.

High resolution display and high computing power application processor of mobile terminal that can process images or videos of hologram and UHD will result in ambiguous border between mobile terminal and portable computer.

As the network evolves into a multi-RAT and multi-layer network, future mobile terminals will be equipped with multiple network interfaces, each for different RAT. They can deliver different multimedia traffic over the different RAT at the same time, after selecting the best RAT that is optimized to network conditions and accessibility, QoS/QoE requirements, mobile terminal conditions such as battery life-time, user preferences, and service cost over the RAT.

The terminals should be able to combine simultaneously several different traffic flows transmitted over channels of the same or different RAT, achieving higher throughput and optimally using the heterogeneous radio resource. They have key functional modules such as RAT connection control, quality policy-based routing, security and policy management, intra/inter-RAT handover control for seamless service continuity, and QoS/QoE control management. The mobile terminal must collect periodically the data such as user preference parameters for QoE satisfaction, user location and velocity information, battery life-time, service cost over any available RAT, and the QoS parameters in RATs.

Moreover, the user terminal performing the highly-sophisticated signal processing, i.e. advanced receiver, is desired. The advanced receiver should be able to work well with further improvement of capability to satisfy the demands for higher user throughput and higher system capacity.

5.5.1 Interference cancellation and suppression

Inter- and intra-cell interference is one of the capacity-limiting factors and various forms of RRM algorithms on the network side are typically used to control the amount of interference experienced by a terminal. However, recently there has been an increasing interest in exploiting interference suppression or cancellation in the terminal to further boost the overall performance. The terminals can blindly attempt to estimate the interference, but further improvements in performance might be obtained if the network provides assisting information.

In case of the higher-order MIMO technologies, the cancellation or suppression of self-interference due to inter-layer interference is applicable even without any assistance from the network.

In the coming future, non-linear detection such as iterative/non-iterative soft interference cancellation or maximum likelihood detection (MLD) is expected as an effective technology used for advanced receiver built in user terminals. Advanced receivers will contribute to increase the number of MIMO streams and spatially-multiplexed users, and thereby the user throughput and the total capacity will be enhanced.

5.6 Network Technologies

5.6.1 Technologies to simplify management and improve network reliability

Tremendous increase in mobile data traffic has been experienced by the networks due to the proliferation of smartphones and tablets during the last few years. The increase of user traffic, especially for OTT application traffic, makes a new network architecture and dense deployment necessary to reduce the CAPEX/OPEX of operators and overcome revenue decrease, as operators introduce more multi-RAT and multi-layer networks leading to increased network complexity. Hence there is a need for solutions to meet those challenges. The advanced self-organized network (SON) technology is one promising solution to enable the operators to improve the OPEX efficiency of the multi-RAT and multi-layer network, while satisfying the increasing throughput requirements of subscribers. Future needs may require more intelligent technology supporting the networks to become self-aware, i.e. the “cognitive network” technology that will allow optimization of networks and making smart decisions for network evolution in less time and without the manual processes.

Annex 2 provides detailed information on Advanced SON.

5.6.2 Technologies to support ease of deployment and increase network reach

Network architecture, no matter logic architecture or deployment architecture, should be rethought by taking the traffic variance into account. From the aspects of network deployment, cost reduction, better QoE, and energy consumption reduction, the key features of novel network architecture should be “soft” and “green”.

5.6.2.1 Network densification

Because of the projected significantly huge capacity requirement in the next ten years, the cell miniaturization and densification is touted as the most favourable way forward.

With the huge number of low cost cells deployed in the network, the transfer of information between small cell with low cost is very critical, so the technology for backhaul link between the small cells, especially wireless solutions for backhaul should be considered.

At the same time, the cost for network programming and network optimization will be extremely increased. The advanced SON technology for future system is therefore a necessity as it will enable the plug and play deployment of small cells in a dense network without manual intervention besides enabling the adjustment and optimization of the parameter such as power, inclination angle, boundary of cell/cell group, and RRM algorithm. Wireless backhaul is also advantageous as compared to fixed backhaul in its flexibility to dynamically adjust to the changes in network requirements. High capacity, low latency and high reliability are the major requirements of wireless backhaul, which must be met with suitable technologies.

With the expected large increase in the number of network nodes resulting from network densification, the complexities of site acquisition and backhaul provisioning will become increasingly more challenging. Heterogeneous deployments may also pose different requirements on the backhaul compared to a macro-only network. For example, in areas where the macro network is already providing basic coverage, the requirements on backhaul availability over time for a low-power node may be relaxed. The importance of SON may also increase to limit the burden of network management, especially in scenarios where the deployment of low-power nodes are less well planned.

5.6.2.2 Small cells

Network densification through the deployment of large number of small cells is being considered as one of the most effective ways for providing increased system spectral efficiency and satisfying the explosive traffic demand. The system capacity per square kilometre can be almost linearly

increased as the number of deployed small cells increases if appropriate interference management techniques are exploited.

From mobile operators perspective small cells will offer improvement of capacity, particularly in urban environments. Thus, the small cells will provide the seamless integration with existing network deployment without causing undue interference. This will most be handled by techniques of self-organizing, self-optimizing, and self-healing capabilities within the small cell network. That will as well reduce the operational expense required to maintain and operate dense deployments.

Along with the current small cell trend, the dynamic virtual cell concept, which coordinates BSs interconnected by direct wireless links, is considered as one of promising technologies because it provides higher link reliability and uniform QoE through user-centric virtual cells formation. New flatter network architecture is also promising since it supports a significant volume of traffic from small cells by distributed Internet access at local nodes and provides enhanced features for small cells such as content cache, edge cloud, etc.

The deployment of small cells is expected to provide more scalability and capacity. The benefits of deploying in small cells in higher frequency bands will impose increased system complexity particularly in terms of RF and antenna design, however with the technical advances in wireless system implementation the technical challenges can be leveraged.

5.6.2.3 Ultra dense network

One of the most important design goals of future IMT networks is to achieve the requirement of being able to provide extremely high traffic capacity and multi-Gbps data rates in specific scenarios such as ultra-dense urban or stadiums. Network densification by deploying ultra large numbers of cells is very effective in increasing spectral efficiency via cell splitting. In extreme cases, indoor access nodes would be deployed in every room of a department and outdoor access nodes would be deployed at lamppost distance apart.

To reliably support ultra high data rates and capacity, ultra dense networks will address:

- network architecture and protocol procedure enhancements: to optimize data and control paths, mobility management and signalling procedure will reduce the end-to-end latency and overhead;
- interference avoidance and inter-cell coordination: interference management and other coordination mechanism among the cells will increase the whole system throughput and guarantee the users' experience;
- energy efficiency: including network energy saving and UE power saving;
- super SON: release the operators' burden for network optimization and increase the flexibility of deployments.

5.6.2.4 Multi-radio access and multi-mode

The trend to integrate multiple radio access technologies seamlessly will accelerate due to the need to integrate new spectrum bands, licensed and unlicensed to meet capacity demands, and to support usages such as IoT wherein IoT devices with non-cellular radio may connect to cellular network through a multi-radio gateway.

The coexistence of multi-RAT (e.g. pre-IMT/IMT/RLAN) introduces many challenges for operators, e.g. burdened maintenance and difficult operation with multiple management system, degraded user experience such as delay and power consumption due to interoperability between different RATs/modes, imbalanced and low resources utilization of different RATs, inflexible and inefficient traffic steering since the RRM entity is independent from each other, and so on.

Therefore, it is beneficial to consider a general access system with new architecture and solution to optimize the multi-RAT coordination and interworking from RAN perspective to meet the following requirements:

- flexible RRM of multi-RAT for the improvement of resource utilization, load balancing and seamless mobility management;
- service aware traffic steering to different RATs for consistent user experience and user satisfactory, e.g. by simultaneously connecting to multi-RAT;
- improve signalling robustness and efficiency with sending the signalling via the most appropriate way;
- scalability of adding new RAT from core network perspective;
- reduce the maintenance and optimization complexity

Multi-RAT/mode network operated by one operator are becoming a typical scenario in the future. It is required to better coordinate among multi-RAT and future new RAT(s) to provide better user experience. Multi-RAT/mode coordination and integration, especially multi-RAT coordination and integration, and integration between FDD and TDD can be considered to ease the burden of interaction among multi-RAT/mode.

5.6.2.5 Mobile relay

High-speed public transportations, e.g. bus, train, or airplane, have been deployed worldwide in an increased pace, and providing multiple services of good quality to users on high speed vehicles is important yet more challenging than typical mobile wireless environments also due to reduced handover success rate and degraded throughput from high Doppler effects. Mobile relay is a technique to solve the above problems. A mobile relay indicates a base station/access point mounted in a moving vehicle likely to provide at least the following key functions:

- wireless connectivity service to end users inside the vehicle;
- wireless backhauling connection to on-land network;
- capability to perform group mobility;
- capability to allow different air interface technologies on the backhaul and access link.

Handover success rate can be improved via mobile relays, where excessive handover signalling is avoided by performing a group mobility procedure instead of individual mobility procedures for every terminal. Separate antennas for communication on backhaul and access link can be used to effectively eliminate the penetration loss through the vehicle and spectrum efficiency can be improved by exploiting more advanced antenna arrays and signal processing algorithms by mobile relay. With mobile relays, only one radio access system is required on the backhaul link, which can possibly reduce the number of radio access systems required at base station along the vehicle path. Those high-speed vehicles inevitably cause the degradation of users' QoS and the network overload that comes from simultaneous handover events for the users on the vehicles. Mobile relay can solve the problem by supporting group handover. In addition, the mobile relay enables network operators to exploit different types of access networks for backhaul. To support group mobility, moving backhaul with very high capacity links will be necessary.

5.6.3 Technologies to enhance network architectures

A number of emerging trends have the potential to drive dramatic changes in the network architecture for service delivery.

From the operators' perspective, the driving factors to exploit a new architecture include, but are not limited to:

- the tremendous increase in mobile data traffic because of the proliferation of smartphone devices;
- opportunities with software defined networking (SDN) and virtualization to effectively support the high rates of Web 2.0 OTT services;
- necessity to lower the CAPEX and OPEX;
- dynamic trends in traffic loads;
- energy efficient communication towards ‘green’ networks.

These allow operators to better differentiate and monetize their network assets. To accommodate increased data traffic in the future IMT systems, there will be an increasing number of intelligent and flexible nodes at the network. These will impose several challenges:

- increased number of intelligent and flexible nodes at the network edge;
- expansion of storage/CDN capabilities;
- the leverage of pre-caching of content based on estimated popularity;
- the need of more processing at the edge of the network;
- aggregation of raw information coming from the multitude of sensors/context hook.

The future IMT will need more flexible network nodes which are configurable based on the SDN architecture and network function virtualization (NFV) for optimal processing of the node functions and improving the operational efficiency of network. Software driven network with virtual functional nodes will provide novel system with flexibility and enhancements for dynamic, scalable and self-optimization capabilities for data processing and connection with the radio access network. In addition, the technical innovations will cultivate the potential capability with remarkable reductions in the cost and complexity. These new capabilities and technologies in the future IMT network need to be enhanced to manage the network and associated nodes with new interfaces supporting real-time software updates as well as new security mechanisms to prevent hackers from modifying or even crashing the network.

5.6.3.1 Novel RAN architecture

The RAN system design shall facilitate different architecture and implementation alternatives to accommodate different use cases. Options ranging from a completely flat architecture with autonomous base station units with moderate inter-node coordination to options for centralized implementations shall be supported. The distributed architecture alternatives shall include various options for logical interfaces between the base station nodes to enable coordination, including exchange of both user-plane and control-plane data. Examples of such base station to base station interfaces are backhaul connections and inband/outband over-the-air radio communication between base station nodes. Options for over-the-air communication between base station nodes are especially foreseen to be promising for small cell indoor base station nodes to facilitate simple and efficient autonomous small cell control-plane coordination.

The system design shall also facilitate options for centralized RAN implementation for clusters of cells. Examples of use cases where this could potentially be attractive include dense clusters of small cells with high degree of mutual inter-cell dependencies, and therefore opportunities for benefiting from centralized multi-cell radio resource management.

The RAN architecture shall support a wide range of options for inter-cell coordination schemes, ranging from simple network centric interference coordination options to more advanced CoMP schemes, mobility, SON, etc. Furthermore, the RAN architecture design shall support options for efficient multi-cell connectivity and assistance schemes, e.g. where a terminal is simultaneously associated with a macro and small cell in some form; having either simultaneous or separate user-plane and control-plane connectivity to the involved cells.

5.6.4 Cloud-RAN

Future networks will deploy dense networks, which will be more heterogeneous than today. Since the increase of the number of nodes poses several challenges, as listed in § 5.6.3, the most important goal is to keep CAPEX and OPEX reasonably low. The deployment of more intelligent and flexible nodes which allows lower CAPEX and OPEX is a key design for RAN. In addition the RAN architecture needs to be very flexible. The architecture can support fully distributed, fully centralized implementations, as well as hybrids of centralized and distributed implementations.

Featuring centralized and collaborative system operation, the cloud RAN (C-RAN) helps operators to address the above-mentioned challenges. A C-RAN network centralizes the baseband and higher layer processing resources to form a pool so that the processing resources can be managed and allocated dynamically on demand, while the radio units and antenna facilities are deployed in a distributed manner. The C-RAN structure offers some potential capabilities below, including but not limited to:

- hierarchical C-plane and U-plane split such that, in dense areas, control signalling may be delivered by the macro cells and user data transmission may be delivered by small cells;
- consolidated traffic steering, management of mobility and call re-direction among multiple cells, and among multiple RATs (e.g. coordination of the future IMT RAT and the existing IMT RAT on the BBU);
- dynamic and scalable joint radio resource management for uniform performance across multiple cells (e.g. cell edge gain improvement by multi-cell coordinated transmission power control and scheduling);
- enable a “virtual transceiver” approach to mobile access. The virtual transceiver process is capable of implementing joint transmission and joint processing at the same time to realize the suitable selection and optimal coordination from among a large number of pooled transmitters/receivers facilities.

As a result of those capabilities above, following benefits are expected:

- uniform performance and quality everywhere over a cell even at cell edge (different sources of cell edge gain include joint transmission, coordinated scheduling, load balance management, and interference coordination among small cells);
- simplified deployment and expansion of flexible cell sites (e.g. Plug-and-play deployment of additional cells);
- improved processing resource efficiency thanks to resource virtualization and the ability to dynamically allocate processing resources to busy cells;
- Total cost of ownership (TCO) reduction since lots of sites could be eliminated and power consumption is decreased. Also, site construction can be sped up since there is no need to find the separate equipment room for every base station. Instead, one centralized site office can accommodate several dozens of base stations;
- improved spectral efficiency due to facilitation of advanced technology implementation, especially CoMP technique by providing high-speed low-latency switching networks to enable timely information exchange among BBU within the pool;
- energy saving, mainly because of facility sharing in the centralization office, especially air-conditioning sharing and due to improved resource efficiency by virtualization;
- increased service innovation when an open general-purpose platform is adopted for C-RAN implementation.

5.7 Technologies to enhance privacy and security

Future IMT networks must provide robust and secure solutions to counter the threats to security and privacy brought by new radio interface technologies, new services and new deployment cases emerged in future IMT network.

New security threats always emerge together with the evolution of the IMT network. Consequently, security solutions must be evolved continuously to counter these security threats so that enhancement of security solutions can keep pace with the IMT network evolution.

IMT network evolution usually happens in three categories: new radio interface technologies, new services and new deployment case. Some of the security and privacy issues related to these three categories are listed as following.

Security and privacy issues caused by new radio interface technologies:

- new cryptographic algorithms are needed for the huge data rate of new radio interface technologies;
- security handling mechanisms needed to be optimized to improve the efficiency of inter-RAT handover.

Security and privacy issues caused by new services provided by the IMT network:

- security solutions for the new services, including M2M, proximity services;
- great care must be taken of the privacy issues caused by some sensitive services carried by the IMT network, e.g. e-bank, location based services.

Security and privacy issues caused by new deployment case:

- security solutions for IMT network devices which are deployed in physical insecure area, e.g. small cells. Trusted computing technologies might be a good choice for establishing a trusted environment in small cells, and security evaluation standards are also helpful to evaluate the security level of a IMT network device;
- security solutions for wireless backhaul technologies, e.g. relay node (RN);
- security solutions for supporting self-establishment feature of the IMT network devices.

6 Conclusion

This Report provides technology trends of terrestrial IMT systems that are applicable to radio interfaces, mobile terminals and network considering the time-frame 2015-2020 and beyond. These technology trends include technologies to enhance user experience, privacy and security, to support wide range of emerging services and to improve network energy efficiency. These trends also include network architecture enhancements which improve the flexibility and the operational efficiency of the network.

Some of these technologies such as the development of small cells, 3D beamforming and massive MIMO techniques may realize their full potential when applied to smaller wavelengths, which are characteristic of higher frequency bands. Further technical information and feasibility studies for higher frequency bands can be found in other ITU-R documents. ITU-R is currently working on a report on the technical feasibility of IMT in the bands above 6 GHz, with expected approval in mid-2015.

7 Terminology, abbreviations

Definitions of some of the following terms are found in Recommendation ITU-R M.1224.

3D-BF 3-Dimension beamforming

AAS	Active antenna system
ASA	Authorized shared access
AVC	Advanced video coding
BBU	Base band unit
CA	Carrier aggregation
CAGR	Cumulative average growth rate
CAPEX	Capital expenditures
CDN	Content delivery network
CoMP	Coordinated multi-point
C-RAN	Cloud-RAN
D2D	Device to device
DAS	Distributed antenna system
DASH	Dynamic adaptive streaming over HTTP
DU	Digital unit
E-CID	Enhanced Cell ID
eMBMS	evolved Multimedia broadcast multicast service
EOTDOA	Enhanced observed time difference of arrival
FBMC	Filter bank multi-carrier
HD	High definition
HEVC	High efficiency video coding
IDMA	Interleave division multiple access
IoT	Internet of Things
LBS	Location based service
LDS	Low density spreading
M2M	Machine-to-machine
MCDN	Mobile content delivery network
MIMO	Multi input multi output
MLD	Maximum likelihood detection
MSA	Multi-stream aggregation
MTC	Machine-type communication
MU-MIMO	Multi-user MIMO
NFV	Network function virtualization
OPEX	Operating expenditures
OTDOA	Observed time difference of arrival
OTT	Over the top
PDMA	Pattern division multiple access
PLMN	Public land mobile network
PRS	Positioning reference signals
QoE	Quality of experience
QoS	Quality of service

RAT	Radio access technology
RFPM	Radio frequency pattern match
RLAN	Radio local area network
RRM	Radio resource management
RTT	Round-trip time
RU	Radio unit
SAMA	SIC-amenable multiple access
SCMA	Sparse code multiple access
SD	Standard definition
SDN	Software-defined networking
SIC	Successive interference cancelation
SON	Self-organized network
STR	Simultaneous transmission and reception
TCO	Total cost of ownership
UTDOA	Uplink time difference of arrival

Annex 1

Enhanced OTDOA/E-CID

The proliferation of heterogeneous network deployments brings some challenges also in the area of efficient terminal positioning and calls for the study of enhanced mechanisms and positioning performance requirements. The addition of multiple nodes in heterogeneous networks may improve the position accuracy. However, UE cannot distinguish where the reference signals for measurement, e.g. Positioning reference signals (PRS) and etc., comes from and the reference points cannot be confirmed clearly particularly when several transmission points share identical cell IDs. Hence OTDOA and E-CID can be enhanced to distinguish the PRS comes from which reference point (eNB or RRH) in heterogeneous deployment scenarios. By the means of high accuracy enhanced positioning algorithm, i.e. enhanced performances of RRM algorithms using user' positioning information, such as inter-cell interference coordination (ICIC), packet scheduling (PS), admission control (AC), load balance (LB), power control (PC), etc., it will benefit the system performance.

Annex 2

Advanced SON

The advanced SON technology is the network thinking capability.

It is expected to enable the multi-RAT and multi-layer to automatically perceive the deployment environment, network operating status, and quality of experience (QoE), work out planning solutions, optimization solutions, and fault rectification solutions accordingly, and automatically implement the solutions after being authorized by the operator. The network thinking involves the self-planning, self-optimization, and self-rectification of faults based on operators' policies. One specific network thinking procedure can be as follows: perceive the network status, identify the network fault, provide the optimization suggestion, and confirm the optimization effect and provide the rollback suggestion when necessary after the optimization is performed.

The network thinking results are new network configuration parameters, which are applied to the network upon operators' authorization. The network that has the thinking capability and can automatically apply the network thinking results upon operators' authorization is called the reconfigurable network.

Annex 3

QoE Enhancements in a multi-RAT environment

With widespread use of multimedia communication, Quality of Experience (QoE) progressively becomes an important factor in networking today. QoE is the overall acceptability of an application or service, as perceived subjectively by the end-user (see Recommendation ITU-T G.1080) while Quality of Service is objective measure of service capabilities such as BER, data rate and latency in radio access network. If the network is aware of the users subjective QoE as well as objective QoS, the network can provide better quality of experience to users by utilizing their satisfaction level as one of scheduling parameters for efficient allocation of network resources⁶. Figure A3.1 shows the network architecture for QoE enhancement in a multi-RAT environment.

In multiple RAN (Radio Access Network) environment with different RAT (Radio Access Technology), universal access algorithm of user terminal with inter-RAT handover functionality can discover and select RAN which provides optimal user QoE, and then may lead to handover to the selected optimal RAN⁷. The inter-RAT handover functionality consists of RAN discovery, RAN selection, and terminal reconfiguration.

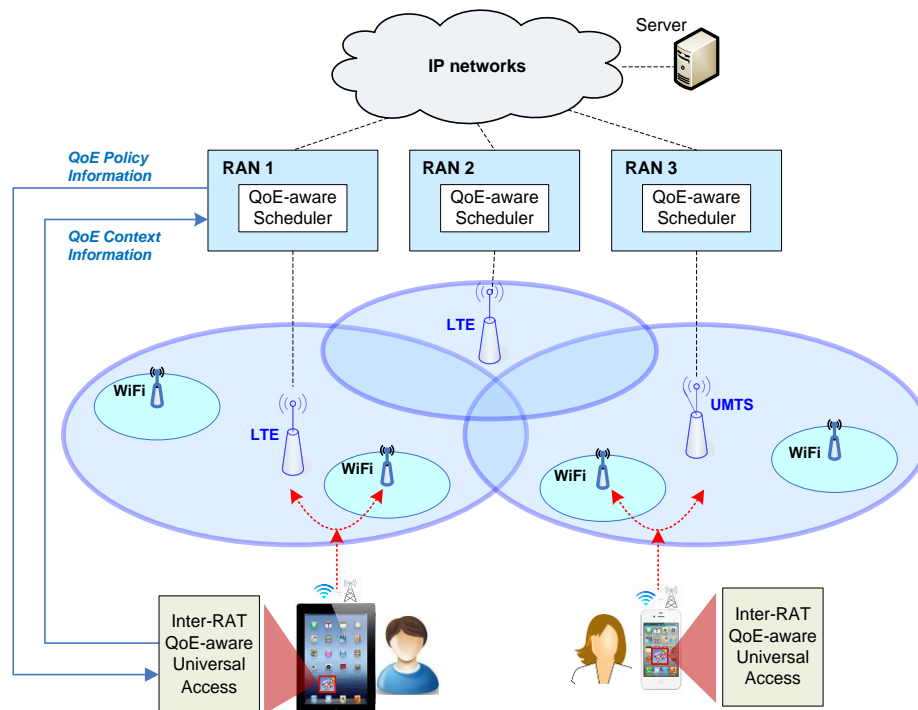
⁶ Kandaraj P., Kamal D.S., Adlen K., Cesar V., Jean-Marie B., "QoE-aware scheduling for video-streaming in High Speed Downlink Packet Access", IEEE WCNC, 2010.

⁷ Report ITU-R M.2330 – Cognitive radio systems in the land mobile service.

To enable QoE-aware scheduling, a user terminal measures corresponding user's QoE and reports it to a base station^{8, 9, 10}. The reported user QoE is used for QoE-aware scheduling. The QoE-aware scheduler takes quality of experience into account when making scheduling decisions.

To meet each user's QoE requirement, the QoE-aware scheduling algorithm of a base station allocates radio resources to users based on the reported user QoE. The universal access algorithm in terminal and the QoE-aware scheduling in base station can be combined to improve overall user QoE in a multi-RAT environment.

FIGURE A3.1
Network architecture for QoE enhancement in a multi-RAT environment



⁸ IEEE Std 1900.4-2009, "IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks", Feb. 2009.

⁹ 3GPP TS 26.247, "Technical Specification Group Services and System Aspects; Transparent end-to-end Packet-switched Streaming Service (PSS); Progressive Download and Dynamic Adaptive Streaming over HTTP (3GP-DASH) (Release 11)", Mar. 2013.

¹⁰ E2R II white paper, "The E2R II Flexible Spectrum Management (FSM) Framework and Cognitive Pilot Channel (CPC) Concept – Technical and Business Analysis and Recommendations", 2007.