GTI White Paper

Global TD-LTE Initiative

TDD/FDD LTE convergence

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Contributors	China Mobile, Optus (Australia), Packet One Network (Malaysia), Augere Wireless Broadband Bangladesh Ltd (Qubee), Ericsson, Huawei, Nokia, Vodafone
Editors	Brendan Jones, Sherri Stephens
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Contents

Executive Summary

This white paper provides an overview of the current global status of LTE TDD/FDD convergence, a technical overview of convergence between TDD and FDD networks, network operator case studies, and insight into the future requirements and timing of operators considering TDD/FDD convergence.

As at August 2015, there are now 60 commercial LTE TDD networks operating globally, of which 18 also operate FDD networks, although not all of those operate what we describe as "converged" networks where 4G TDD and 4G FDD network coverage overlaps and user devices may move in connected mode between TDD and FDD.

Technical Scenarios and Solutions of TDD/FDD Convergence are then presented in detail, including operational scenarios, use cases, mobility, load and traffic management, carrier aggregation and dual connectivity, and VoLTE.

Finally operator case studies and a convergence roadmap are presented, based on a GTI survey of operators who own both TDD and FDD spectrum. It is clear that interest in TDD/FDD convergence is growing and more and more operators are planning to converge their networks to realise the benefits of improved spectrum utilisation and improved customer experience.

Terminology

Abbreviation	Explanation
3GPP	3rd Generation Partnership Project
BS	Base Station
CEPT	European Conference of Postal and Telecommunications Administrations
ECC	Electronic Communications Committee of the CEPT
ERM	Technical Committee ERM (Electromagnetic Compatibility) and Radio of ETSI
ETSI	European Telecommunication Standardisation Organisation
FCC	Federal Communications Commission
FM	Working Group Frequency Matters of ECC
GTI	Global TD-LTE Initiative
HetNet	Heterogeneous Networks
IMT	International Mobile Telecommunication
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union - Radio
LTE	Long Term Evolution
MNO	Mobile Network Operator
MWC	Mobile World Congress
NRA	National Regulatory Authority
OAM	Operation, Administration and Maintenance
QoS	Quality of Service
SRDoc	System Reference Document of ETSI
RAN	Radio Access Network
RRM	Radio Resource Management
RRS	Technical Committee Reconfigurable Radio Systems of ETSI
RSPG	Radio Spectrum Policy Group
TD-LTE	Time Division Long Term Evolution
TDD	Time Division Duplex
UHF	Ultra High Frequency
WRC	World Radio communication Conferences

1. Industry trends on TDD/FDD LTE convergence

1.1. Industry trends

4G TDD/FDD Network Convergence is the concept where 4G TDD and 4G FDD network layers are seamlessly operated together – the networks are not operated separately, segregated or partitioned and mobile customers may seamlessly access either layer.

Converged 4G TDD/FDD networks typically have these characteristics:

- TDD and FDD networks operate off the same core network;
- TDD and FDD coverage overlaps, in most cases TDD and FDD base stations are co-located, for example, on the same tower or rooftop;
- User devices may move between TDD and FDD either in idle mode or connected mode;
- TDD services are not "partitioned" from FDD services, i.e. TDD is used fully or partly for mobile services, and TDD is not restricted to one service type (e.g. fixed wireless)

There are also degrees of 4G TDD/FDD network convergence:

- **Network level only:** TDD and FDD operate off the same core network and share infrastructure, but there are no common services (e.g. TDD is used for fixed wireless and FDD for mobility).
- **Partial segregated:** TDD spectrum is partitioned between fixed and mobile services, and only mobile user devices may move between TDD and FDD layers, or only devices in idle mode
- **Partial non-segregated:** TDD spectrum is pooled for all service classes but only mobile user devices may move between TDD and FDD layers, or only devices in idle mode.
- **Complete:** TDD spectrum is pooled for all service classes and user devices are unrestricted in moving between TDD and FDD layers in idle or active mode.

Interworking between LTE FDD/TDD in converged TDD/FDD LTE networks is of increasing importance for operators that have spectrum for both LTE modes. It will allow operators to seamlessly offer Mobile Broadband services on both FDD and TDD spectrum, making the most of their spectrum investments and increasing capacity and improving their consumer experience and service quality. The operator will, in turn, profit from having increased network capacity and greater efficiency, allowing it to better serve not only its current subscribers but also future subscribers. This, combined with the enhanced roaming capabilities, will allow operators to differentiate itself from its competition, making it the most advanced in a highly competitive mobile market.

The converged TDD/FDD network also benefits the industry. The LTE ecosystem will gain from greater economies of scale as the market adopts both FDD and TDD technologies. Longer term, the expectation is that 4G TDD will be treated no differently to 4G FDD, and both modes will be standard on 4G user devices.

The immense and growing customer demand of data usage is driving operators to implement 4G networks, because 4G is much more efficient than 3G in carrying mobile data traffic, and it is also driving operators to acquire more spectrum on different bands, either through spectrum auctions or acquisition of existing companies which own spectrum. Much of the new spectrum acquisition is in the higher frequency bands (above 2100 MHz) where more spectrum is available, at historically a much lower cost than spectrum at 2100 MHz and below.

As a result, there is a rapidly growing interest in 4G TDD among traditionally FDD network operators. Of the eight spectrum bands defined by 3GPP (Release 12)[1] above 2100 MHz (Bands 7, 22, 30, 38, 40, 41, 42 and 43), only three of them are FDD, and of those, only one (2600 MHz, Band 7) has any sort of ecosystem. Bands 22 and 30 do not appear to have any operator or vendor support globally and are, in effect, the FDD versions of Bands 42 and 40 respectively. Band 30 is only 10 MHz paired. In contrast, TDD bands 38, 40, 41, 42 and 43 have an active and growing ecosystem and spectrum allocations ranging from 50 to 200 MHz. Hence there is a clear drive to spectrum above 2100 MHz and more likely than not these systems will be TDD based.

According to the Global mobile Suppliers Association (GSA) *"Evolution to LTE"* report (21 July 2015), 422 LTE networks are commercially launched in 143 countries and 86% of them are FDD networks. Both FDD and TDD have their own strengths and weaknesses. FDD is well suited for symmetric traffic such as voice calls, but the bandwidth available for downlink and uplink mobile data traffic is equal, hence for asymmetric data traffic, the utilised spectrum efficiency is less than in TDD systems. Therefore TDD is better suited for asymmetric "data consumption" type traffic such as email, file downloading, video, and internet browsing.

Already 18 operators have launched 4G both in TDD and FDD modes including China Mobile Hong Kong, Sprint USA, Telus and Bell Mobility in Canada, Softbank Mobile Japan, Megafon and MTS Russia, Hutchison 3 Sweden, Aero2 Poland, and Optus Australia. Devices were once a bottleneck for the operators trying to deploy converged TDD/FDD LTE networks, but today a growing number of multiband multimode devices give operators the opportunity to implement TDD/FDD convergence.

2. Global Status of TDD/FDD Network Convergence

2.1. TDD/FDD Network Operators

The Global mobile Suppliers Association (GSA) provides regular reports as to the global status of 4G TDD network rollout. The most recent *"GSA Evolution to LTE report"* report was released on 21 July 2015[2].

This report showed that there are now 60 commercial LTE TDD networks operating globally as detailed in Table 2.1-1 below.

Country	Operator	LTE Modes	TDD Launch	FDD Launch	TDD Bands
Australia	NBN Co.	TDD	01-Apr-12	-	40
Australia	Optus	TDD + FDD	20-May-13	26-Apr-12	40
Bahrain	Menatelecom	TDD	19-Nov-13	-	42
Belgium	b•lite	TDD	22-Apr-14	-	42
Brazil	On Telecomunicacoes	TDD	01-Mar-13	-	38
Brazil	Sky Brasil Services	TDD	13-Dec-11	-	38
Canada	ABC Communications	TDD	23-Apr-14	-	42
Canada	Bell Mobility	TDD + FDD	01-Oct-14	14-Sep-11	42
Canada	CCI Wireless	TDD	15-Dec-14	-	42
Canada	Telus	TDD + FDD	30-Apr-14	10-Feb-12	40, 42
Canada	Xplornet	TDD	03-Dec-14	-	42
Canada	Sasktel	TDD + FDD	23-Sep-13	31-Jan-13	41
China	China Mobile	TDD	18-Dec-13	-	39, 40, 41
China	China Telecom	TDD	14-Feb-14	-	40, 41
China	China Unicom	TDD	18-Mar-14	-	40, 41
Colombia	DirecTV	TDD	25-Jul-14	-	38
Côte d'Ivoire	YooMee	TDD	04-Apr-14	-	40
Dominican Republic	WIND Telecom	TDD	19-Feb-15	-	38
Finland	Ukko	TDD + FDD	17-Nov-14	17-Nov-14	38
Gambia	Netpage	TDD	15-Mar-15	-	40
Ghana	BLU	TDD	14-Oct-14	-	38
Ghana	NITA	TDD	15-Feb-14	-	41
Hong Kong	China Mobile Hong Kong	TDD + FDD	01-Dec-12	25-Apr-12	40
India	Aircel	TDD	16-Jul-14	-	40
India	Bharti Airtel	TDD	10-Apr-12	-	40
Indonesia	PT Internux	TDD	14-Nov-13	-	40
Indonesia	Smartfren	TDD + FDD	07-Jul-15	07-Jul-15	40
Italy	Linkem	TDD	03-Dec-14	-	42
Japan	Softbank Mobile	TDD + FDD	24-Feb-12	21-Sep-12	41
Japan	UQ Communications	TDD	31-Oct-13	-	41
Madagascar	Blueline	TDD	01-Apr-14	-	41

Country	Operator	LTE Modes	TDD Launch	FDD Launch	TDD Bands
Nigeria	Spectranet	TDD	20-Aug-13	-	40
Nigeria	Swift Networks	TDD	01-Nov-13	-	40
Oman	Omantel	TDD + FDD	16-Jul-12	30-Dec-12	40
Oman	Ooredoo	TDD + FDD	03-Sep-14	17-Feb-13	40
Peru	Americatel (Entel)	TDD	13-Oct-14	-	40
Philippines	PLDT	TDD	29-Apr-14	-	42
Poland	Aero2	TDD + FDD	15-May-11	07-Sep-10	38
Romania	Idilis/2K Telecom	TDD	15-Mar-15	-	38
Russia	Megafon / Moscow	TDD + FDD	01-Sep-12	05-Jan-12	38
Russia	MTS / Moscow	TDD + FDD	01-Sep-12	31-May-13	38
Russia	Vainakh Telecom	TDD	03-Sep-13	-	40
Saudi Arabia	Mobily	TDD + FDD	14-Sep-11	15-Jan-13	38
Saudi Arabia	STC	TDD + FDD	14-Sep-11	01-Feb-13	40
South Africa	Telkom Mobile (8ta)	TDD	21-Apr-13	-	40
Spain	COTA/Murcia4G	TDD	01-Mar-13	-	38
Spain	Neo-Sky	TDD	01-Jun-13	-	42
Sri Lanka	Dialog Axiata	TDD + FDD	30-Dec-12	02-Apr-13	40
Sri Lanka	Lanka Bell	TDD	04-Feb-14	-	40
Sri Lanka	SLT	TDD	19-Jan-14	-	38
Sweden	Hutchison 3	TDD + FDD	23-Apr-12	15-Dec-11	38
Trinidad & Tobago	TSTT	TDD	18-Dec-14	-	41
Uganda	MTN	TDD	25-Apr-13	-	41
Uganda	Vodafone	TDD	09-Feb-15	-	38
UK	UK Broadband	TDD	28-Jun-12	-	42
USA	Redzone Wireless	TDD	03-Jun-15	-	41
USA	Speedconnect	TDD	19-May-15	-	41
USA	Sprint	TDD + FDD	19-Jul-13	15-Jul-12	41
Uzbekistan	EVO	TDD	01-Apr-15	-	40
Vanuatu	WanTok	TDD	01-Apr-14	-	40

Table 2.1-1 - Global TDD Operators [2]

The number of 4G TDD commercial network operators has steadily grown since Aero2 in Poland launched the world's first TDD network on 15 May 2011. Figure 2.1-1 below shows the growth over time in the number of commercial TDD and TDD+FDD operators.

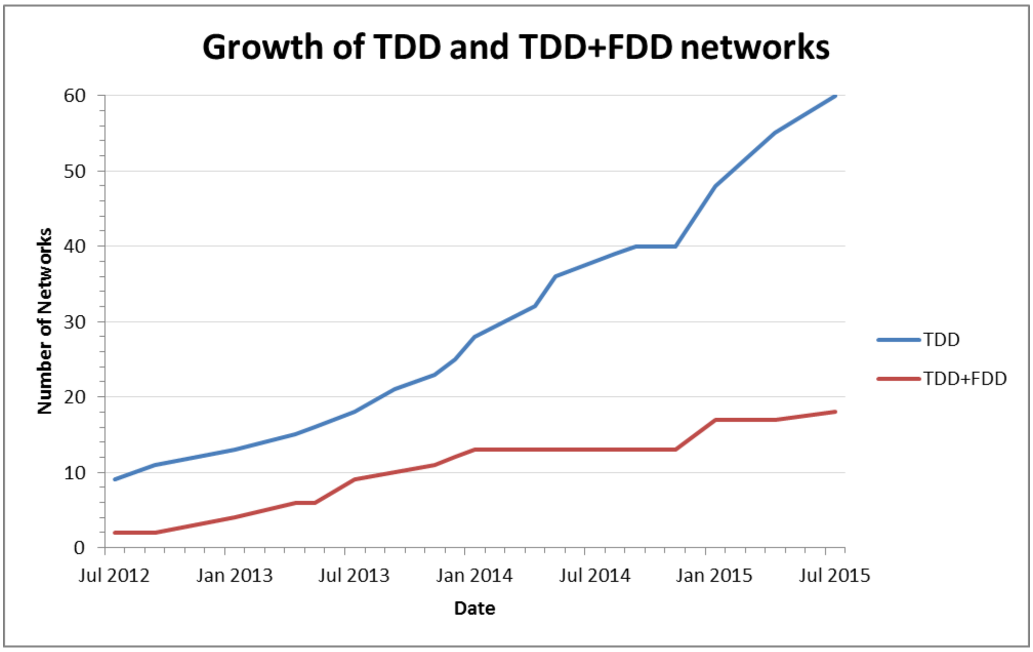


Figure 2.1-1 – Growth in number of TDD operators. Note the TDD operator count (blue line) includes the TDD+FDD operators (red line)

As can be seen from Table 2.1-2 and Figure 2.1-1, 18 operators now operate 4G in both TDD and FDD modes. Not all of these operators, however, operated a converged network, as can be seen in Table 2.1-1. Based on GSA data and other publicly available information, nine operators have converged TDD/FDD networks, five operators do not (i.e. the TDD network is separate to the FDD network and is used to provide fixed wireless services, not mobile services), and the status of the remaining networks are to be confirmed.

Country	Operator	TDD Launch	FDD Launch	Convergence Launch
Australia	Optus	20-May-13	26-Apr-12	13-Sep-13
Canada	Bell Mobility	01-Oct-14	14-Sep-11	Not converged
Canada	Telus	30-Apr-14	10-Feb-12	Not converged
Canada	Sasktel	23-Sep-13	31-Jan-13	Not converged
Finland	Ukko	17-Nov-14	17-Nov-14	17-Nov-14
Hong Kong	China Mobile Hong Kong	01-Dec-12	25-Apr-12	19-Dec-12
Indonesia	Smartfren	07-Jul-15	07-Jul-15	07-Jul-15
Japan	Softbank Mobile	24-Feb-12	21-Sep-12	TBC
Oman	Omantel	16-Jul-12	30-Dec-12	30-Dec-12
Oman	Ooredoo	03-Sep-14	17-Feb-13	Not converged
Poland	Aero2	15-May-11	07-Sep-10	15-Sep-11
Russia	Megafon / Moscow	01-Sep-12	05-Jan-12	TBC
Russia	MTS / Moscow	01-Sep-12	31-May-13	31-May-13
Saudi Arabia	Mobily	14-Sep-11	15-Jan-13	TBC
Saudi Arabia	STC	14-Sep-11	01-Feb-13	TBC

Country	Operator	TDD Launch	FDD Launch	Convergence Launch
Sri Lanka	Dialog Axiata	30-Dec-12	02-Apr-13	Not converged
Sweden	Hutchison 3	23-Apr-12	15-Dec-11	15-Dec-11
USA	Sprint	19-Jul-13	15-Jul-12	17-Mar-14

Table 2.1-2 – The eighteen TDD/FDD Operators

This table reveals that in terms of commercially operating networks TDD/FDD Convergence is relatively rare, but this number should rapidly grow as operators around the world increasingly turn to TDD spectrum to satisfy the data demands of their customers.

2.2. **Motivations for building a TDD/FDD network**

It is interesting to note from Table 2.1-2 that of the 18 TDD+FDD operators, seven operators launched TDD LTE first, ten operators launched FDD LTE first, and two operators launched both on the same day. In other words, there is a fairly even split between which network came first. Clearly there are motives for both existing FDD operators to adopt TDD, and for existing TDD operators to adopt FDD.

For operators who started initially with FDD services (typically mobile) the motives for adding a TDD layer include:

- The business case to acquire lower cost and more abundant unpaired spectrum is increasingly compelling;
- The ability to add high capacity LTE layers in metro areas / hot spots – larger spectrum allocations are typically available in the TDD spectrum bands;
- The ability to add new service types to existing mobile product offering, e.g. fixed wireless broadband, which are unsuited to FDD bands due to their highly asymmetric traffic characteristics and extremely high capacity requirements.

For operators who started initially with TDD services (typically fixed wireless) the motives for adding a FDD layer include:

- The ability to add mobility services to their product portfolio and hence grow their business (some fixed wireless TDD operators are not allowed to offer mobility services, an FDD licence usually removes such restrictions).
- The ability to compete more effectively with FDD operators in traditional or innovative mobile telephony services, including the access to a larger device ecosystem and the ability to churn customers away from the traditional mobile network operators.

Hence the move towards converged TDD/FDD networks is not being solely driven by existing FDD operators seeking new capacity solutions, nor existing TDD operators seeking to tap into traditional mobility markets. We are truly seeing convergence.

3. Scenarios and Solutions of TDD/FDD Convergence

In this section, typical scenarios of TDD/FDD convergence are introduced. We will then look into common requirements of different scenarios and the corresponding end-to-end solutions. Service of high importance in LTE system, such as VoLTE, are then considered in the context of converged networks. Following the comprehensive analysis of scenarios and solutions, requirements on both network and UE products are concluded in the last section.

3.1. Scenarios of TDD/FDD Convergence

The build out of a TDD/FDD converged network depends on the chosen deployment strategy. For some operators, TD-LTE is their main choice of mobile broadband technology. And for other operators deployment of TD-LTE is for enhancing network capacity and user experience.

A partially converged network may be deployed in the primary stage, in which TDD and FDD may have different levels of coverage with partially overlapped coverage areas. With separate sites and layout, TDD and FDD could be entirely independent operated except for mobility between them. Partially converged scenario may be used for initial TDD and FDD network deployment to satisfy the coverage requirements.

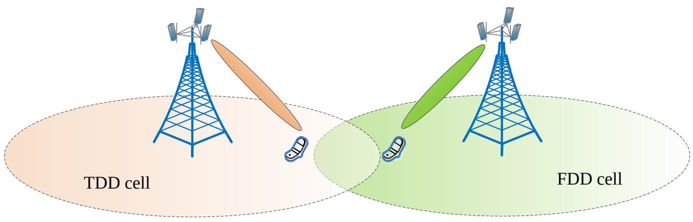


Figure 3.1-1: partially converged network

There are two major deployment scenarios for TDD/FDD convergence network, using different frequency bands.

- **Co-locate TDD/FDD**

In many scenarios, operators may want or need to co-site their FDD/TDD base stations. Co-located cells may use different frequency bands. Both networks offer full coverage of the same area. This can be an economical option, since both technologies occupy the same real estate, use the same backhaul and potentially the same core network.

The challenge with co-located TDD/FDD deployment is the small coupling loss between the TDD radio and FDD radio, which may cause cross-link interference, i.e. DL transmission of one BS interferes with the UL reception of the co-located BS.

When the frequency separation between FDD and TDD is large, the cross-link interference is not a big problem since the spurious emission from one BS into another BS's operating band is low.

For co-located TDD/FDD deployment on adjacent frequency bands, the coexistence problem is well known. A lot of studies and experiments have been conducted on the issue, in areas of BS radio frequency requirements and field engineering to understand the practical coupling loss.

Taking B7 and B38 (2600 MHz FDD and mid-band TDD band) as example, in 3GPP the spurious emission requirement is defined as -86dBm/MHz for co-location scenario, assuming 30dB coupling loss. It should be noted that the spurious emission requirement is defined to apply in the frequency range that is 10MHz separated from the BS operating band. The -86dBm/MHz requirement is also very stringent from implementation point of view, in particular when the guard band is being minimized.

On the other hand, the coexistence problem is typically covered by regional or national regulatory requirements. In Europe, CEPT have developed the emission mask to support TDD/FDD coexistence in B7 and B38. One possible deployment scenario enabled by the CEPT requirement is 5MHz guard band between TDD and FDD carriers, and BS emission is limited to -62dBm/MHz with typical antennas. The coupling loss is assumed as 53dB in the requirement development.

As mentioned, the coupling loss is the limiting factor for TDD/FDD co-located deployment. With small coupling loss, the coexistence problem can only be solved by reserving more guard band or adding (expensive) extra filter to the BS equipment. With proper field engineering, the coupling loss of 50dB can be achieved for antennas at the same mast for B7 and B38.

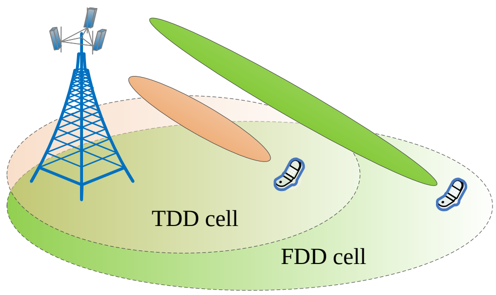


Figure 3.1-2: co-locate TDD/FDD with different coverage

❷ TDD/FDD HetNet

Some operators may deploy TDD/FDD in a HetNet, deploying TDD to cover hotspots, enabling traffic to be offloaded from the FDD network. In this scenario, TDD may be deployed with high frequency spectrum to fill the coverage gaps or holes, also for dense hotspot capacity. On the other hand, if FDD spectrum is higher than TDD, it may be use FDD to cover hotspots.

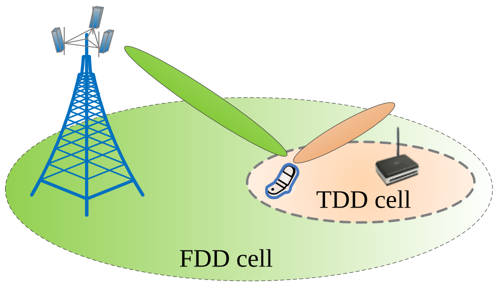


Figure 3.1-3: TDD/FDD HetNet

3.2. Solutions on TDD/FDD Networking

Although diverse deployment scenarios are considered for TDD/FDD convergence network, solutions on convergence networking are clear and definite for the common requirements of each scenario, which can be summarized as requirements on coverage, radio resource utilization efficiency, as well as performance enhancement. Solutions aimed at these requirements are focused on in this section.

3.2.1. Development stages of TDD/FDD LTE networking

With an increasing developing scale on TDD and FDD LTE deployment, there are three typical deployment phases of TDD/FDD convergence, as is shown by Figure 3-2.1.

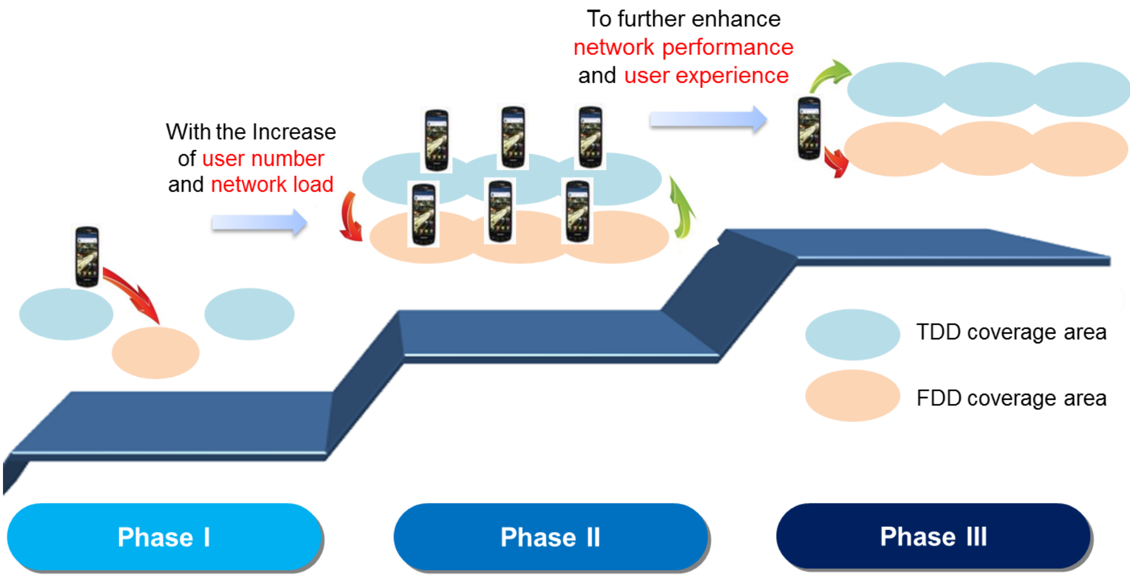


Figure 3.2-1: Development phases of TDD/FDD convergence

Phase I: TDD and FDD deployed with different coverage. In preliminary phase of TDD and FDD convergence networking, TDD and FDD LTE radio network infrastructures are separately constructed and optimized. Objective of phase I are mainly concerned on guaranteeing coverage and ensuring seamless service continuity. Mobility, not only for data service, but also for voice, is the most important requirement of this phase.

Phase II: Radio resource management between two layers formed by TDD and FDD in same coverage area. Where TDD and FDD are formed with two layers with overlapped coverage area, with an increase in subscribers and types of services, it is necessary to take full advantage of TDD and FDD radio resources for service bearing. Thus radio resource management between TDD and FDD is required to be introduced.

When TDD and FDD are aimed at bearing same type of service, load balancing between TDD and FDD is required to optimise the network utilization and ensure better user experience. When TDD and FDD are aimed at carrying different kinds of services (e.g. TDD is prioritised for data service while FDD is prioritised for VoLTE), a single user should be transferred to corresponding layer according to its type of service. Particularly, service aware balancing is required under circumstance of specific service requirements, such as dynamic frequency allocation, bandwidth requirements, symmetry requirements, etc. Not only mobility, but also radio resource management of different layers should be mainly concerned in phase II.**Phase III: Joint operation between two layers formed by TDD and FDD in same coverage area.** In this case TDD and FDD are formed of two layers with overlapping coverage area, with radio resource management as described in phase II above, but additionally with joint operation of overlapped layers, such as Carrier Aggregation or Dual Connectivity. Therefore

TDD and FDD resources can be jointly utilized and optimized for one single UE to further enhance the user experience. Not only mobility and radio resource management, but also joint operations of TDD and FDD for higher transmission data rates are the key requirements in phase III.

Table 3.2-1 summarizes the requirements of each TDD/FDD convergence phase and relates the deployment scenarios.

Table 3.2-1: TDD/FDD convergence scenarios

Phase	Objective	Solution	Related deployment scenarios
Phase I: Coverage based Mobility	Ensuring coverage and seamless service continuity	Mobility Management ● Reselection ● PS handover ● Redirection	● Partially converged network ● Co-locate TDD/FDD ● TDD/FDD HetNet
Phase II: Load/Service based Radio Resource Management	Maximizing radio resource utilization efficiency	Radio resource management ● Load balancing ● Service based UE transferring ● dynamic frequency allocation	● Co-locate TDD/FDD ● TDD/FDD HetNet
Phase III: Performance based Joint Operation	Network performance enhancement	Joint Operation ● carrier aggregation ● dual connectivity	● Co-locate TDD/FDD ● TDD/FDD HetNet

For every phase it may be concerned, end to end solutions should be introduced to ensure the relative functionalities.

3.2.2. Coverage Requirements: End to End Solution of Mobility

Coverage and priorities of FDD and TDD LTE may be different in different convergence networking phases. Mobility solutions are in need to guarantee service continuity when UE moves to a higher priority network or a better coverage area. Interworking of TDD/FDD convergence mainly includes reselection, redirection and PS handover.

3.2.2.1. Mobility of idle mode

Idle mode mobility is actually about the cell re-selection process. During cell reselection, it is UE that decides which cell to camp on.

Reselection of TDD/FDD works only under prerequisite that FDD and TDD cells have been configured with neighbour cell relationship. UE obtains information needed for cell reselection (e.g. threshold values used to decide whether to measure the signal strength of neighbour cells or not, parameters used for calculating rank of the serving cell and neighbour cells, etc.) from the system information broadcasted by eNB. eNB should even guide UE reselecting to a specific carrier or cell by configuring and delivering corresponding priority parameters.

Cell reselection in FDD/TDD convergence network shares similar procedure with intra-LTE inter-frequency cell reselection. eNB configures and delivers cell reselection related parameters by system information or RRC message, guiding UE to select camping cells. The cell reselection triggering mechanism includes:

- Serving Cell Measurement: UE, in idle state, measures the signal of its serving cell and calculates the received signal level of the serving cell to decide whether it should stay or move to another cell. The UE's transmission and reception conditions are reflected in the calculation, for example by applying minimum received signal level Qrxlevmin, allowed maximum TX power level PEMAX, etc.
- Cell Reselection Triggering: if the received signal level of the serving cell is greater than the specified threshold value, the UE stays in the current serving cell. If not, it triggers a cell reselection procedure.

3.2.2.2. Mobility of connected mode

Redirection, as well as PS handover, serves as primary mobility solutions of connected mode.

By redirection, when a UE in connected mode is moving to a target cell with better coverage, frequency and system information of target cell is informed to the UE in *RRC Connection Release* message sent by serving cell. UE is required to release the RRC connection with serving cell, then synchronize, attach and establish RRC connection again in target cell. Due to the release and re-establishment of RRC connection, the service would be cut off for several seconds, which may influence the user experience.

Service continuity of connected mode is required to be guaranteed by PS handover. TDD/FDD handover shares the same procedure with standard inter-frequency handover in the same LTE mode, which is the prerequisite to support TDD/FDD handover. TDD/FDD handover simply extends inter-frequency handover to carriers of different modes (FDD and TDD).

Requirements from eNB and UE sides:

To execute PS handover in a convergence network, both source cell and target cell should support standard inter-frequency handover procedure. From UE side, UE must be also capable of handling both inter-frequency and inter-mode handover. The following FeatureGroupIndicator (FGI) bits must be checked:

- bit 25 indicates inter-frequency measurements support
- bit 13 indicates inter-frequency handover support
- bit 30 indicates inter-mode handover support.

PS handover procedure can be divided into phases of measurement control, measurement report, handover decision and handover execution

Measurement Control: Source eNB configures UE with measurements, including the frequency to measure, the threshold and the event to trigger measurement report. When signal power of serving cell drops below a defined threshold, 6ms measurement gap is specified for inter-frequency measurements, in which period UE switches to measure the frequency of target cell/system.

Measurement Report: UE sends an event-triggered periodic measurement report to serving cell if signal condition measured satisfies the defined hysteresis, offset, and time to trigger.

Handover Decision: When a measurement report is received by the serving cell, the serving cell analyses the measurement reports and determines if a handover should be initiated for the UE, and if so, selects the most suitable handover candidate cell, which is referred to as the target cell.

Handover Execution: The serving cell communicates with the target cell to prepare a handover attempt. Target cell proceeds to prepare corresponding resources for UE access. Serving cell informs UE to access in target cell. The user plane data flow from the SGW is redirected to the target cell once the UE has successfully attached. Then the original serving cell is then informed of the successful handover and it releases the resources assigned to the UE.

PS handover could be triggered either on the measurement report received from the UE (measurement based handover) or be based on pre-configured information (blind handover), where the former is recommended for better service continuity guaranteeing.

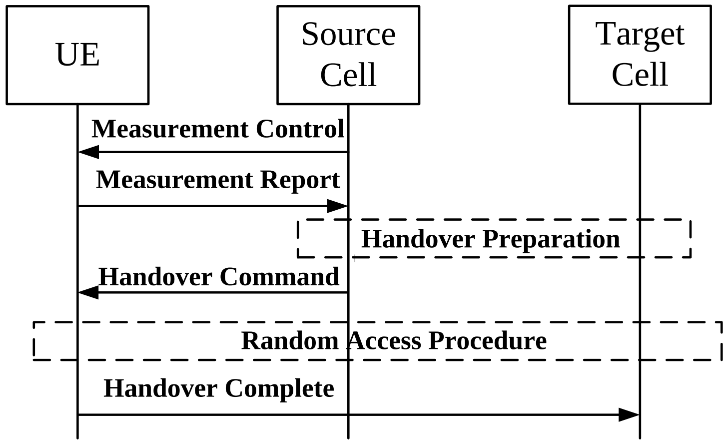


Figure 3.2-2: PS Handover

Comparison of redirection with PS handover

Although shortcomings such as the service cutting off for several seconds are present for redirection, no upgrade is required either for radio network or core network to support the feature. Redirection serves as an potential connected mobility solution before PS handover is supported by target cell or terminal.

PS handover provides the most efficient solution for mobility in connected mode. Latency of TDD/FDD handover is similar to that of inter-frequency handover in same LTE mode, which is less than 100ms. PS handover requires both eNB and UE sides supporting handover standard procedure.

3.2.2.3. Inter-vendor interworking

In some circumstances, a multi-vendor convergence network is deployed. Infrastructures of different vendors are usually divided by geographic territory but not by LTE technology. Hence for co-location deployment scenarios, interworking of different layers is normally executed by same vendor. But multi-vendor inter-operability is still a must at least for edge users at boundaries of non-co-located TDD and FDD networks with different vendors.

Coverage-based mobility management solutions between LTE FDD and TDD are standardized procedures thus can be easily extended to inter vendor scenarios. But parameters should be carefully configured between different vendors to prevent frequent bi-directional handovers. Moreover, interoperability tests (IOT) should be done to guarantee the performance.

3.2.3. Radio Resource Utilization Efficiency Requirements: End to End Solution of Load Balancing

After the initial launch of LTE TDD/FDD converged network, in which coverage was the main driver, network capacity becomes the driver for the converged network with the growth of subscribers and traffic. Under this scenario, two layers formed by TDD and FDD LTE in same coverage area are deployed. Load may be extremely imbalanced between two layers due to difference in frequency, priority or services bearing strategy. Coverage based reselection or handover may relieve this, but with only limited effect.

In order to address the customer's needs, load balancing between FDD and TDD is another important requirement to resolve the distribution of traffic load between FDD and TDD. It enables the efficient use of the network resources on both FDD and TDD and targets similar user experience independent of the technology in use.

Furthermore, radio resource management solutions, including but not limited to load balancing, between FDD and TDD layers are required to be introduced into converged networks for not only fully taking advantage of radio resource of TDD and FDD but also better meeting service requirements. For instance, based on service characteristics (symmetrical or asymmetrical), service type (voice or data service) and QoS requirements (bandwidth, data rate or latency), UE or bearer could be flexibly transferred to TDD or FDD layer, depending on the radio resources (bandwidth, DL/UL configuration, interference, PRBs, etc.) of each layer.

As the most important radio resource management solution, load balancing algorithm is further discussed below.

3.2.3.1. Load balancing

Load balancing is introduced into convergence network to flexibly adjust the traffic load between FDD and TDD layers. Load balancing is achieved by transferring the UE to carriers that are underutilised compared with the carriers in use, according to the differences in radio resource occupation. Load balancing makes it possible that loads can be shared or offloaded from the serving cell (loaded condition) to neighbour cells with overlapping coverage.

There are two major types of load balancing deployed in convergence network, idle mode load balancing as well as connected mode load balancing.

Idle mode load balancing:

Idle mode load balancing is controlled by configuration in the cell reselection priority. When an operator has TDD and FDD network convergence (with overlapping coverage), it should be set in cell reselection priority to instruct UEs connect to the layer network with highest theoretical capacity by default. Coverage and/or Quality based (RSRP and/or RSRQ) cell reselection can be triggered within FDD and TDD network convergence for load balancing purpose. System parameters that control cell reselection and operator's channel frequency preferences are transmitted to UEs in the Systems Information Blocks (SIBs)

The advantage of idle mode load balancing is eNB to instruct UE to select or reselect to the cell with less load or not overload cells to maintain user experience and achieve capacity/ throughput enhancement. This will reduce the need of load balancing in connected mode and minimize the handover failure happens when UE is in connected mode and triggered by eNB to perform inter frequency handover.

By configuring frequency priority and reselection threshold, balanced load of TDD and FDD layers could be preliminarily achieved.

Connected mode load balancing:

Load balancing in connected mode is based on handover. There are two major connected mode load balancing options: measurement-based and blind. Blind handover is only considered in circumstances where no delay can be tolerated during handover, benefitting from the reduction of signalling exchange. However, blind handover is not recommended for execution usually due to higher handover failure that might be caused under the absence of measurement reports.

In the measurement based load balancing procedure, measurement reports from UE as well as load information sharing through X2 or S1 interface are required. There are four phases during load balancing:

- **Load assessment:** Load assessment in each cell is performed repeatedly at certain interval.
- **Load information interaction:** Serving cell and load balancing target cell (usually cells of another layer with same coverage) exchange load information, usually by X2 message *Resource Status Request*， *Resource Status Response* and *Resource Status Update*
- **UE selecting:** Based on the load information received from other cells, each serving cell determines the amount of traffic load that should be handed over to each target cell. If serving cell is overloaded (usually assessed as heavier than transferring threshold) while load in target cell is under loaded (usually assessed as lower than access admission threshold), UE selecting for load balancing will be undertaken with specific principle.

In the UE selection process, the UE perform measurements on the target frequency. Inter-frequency measurement reporting is used. Only UE supporting the target frequency band and triggering an inter-frequency measurement report on the target cell are selected.

- **UE transferring:** serving cell triggers selected UE transferring from serving cell to target cell. UE transferring is performed using normal inter-frequency handover procedures

Non-GBR UEs will be prioritized for handover to target cells than GBR UEs. This is to avoid throughput performance and experiences of GBR UEs being affected by improper handover.

By load balancing, radio resources of different layers can be flexibly allocated and well utilized, but the extra handover procedure may influence the QoS of non-GBR services and call drops. A unified principle for load assessment as well as interaction on load information and thresholds are required to avoid frequent handovers and call drops caused by improper handover.

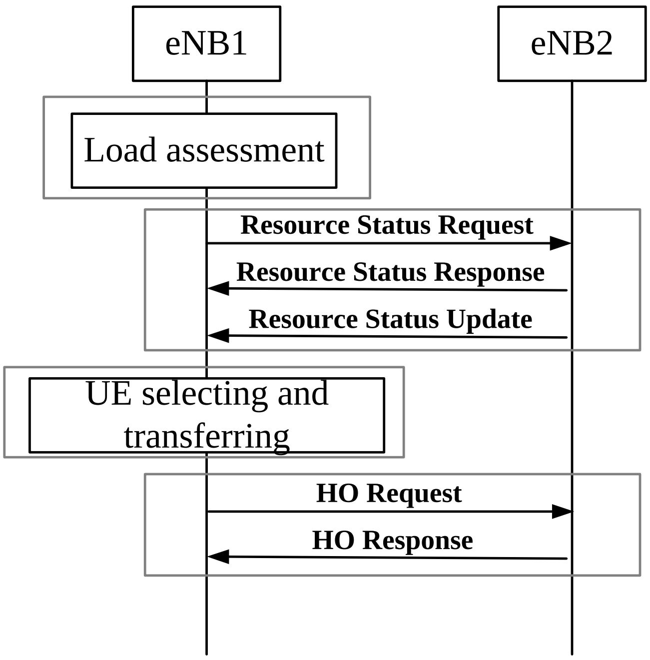


Figure 3.2-3: Load Balancing

Requirements and configurations on both eNB and UE sides:

- Load balancing cell relationships should be configured between overlapping inter-frequency cells.
- Load balancing between cells requires an X2 connection, load information interaction on X2 message should be supported
- Unified load assessment principle should be configured and applied.

3.2.3.2. Inter-vendor load balancing

Scenarios of inter-vendor load balancing will be much less common than intra-vendor interworking as co-located TDD and FDD infrastructure are usually from the same vendor. But inter-vendor load balancing in TDD/FDD HetNet or at the boundary of cells with different vendors will still be needed.

For intra-vendor load balancing, the performance can be guaranteed since the definitions and understandings of load evaluation, user transfer, load information exchange are the same for both source and target eNBs. However for inter-vendor load-balancing functionality, the definitions and understandings of these critical issues involved in this feature might be different, causing performance degradation. In this scenario, definitions should, as far as possible, be unified to enhance user experience and network efficiency during load-balance handover.

Extensive efforts have been made in standard organizations to enhance the performance of inter-vendor load balancing. An item related to this feature was created in NGMN, and China Mobile is leading this item with Telecom Italia and Alcatel-Lucent. Final conclusions were reached and a final version of white paper was generated in December 2013. In 3GPP a specification has been refined based on the enterprise protocol, and the target for inter-vendor enhancement has been reached. For commercial deployment of this function in the inter-vendor scenario, these unified definitions should be adopted by the vendors involved to guarantee the performance of load balancing.

3.2.3.3. Service based radio resource management

Besides load balancing, radio resource management of TDD/FDD convergence network enables UE to be transferred between TDD or FDD carriers to better meet service requirements and an operator's strategy. For example, FDD layer can be more suitable to bear UL/DL symmetric services such as VoLTE, while TDD layer may better match services with flexible UL/DL ratio such as web browsing. Frequency priority and cell specific priority can be configured to UE in connected mode, leading to service based UE management.

By setting dedicated priority to certain UE types, load balancing in a converged TDD and FDD network can be managed in terms of UE types: for example, CPE and data package UEs prior to camp on TDD, voice package UE prior to camp on FDD.

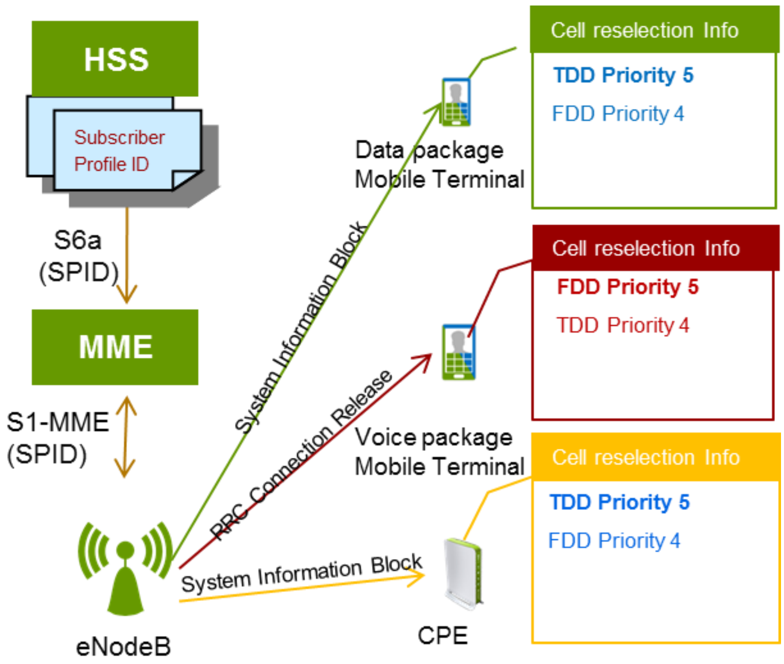


Figure 3.2-4: service and UE type based transferring

Similarly, other service requirements such as bandwidth could be also taken into consideration for radio resource management of TDD/FDD convergence network, for example, dynamic frequency allocation for service.

3.2.4. Data Rates Enhancement Requirements: End to End Solution of TDD/FDD LTE Joint Transmission

By radio resource management of TDD and FDD layers in same coverage area, it is possible to balance in terms of load. Service bearing could be either on TDD or FDD layer according to service features and requirements. Although radio resources of TDD and FDD can be optimized and exploited, the service is still carried on a single LTE network.

In the third phase of convergence, TDD and FDD can be jointly operated in a more advanced manner. Joint operation of TDD and FDD carriers makes it possible to carry the service on both layers, which would be an efficient way to make full use of spectrum resources. The two solutions for TDD-FDD joint operation are TDD-FDD carrier aggregation and dual connectivity.

The main objectives for network performance enhancement by joint operation:

- Service carried on both TDD and FDD radio resources for higher peak data rates.
- More flexible and dynamic resources sharing between TDD and FDD without handover. (e.g., enable flexible and dynamic/semi-dynamic load balancing between

TDD and FDD layers, increase the cell average and cell-edge data rate by dynamic/semi-dynamic scheduling of resources on both TDD and FDD.)

- Further improvement on coverage and mobility. (e.g., more reliable service transmission by dual connectivity to the network.)

Deployment scenarios must be taken into consideration on joint operation. Typical deployment situations include:

- Co-site TDD and FDD carriers with ideal backhaul
- Non-co-site TDD and FDD carriers with ideal backhaul by fibre connection
- Non-co-site TDD and FDD carriers with non-ideal backhaul (in terms of capacity and latency)

Apart from the network deployment status, capabilities of terminals are also vital. FDD/TDD dual mode should be supported at least, with different capabilities as below:

- Transmission on both TDD and FDD carriers simultaneously
- Reception on both TDD and FDD carriers simultaneously
- Transmission and Reception on both TDD and FDD carriers simultaneously

The good commonality between FDD and TDD design in LTE offers the possibility of the efficient joint operation of FDD and TDD networks. But joint operation either by carrier aggregation or by dual connectivity depends not only on whether the TDD and FDD are co-baseband, but also on the radio network capabilities as well as UE capabilities. Following provides a comparison on application requirements of the two available joint operation solutions.

Table 3.2-2: Application Requirements of Joint Operation Solution

Solutions	TDD/FDD Carrier Aggregation	TDD/FDD Dual connectivity
Deployment scenarios	● Co-site and co-baseband TDD and FDD carriers ● Non-co-site and co-baseband TDD and FDD carriers with ideal backhaul by fibre connection TDD and FDD equipment is required to be provided by same vendor	● Non co-site TDD and FDD carriers with non-ideal backhaul TDD and FDD could be provided by different vendors

Solutions	TDD/FDD Carrier Aggregation	TDD/FDD Dual connectivity
Network capability requirements	● Shared data and baseband operation ● Joint scheduling of both TDD and FDD carriers ● Aggregated TDD and FDD carriers are required to be synchronized.	● Separate operation on data streams ● Interaction between two eNB is required by X2 interface and/or core network ● Separate scheduling of TDD or FDD ● TDD and FDD are not required to be synchronized.
UE capability requirements	FDD/TDD dual mode terminal, at least with: ● Simultaneous Rx on both TDD and FDD ● Single Tx on either TDD or FDD	FDD/TDD dual mode terminal, at least with: ● Simultaneous Rx on both TDD and FDD ● Simultaneous Tx on both TDD and FDD

Regardless of solutions, the combination of TDD and FDD bands are of great importance to apply TDD/FDD joint operation. So, before looking deeper into the two solutions, it is required to consider the combination of TDD and FDD bands.

Table 3.2-3: Potential Combination Bands of TDD/FDD Joint Operation

Region	China	Hong Kong	Europe	US	Japan	Korea	Saudi, Middle East and many other regions
FDD band	B1, B3, B8	B1, B3, B7, B8	B1, B3, B7, B8, B20	B2/25	B1, B3, B8, B18, B19, B21, B26, B28	B1, B3, B8, B5	B3,B5
TDD band	B39, B40, B41	B40	B38, B40	B41	B41, B42	B40	B40, B38/41

The two main solutions, TDD/FDD carrier aggregation and dual connectivity are discussed in details in the following subsections.

3.2.4.1. TDD/FDD Carrier Aggregation

Carrier aggregation (CA) was first introduced in 3GPP Release 10. As further enhancement in Release 12, downlink TDD and FDD carrier aggregation was introduced supporting either TDD or FDD as PCell (Primary Cell) with backward compatible with legacy UEs.

The 3GPP specification allows either TDD or FDD to serve as PCell, and the configuration of TDD or FDD as PCell is allowed to be UE-specific. For operators, the configuration of PCell can depend on the band location of available TDD and FDD carriers and the network deployment situation. For example, if the FDD band is much lower than TDD band, the corresponding FDD carrier is suitable for PCell to ensure coverage, and the TDD carrier can be configured as SCell (secondary cell) to enhance the downlink throughput and UE data rate. If the TDD network has been well developed with satisfactory coverage, and the FDD network is newly deployed, TDD carrier can be configured as PCell. Consequently, both network equipment and UE equipment are desired to support both TDD and FDD as PCell, so as to provide more flexibility for operators to choose according to the requirements.

Recently, interests for operators who want to deploy additional TDD configuration(s) except for the existing 7 TDD configurations, e.g., downlink only TDD configuration, are raised for a non-standalone carrier deployment on TDD band. In 3GPP, there has not been any consensus on whether additional new TDD configuration, e.g., downlink only TDD configuration, shall be introduced for LTE TDD. To gain a better understanding on the issues related to the potential introduction of additional new configuration for LTE TDD, 3GPP started a study item in early 2015[3]. This study item shall not provide any recommendation on any follow-up normative work. Upon completion of this study item, the follow-up actions shall be discussed on the 3GPP PCG level no earlier than September 2015.

From TD-LTE eco-system perspective, introducing additional new TDD configuration needs to be carefully studied:

- TD-LTE with legacy configurations have been widely deployed, with a large penetration ratio of the LTE FDD/TDD dual mode devices, which are already very mature. These devices would not support any new TDD configurations.
- The introduction of any new configuration(s) in TD-LTE will cause eco-system challenges, esp. the downlink only configuration will bring the risk of different UE designs and fragment the TD-LTE market.
- Any new configuration will cause the additional complexity, esp. in UE side. It needs to be justified whether there is any potential benefit worth such an impact on the eco-system.

Band Combinations:

It is recommended that TDD/FDD carrier aggregation can support any flexible combination of FDD and TDD so as to support the band combinations referring to Table 3.2-3.

The following green highlighted items have already been frozen in 3GPP R12 (version c70). With the consideration of market size, time urgent and technical risks, the following yellow highlighted is recommended for higher priority.

Table 3.2-4: Potential Combination Bands of TDD/FDD Carrier Aggregation

	B1 (2.1GHz)	B2 (PCS 1.9GHz)	B3 (1.8GHz)	B5 (CLR 850MHz)	B7 (2.6GHz)	B8 (900MHz)	B18 (Japan 800MHz)	B19 (Japan 800MHz)	B20 (DD800MHz)	B21 (1.5GHz)	B25 (Ext PCS 1.9GHz)	B26 (Ext CLR 850MHz)	B28 (APT 700MHz)
B38 (2.6GHz)			EU, ME, Korea		EU								
B39 (1.9GHz)			China			China							
B40 (2.3GHz)	Korea, China, HK, EU		EU, China, HK, AU, Korea, ME, India	Korea, ME	China, HK, EU	China, HK, EU, Korea			EU				AU
B41 (2.6GHz)	China, Japan		China, Japan, ME			China, Japan, ME					US	USA, China	
B42 (3.5GHz)	Japan, China		Japan, China		EU	Japan, China		Japan	EU	Japan			

Notes:

FDD Bands are in **columns**
TDD Bands are in **rows**
HK = Hong Kong, EU = European Union, ME = Middle East, AU = Australia

For more than two bands TDD+FDD CA combination, the following is recommended with yellow highlighted as higher priority:

Band 40 combinations (2.3GHz):

For Korea, Europe, China and Hong Kong:

- B1 (2.1GHz) + B3 (1.8GHz) + B40 (2.3GHz)
- B1 (2.1GHz) + B8 (900MHz) + B40 (2.3GHz)
- B3 (1.8GHz) + B8 (900MHz) + B40 (2.3GHz)

For Japan and Australia:

- B3 (1.8GHz) + B40 (2.3GHz) + B40 (2.3GHz)
- B3 (1.8GHz) + B40 (2.3GHz) + B40 (2.3GHz) + B40 (2.3GHz)

For Australia:

- B28 (700 MHz) + B40 (2.3GHz) + B40 (2.3GHz)
- B28 (700 MHz) + B40 (2.3GHz) + B40 (2.3GHz) + B40 (2.3GHz)

For Korea and Middle East:

- B1 (2.1GHz) + B3 (1.8GHz) + B5 (850MHz) + B40 (2.3GHz)

Band 38 combinations (2.6GHz):

For Europe:

- B7 (2.6GHz) + B20 (800MHz) + B38 (2.6GHz)
- B3 (1.8GHz) + B7 (2.6GHz) + B38 (2.6GHz)

Band 41 combinations (2.6GHz):

For China:

- B3 (1.8GHz) + B8(900MHz) + B41 (2.6GHz)
- B1 (2.1GHz) + B3(1.8GHz) + B41(2.6GHz)

Band 42 combinations (3.5GHz):

For Japan and Australia:

- B1 (2.1GHz) + B3 (1.8GHz) + B42 (3.5GHz)
- B1 (2.1GHz) + B3 (1.8GHz) + B42 (3.5GHz) + B42 (3.5GHz)

For Japan:

- B1 (2.1GHz) + B19 (800MHz) + B42 (3.5GHz)
- B1 (2.1GHz) + B21 (1.5GHz) + B42 (3.5GHz)
- B3 (1.8GHz) + B19 (800MHz) + B42 (3.5GHz)
- B19 (800MHz) + B21 (1.5GHz) + B42 (3.5GHz)
- B1 (2.1GHz) + B3 (1.8GHz) + B19 (800MHz) + B42 (3.5GHz)
- B1 (2.1GHz) + B19 (800MHz) + B21 (1.5GHz) + B42 (3.5GHz)
- B1 (2.1GHz) + B19 (800MHz) + B42 (3.5GHz) + B42 (3.5GHz)
- B1 (2.1GHz) + B21 (1.5GHz) + B42 (3.5GHz) + B42 (3.5GHz)
- B19 (800MHz) + B21 (1.5GHz) + B42 (3.5GHz) + B42 (3.5GHz)

For Europe (France)

- B7 (2.6GHz) + B42 (3.5GHz) + B42 (3.5GHz)
- B20 (2.3GHz) + B42 (3.5GHz) + B42 (3.5GHz)

For China

- B1 (2.1GHz) + B3 (1.8GHz) + B42 (3.5GHz)
- B3(1.8GHz) + B8 (900MHz) + B42 (3.5GHz)

Deployment scenarios:

As shown by Figure 3.2-5, TDD and FDD carrier aggregation is feasible for deployment in two scenarios—co-site TDD and FDD carriers as well as non-co-site TDD and FDD with ideal backhaul[1].

Co-located TDD/FDD using different frequency bands will generally be used by operators in the initial stage. Further development of network planning and capacity dimension will depend on the network strategy. UEs of category 6 and above are only allowed to support for carrier aggregation where the frequency bandwidth aggregated is more than 20MHz.

[1] delay less than 2.5 us, bandwidth up to 10Gbps

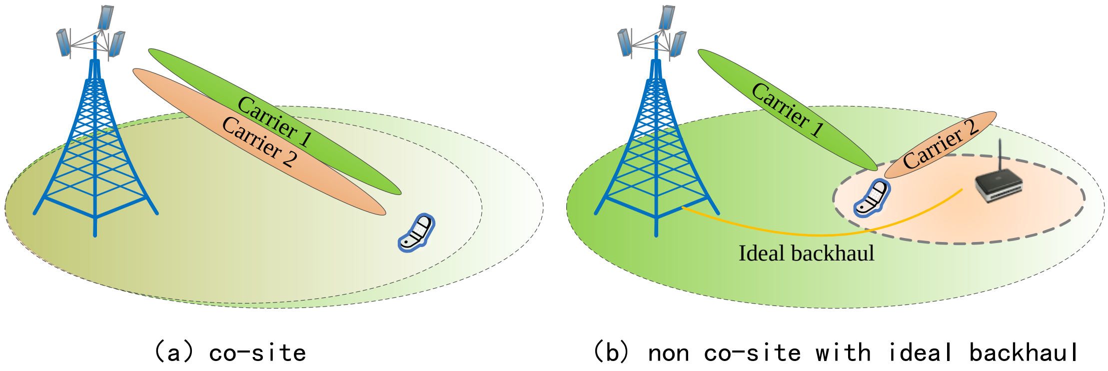


Figure 3.2-5: Deployment Scenarios of TDD/FDD CA

Additional requirements on eNB and UE parts:

From eNB side, the TDD and FDD should have a common baseband and be provided by same vendor. A joint scheduler is required for joint resource allocation and scheduling between the TDD and FDD carriers, thus flexibility in utilizing radio resources could be achieved. In order to make full use of current radio network infrastructures and guarantee backward compatible of TDD or FDD single mode terminals, both TDD and FDD should be able to serve as PCell. In addition, synchronization of TDD and FDD carriers is required.

TDD/FDD carrier aggregation shares similar requirements on radio network capabilities with R10/R11 carrier aggregation (i.e. FDD+FDD or TDD+TDD CA), except for some modifications in physical layer procedures caused by difference in duplexing as well as additional RF requirements on supporting TDD and FDD CA. The main requirements from radio network part include: support both TDD and FDD as PCell, HARQ timing of support for either TDD or FDD as PCell, support self-carrier scheduling and cross-carrier scheduling, support for up to 5 CCs CA, support PUCCH format 3 &format 1b with channel selection, and PUCCH is only transmitted on PCell.

From UE side, TDD/FDD CA requires the UE to be capable of simultaneous Transmit-Receipt, to support simultaneous Reception on both TDD and FDD carriers and at least support Transmission on a single carrier.

Feasibility of low band FDD and high band TDD CA, as well as TDD/FDD CA within one frequency band, are often highlighted. Analysis and suggestions are given as follows.

1. Low band FDD and high band TDD CA:

At the eNB side interference is not a big problem since two separate RRUs are usually required for large frequency differences especially with the considering the different duplex mode. However it may be necessary for eNB to consider the propagation time difference between the aggregated carriers when they are far separated. In this case eNB and UE should support multiple Timing Advance for the aggregated carriers.

From UE side, TDD and FDD require separate radio units in UE which can naturally match to high and low bands. Since modern UEs antenna systems already can support far-separated bands like 900MHz and 2.6GHz, only a diplexer is required for TDD-FDD CA. So high-low band TDD-FDD CA combination can be supported at UE.

2. TDD-FDD CA within one frequency bands such as Bands 7 and 38 (2600 MHz), Bands 22 and 43:

The highest risks of TDD-FDD CA within one frequency band are blocking and spurious interference.

For TDD-FDD CA with band combination B22+B43, only the carrier on Band 22 can be supported as PCell. This is because if the carrier on Band 43 is configured as PCell, the UL Transmit on Band 43 will cause severe interference to Reception on Band 22.

Considering the interference between aggregated TDD BS and FDD BS for TDD-FDD CA with band combination B7+B38, , the traditional non-CA solution still works: keep a guard band and suppress remaining interference either by an extra filter with sufficient isolation or by sufficient space isolation. For the interference between aggregated TDD UE and FDD UE, this is a new challenge for UE especially considering the limited space inside the UE. An extra filter and special antenna layout is required for the UE design. This is key for successful TDD-FDD CA within one frequency band.

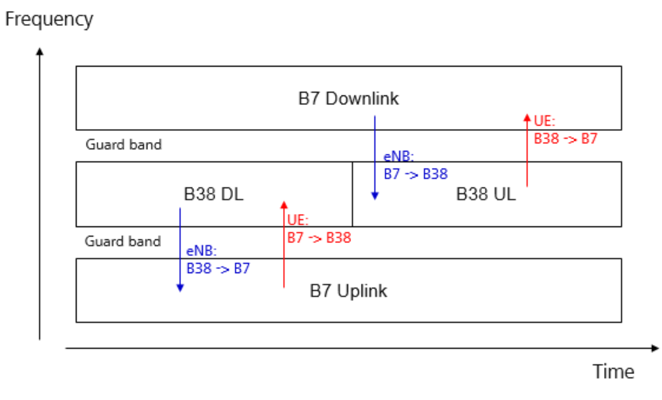


Figure 3.2-6: Interference Model of B7 + B38 CA

Interference between B7 and B38 BS: to address this challenge, several scenarios may be considered.

- B7 & B38 BS use separate antenna: in this scenario, the interference can be controlled by the physical separation between antennas and extra isolation provided by TDD&FDD BS filters to meet the following industry requirements.
  According to CEPT requirements: 100m spatial isolation, which requires eNB provide spurious emission <= -45dBm/MHz, blocking >= -8dBm/5MHz
  Usually 5~10MHz guard band is required to meet the isolation requirements with the help of customized narrow band filter.

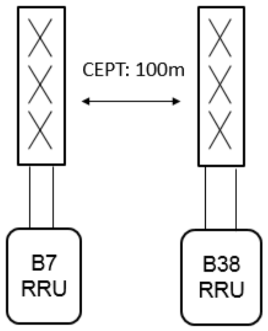


Figure 3.2-7: B7+B38 CA with separate antennas

- B7 & B38 BS use same antenna with separate ports: in this scenario, the required isolation is provided by (a) isolation between ports (normally around 30dB) and extra isolation provided by TDD&FDD BS filters.
  To meet the requirements of spurious emission <= -86dBm/MHz, blocking >= 16dBm/5MHz, usually 10MHz guard band is required with the help of customized narrow band filter.

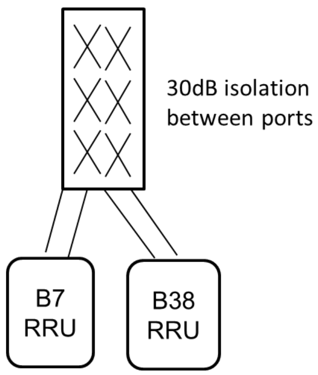


Figure 3.2-10: B7+B38 CA with one antennas different ports

- B7 & B38 BS use same antenna with same ports: in this scenario, the isolation can be provided by the extra combiners and TDD&FDD BS filters.

Usually 5~10MHz guard band is required to provide enough the isolation with the help of customized narrow band filter.

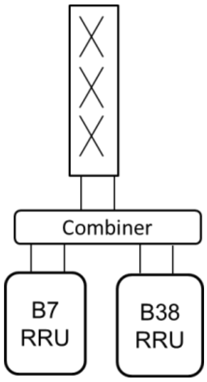
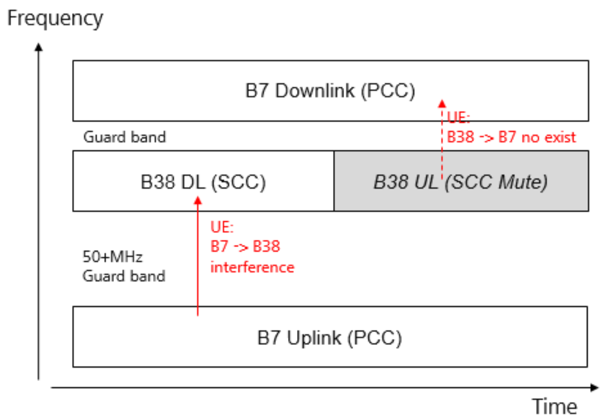


Figure 3.2-11: B7+B38 CA with one antennas + extra combiner

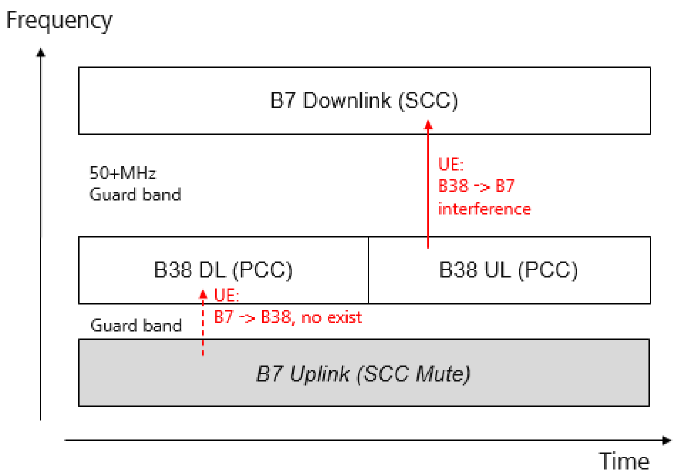
Interference in B7+B38 CA UE: With similar reasons, interference will happen inside B7+B38 CA UE during the TDD or FDD transmission opportunities. Potential solutions to address such interference could be:

- UE shares same Primary antenna and Diversity antenna for both B7 & B38. In this case, system loss comes from extra combiner and notch filter in B7. It is estimated total 6~7dB of loss will be introduce which is totally unacceptable.
- Special UE antenna layout to separate B7 & B38 Primary antenna. Option 1, lay a dedicated B38 primary antenna. However it is very difficult to lay an extra antenna in the very limited UE space. Option 2, share B38 primary with other radio system such as WiFi/GPS. In this case the isolation between B38 & WiFi is also very challenging due to its insufficient separation. For interference control reasons, 50+MHz of guard band is recommended for the B7 interference with B38.
- In the case of 50+MHz guard band between B7 UL & B38, the interference inside UE from B7 UL to B38 DL can be suppressed by filters. However CA UE should set B7 as PCC and mute the B38 UL so that the B38 UL will not interference the B7 DL.



- ***Figure 3.2-8: B7+B38 CA, 50+MHz guard band between FDD UL & TDD***

- In the case of 50+MHz guard band between B7 DL & B38, the interference inside UE from B38 to B7 DL can be suppressed by filters. However CA UE should set B38 as PCC and mute the B7 UL so that the B7 UL will not interference the B38 DL.



- ***Figure 3.2-9: B7+B38 CA, 50+MHz guard band between FDD DL & TDD***

To summarize: TDD/FDD CA provides an efficient solution for TDD and FDD radio resource utilization. With TDD/FDD CA, not only the UE peak data rate can be greatly increased, but also the cell-average and cell-edge data rate can be improved by joint scheduling through flexibly and quickly sharing the TDD and FDD resources.

3.2.4.2. Coexistence issues with B7+B38 aggregation (2600 MHz TDD+FDD)

B7 and B38 are adjacent FDD and TDD bands, and supporting carrier aggregation of these two bands raises the big challenge in UE RF implementation. Within the same device, the receiver of one band can be blocked by the transmitter of the other band. Therefore, implementation of TDD-FDD CA of B7 and B38 requires a complex UE design, which should be based on 2 sets of RF frontend and antennas separate for B7 and B38, which will impact size and cost of UEs. it is thus difficult to find a solution that is technically and commercially feasible.

As an alternative, a third band can be aggregated as PCell, while B7 and B38 are only used for SCell. Since there is no UL on B7 or B38, the in device coexistence issue is avoided. This leads to some CA combinations with 3DL/1UL in 3GPP, e.g. CA_3A_7A_38A. For this combination, B3 is always used for PCell (which means UL can only happen on B3), and B7+B38 is not considered as a valid fall-back combination. Though there are some limitations the alternative enables aggregation of B7 and B38 in DL without any big impact to UR RF design

3.2.4.3. Dual Connectivity

Another option for tight convergence of TDD/FDD is Dual Connectivity. Dual Connectivity in 3GPP Release 12 extends Carrier Aggregation (CA) and CoMP operations to higher layer (MAC and upward), and makes it possible for the UE to receive traffic streams from multiple transmission nodes. In scenarios where coverage areas of Master eNB (MeNB) and Secondary eNB (SeNB) are overlapped, UE could simultaneously connect with multiple eNBs, thus resources of multiple eNBs are available for data transmission. Benefits of dual connectivity include increasing UE throughput, reducing signalling overhead and improving mobility robustness. Dual connectivity also provides an efficient solution for flexible load balancing and traffic offloading.

Deployment scenarios:

Dual connectivity can be deployed in scenarios of TDD and FDD convergence with both ideal and non-ideal backhaul. Since dual connectivity provides convergence solutions on higher layer, it is feasible to deploy under scenarios with non-ideal backhaul, even deployed in TDD and FDD radio network with different vendors, which serves as its main deployment scenarios compared to TDD/FDD carrier aggregation.

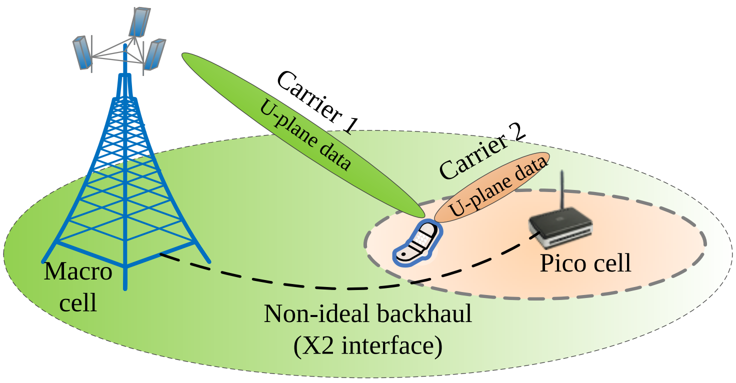


Figure 3.2-6: Deployment Scenarios of Dual Connectivity

A categorization of non-ideal backhaul based on operator inputs is listed in Table 3.2-4:

Table 3.2-4: Categorization of non-ideal backhaul

Backhaul Technology	Latency (One way)	Throughput
Fibre Access 1	10-30ms	10M-10Gbps
Fibre Access 2	5-10ms	100-1000Mbps
Fibre Access 3	2-5ms	50M-10Gbps
DSL Access	15-60ms	10-100 Mbps
Cable	25-35ms	10-100 Mbps
Wireless Backhaul	5-35ms	10Mbps – 100Mbps typical, maybe up to Gbps range

A categorization of ideal backhaul based on operator inputs is listed in Table 3.2-5:

Table 3.2-5: Categorization of ideal backhaul

Backhaul Technology	Latency (One way)	Throughput
Fibre Access 4	less than 2.5 us	Up to 10Gbps

Additionally, dual connectivity can be deployed in scenarios of MeNB and SeNB convergence with synchronous or asynchronous mode, where synchronisation DC is defined as DL maximum receiving time difference between MeNB and SeNB less than 33 µs.

Aggregation Points:

To fulfil dual connectivity for traffic transmission of user-plane, 3GPP R12 introduces two downlink data split modes: CN S-GW based split, and eNodeB based split.

1. S-GW based split:

S-GW splits downlink data into two parts and sends to MeNB and SeNB separately.

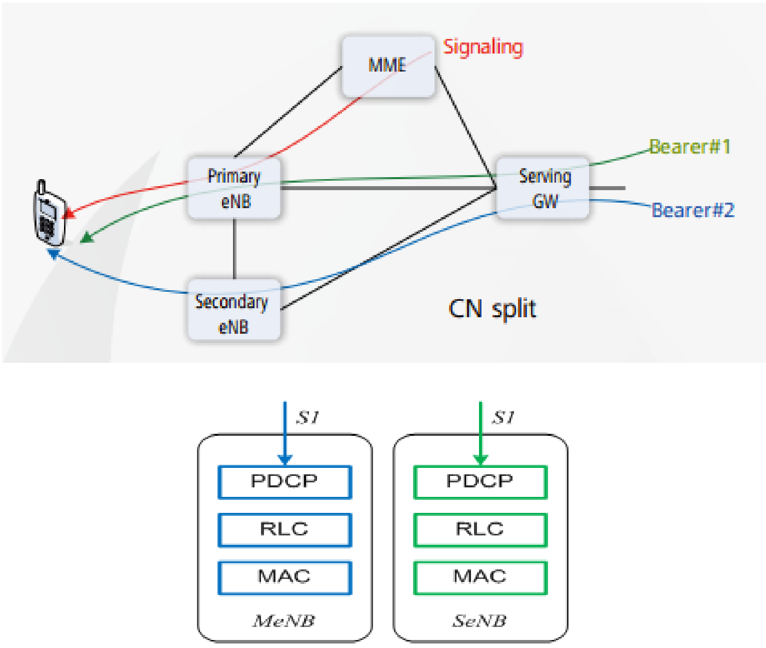


Figure 3.2-7: S-GW based split

In this mode, MeNB and SeNB have its own S1-U link to S-GW and separate PDCP.

2. eNodeB based split:

In this mode, MeNB splits parts of the downlink data to SeNB RLC. Only MeNB have S1-U link to S-GW.

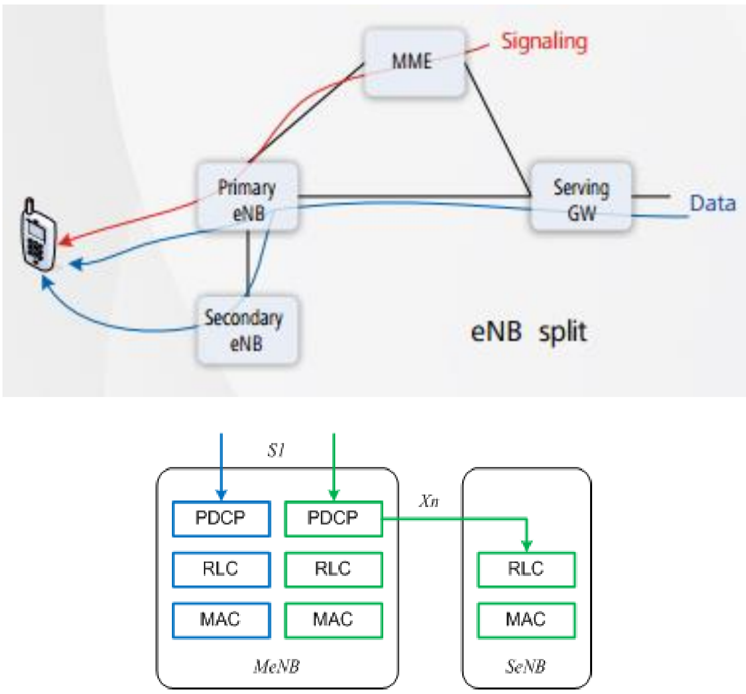


Figure 3.2-8: eNB based split

In terms of user plane, a single UE is required to connect with multiple eNBs and make use of their radio resources simultaneously, therefore the peak data rate is enhanced. But in terms of control plane, the same mechanism is specified for both split modes: only MeNB sends RRC signalling to UE, MeNB communicates to SeNB with standard X2 interface, which simplifies the UE mobility management.

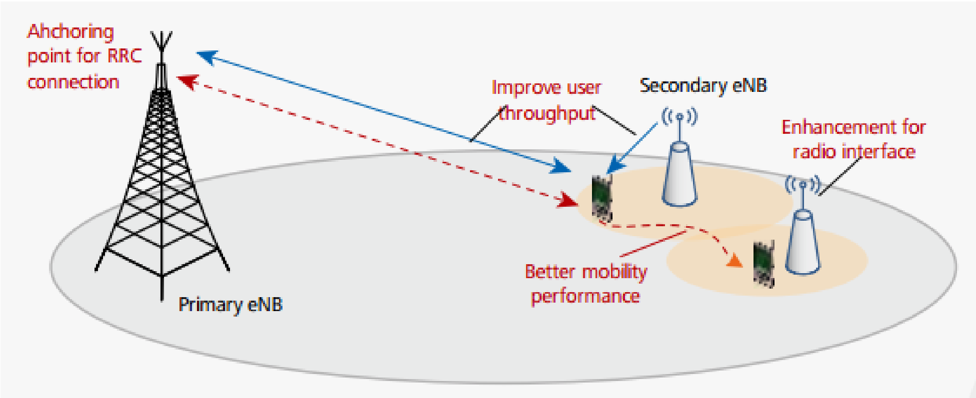


Figure 3.2-9: U-Plane and C-Plane of Dual Connectivity

Additional Requirements on eNB and UE:

For R12 network deployment, at any time simultaneous configuration of both modes are not supported.

From eNB side, for both modes, following functionalities should be supported:

- establish, modify and release radio resources of SeNB
- radio resource management and coordination between MeNB and SeNB
- maintenance and management of interfaces between MeNB and SeNB, such as interaction of UE configuration.

From UE side, UE with dual connectivity is required to have multiple Transmit-Receive capability and at least supporting both simultaneous Receive and Transmit on separate carriers with different duplexing.

Pros and cons of dual connectivity network architectures:

Table 3.2-4: comparison between dual connectivity network architectures

	S-GW based split	**eNB based split**
Application Limitation	[Con] Gains only obtained when UE has multiple bearers with similar throughput	[Pro] Gains can also be obtained when UE has only one bearer, e.g. only has default bearer
Load Balance	[Con] CN based load balance, which is static load balance	[Pro] eNB based load balance, more dynamic

<table>
<tr><th></th><th>S-GW based split</th><th>eNB based split</th></tr>
<tr><td>Mobility Robust</td><td>[Con] Mobility among S-eNBs is visible of CN, may need data forwarding and has traffic interruption</td><td>[Pro] Mobility among S-eNBs is transparent of CN, do not need data forwarding and do not has traffic interruption</td></tr>
<tr><td>CN</td><td>[Con] Introduce impact on CN (e.g., SGW) when switch the stream</td><td>[Pro] No impact on CN.</td></tr>
<tr><td>TN</td><td>[Pro] do not have impact on transport network</td><td>[Con] has extra transportation bandwidth requirement for transport network</td></tr>
<tr><td>eNB</td><td>[Pro] One Tunnel between Secondary eNB and SGW which means minimized processing in GTP-U level.
[Con] Not support dynamic data splitting, e.g., packet based splitting within one radio bearer based on radio conditions.</td><td>[Con] Two tunnel between Secondary eNB and SGW, which increase Primary eNB complex and latency.
[Pro] Packet based splitting within one radio bearer with awareness of radio conditions can be supported.</td></tr>
<tr><td rowspan="2">UE</td><td colspan="2">Support dual connectivity to MeNB and SeNB, and separate PUCCH on MeNB and SeNB.
Possible requires more transmit power for dual connectivity.</td></tr>
<tr><td>[Pro] Support AM and UM DRB without additional enhancement.</td><td>[Con] Need to enhancement current reordering function in PDCP for AM DRB, while not support UM DRB for this mode.</td></tr>
</table>

Comparison of CA and Dual Connectivity:

Although having similar aims on peak throughput enhancement and flexible radio resource sharing, TDD/FDD dual connectivity and CA have some differences on aggregation entity and deployment scenarios.

Dual connectivity re-uses most of the current CA PCell/SCell management mechanisms in an inter-site way, so that the connection of SeNB can be dynamically activated and deactivated. Compared with TDD/FDD carrier aggregation, dual connectivity has the following features:

- Dual connectivity extends CA to inter-eNB scenarios with non-ideal backhaul between two eNBs with up to 60ms of delay
- Possible for inter-vendor eNBs
- Reduces the signalling overhead of handover towards core network (eNB based split)
- Optimizes mobility performance (Anchor at MeNB):
    - Reduces mobility issue (e.g. Handover failure, Ping-pong).

- Avoids service interruption e.g. for VoIP

Table 3.2-5: Comparison of TDD/FDD CA and dual connectivity

Compare		TDD+FDD CA	TDD+FDD Dual Connectivity
Similarity		UE receives data from multiple cells. Flexible radio resource sharing between different cells Similar PCell/SCell management mechanism	
Difference	Aggregated cells	Intra-eNB or inter-eNB based on ideal backhaul, requires synchronization between aggregated cells	Inter-eNB aggregation for even non-ideal backhaul
	Aggregation Points	eNodeB	S-GW or MeNB
	Aggregation Level	MAC	IP, PDCP
	PUCCH	Only on PCell	Both PCell and SCell

3.2.5. Operator experience and recommendations

LTE in the TDD and FDD bands are complementary and convergence of these network layers opens up new possibilities for network operators. In many cases, the 4G FDD system operates in a lower frequency band and can act as coverage layer while the 4G TDD system with higher bandwidth available can act as a capacity layer in the network. Both TDD and FDD network systems can operate in multi-layer scenarios to enhance network coverage, capacity and performance especially for dense urban areas.

For mobility management solutions, both FDD and TDD use the same procedures defined in 3GPP standards. This will ease network implementation and both coverage and capacity extension to ensure the smooth mobility when a handover process is required. In mobility scenarios, there are different types of load balancing and strategies which can be deployed in the network as described in the previous section.

Network technology evolution is necessary to cater for rapidly growing LTE traffic. To enhance network spectrum efficiency and fully utilize network capacity to cater for users' throughput demand, carrier aggregation will become an important feature for converged networks. By aggregating TDD and FDD LTE carriers in common coverage areas, UE throughput performance and experience can improve significantly. FDD and TDD Carrier aggregation is still in the finalization stage in 3GPP Release 12 documentation and operators are looking forward to vendor equipment and UEs being developed to support TDD/FDD CA and being brought to market.

3.3. VoLTE in a Converged TDD/FDD network

3.3.1. VoLTE Coverage Comparison between TDD and FDD

LTE TDD and FDD enjoy over 90% technical similarity, and the differences mainly exist in the physical layer. When VoLTE is introduced in a converged network, questions such as whether these differences will cause discrepancies in VoLTE coverage capability, and which technology has better VoLTE coverage performance need to be considered, in case this will significantly impact the networking strategy.

Theoretical analysis has shown that with no coverage enhancement features, the Physical Uplink Shared Channel (PUSCH) usually becomes the bottleneck and limits the coverage of VoLTE service. However several coverage enhancement techniques, such as Hybrid Automatic Repeat request (HARQ) retransmission, RLC segmentation, and TTI-Bundling, can be used in LTE network to extend the coverage for VoLTE service. With combinations of these features, the coverage of PUSCH can be extended. In this scenario, the control channels, such as Physical Random Access CHannel (PRACH) or Physical Downlink Control Channel (PDCCH) where these techniques cannot be applied, may become the bottleneck. The coverage enhancement features are illustrated in Table 3.3-1 below.

Table 3.3-1: VoLTE Coverage Enhancement Features

Feature	Layer	Feature Definition	Advantage	Disadvantage
HARQ retransmission	MAC	An error correction mechanism: If transmitter received a NACK, a different redundancy version (RV) of the same data is sent & combined at Receiver side	Enhance reliability for data reception	■ Introduce delay in data reception: 8 ms/ReTx for FDD, around 10ms/ReTx for TDD ■ Control overhead
RLC Segmentation	RLC	VoIP payload is split into smaller size RLC protocol data units (PDU) for transmission	Smaller RLC PDUs results in smaller transport blocks (TB), which can be decoded with better accuracy	■ Overhead increases: multiple RLC/MAC headers needed since more than one RLC PDU is transmitted ■ Control overhead

Feature	Layer	Feature Definition	Advantage	Disadvantage
TTI-Bundling	MAC	One TB from MAC layer is sent repeatedly in 4 consecutive subframes	Less control overhead	▪ Less flexible

The frame structures of TDD and FDD determine how the coverage enhancement features can be exploited when VoLTE service is carried in these systems. For example the TTI-Bundling feature cannot be employed in TDD systems with uplink-downlink configuration 2, since there are not enough uplink timeslots to bundle.. On the other hand, this feature is supported by FDD and TDD with uplink-downlink configuration 1. Table 3.3-2 below is an excerpt from ETSI TS 136 213, which shows that TTI bundling is only supported with TDD configurations 0, 1 and 6.

Table 3.3-2 – Excerpt from ETSI TS 136 213

Table 8-1: Number of synchronous UL HARQ processes for TDD

TDD UL/DL configuration	Number of HARQ processes for normal HARQ operation	Number of HARQ processes for subframe bundling operation
0	7	3
1	4	2
2	2	N/A
3	3	N/A
4	2	N/A
5	1	N/A
6	6	3

How these coverage enhancement features can be exploited in FDD and TDD systems, and the corresponding gains can be achieved with each of these features are illustrated in Table 3.3-3.

Table 3.3-3: Coverage Enhancement Features in TDD and FDD

Within 20ms (VoLTE scheduling period)	LTE FDD	TD-LTE（2:2） UL-DL config. 1	TD-LTE(3:1) UL-DL config. 2
Number of symmetric DL/UL subframes	20	8	4
Maximum number of HARQ Retransmission	4 (due to VoLTE packet delay requirement,)		

Within 20ms (VoLTE scheduling period)	LTE FDD	TD-LTE（2:2） UL-DL config. 1	TD-LTE(3:1) UL-DL config. 2
Maximum number of RLC Segmented Units (coverage enhancement)	20	8	4
Support TTI-Bundling?(coverage enhancement)	Yes	Yes	No

The scenarios in Table 3.3-4 will be considered when comparing the coverage capability of TDD and FDD systems. In addition, we assume that FDD and TDD systems are deployed using the same or close frequency bands.

Table 3.3-4: Scenarios considered in the coverage comparisons

		HARQ Retransmission	RLC Segmentation	TTI bundling
Trigger Condition for the feature		NACK is received at Transmitter; the number of Retransmission is determined by actual channel condition during transmission	Physical layer resource in single TTI cannot handle payload of a VoLTE packet	TTI-B enable and channel cond. for triggering TTI-B is met
Scenario	1	Not considered	Not considered	Not considered
	2	4 ReTx	Not considered	Not considered
	3	Not considered	4 units/8 units/20 units	Not considered
	4	Not considered	Not considered	TTI-B enable for FDD/TDD(2:2)

According to theoretical analysis, the coverage capabilities of TDD and FDD systems in these scenarios are shown in Table 3.3-5, where TDD systems with 8-port, 2-port and FDD with 2-port antenna deployment are all considered.

Table 3.3-5 Comparison Scenarios

Scenario	Comparison Results
1	**TDD(8-Port)>TDD(2-port)=FDD(2-port)**
2	With the same number of Retransmission: **TDD(8-Port)>TDD(2-Port)=FDD(2-Port)**

Scenario	Comparison Results
3	With the same number of RLC segmented units: **TDD(8-Port)>FDD(2-Port)=TDD(2-Port)** When the number of RLC segmented units FDD>TDD: **TDD (8-Port)>FDD(2-Port)>TDD (2-Port)**
4	TTI-B not supported by TDD: **TDD (8-Port)≈FDD(2-Port)>TDD (2-Port)** TTI-B supported by TDD: **TDD (8-Port)>FDD (2-Port)≈TDD (2-Port)**

The table above shows that for 2-port antenna deployment, the VoLTE coverage is the same for TDD and FDD under same condition. However, FDD has more options for choosing the coverage enhancement features as shown in Table 3.3-2. When the number of RLC segmented units in FDD is larger than that of TDD or when TTI-Bundling is not supported by certain configurations of TDD, the coverage of FDD is slightly better than that of TDD.

8-port antenna deployment can enhance UL coverage of 2-port antenna deployment, reducing dependence on coverage enhancement functions such as HARQ, RLC Segmentation and TTI-Bundling.

In summary, FDD has more options for choosing coverage enhancement features, while TDD can benefit from the 8-port antenna deployment. Overall, with the same or similar frequency band, the coverage capability of TDD and FDD are at the same level. Therefore, carrying VoLTE service in a TDD/FDD converged network is the same as carrying it in a multi-layer (frequency) TDD or FDD network, where the location of the frequencies will have a larger impact on the coverage capability than the technology.

3.3.2. VoLTE Mobility Management in a TDD/FDD Converged Network

The process for VoLTE handover between TDD and FDD is the same as the inter-frequency handover within TDD or FDD, therefore, the performance of the former should be at the same level as the latter. This conclusion is also confirmed by field test results. It has been shown that the average control plane latency[2] of TDD/FDD VoLTE handover is 23-24 ms, while that of inter-frequency handovers within LTE FDD is 23 ms in the same test. As for the user plane, the handover latency between TDD and FDD is 52-61 ms, while that of inter-frequency handovers within TDD is 53 ms.

[2] The handover latency in control plane is defined as the time difference between UE receiving handover command message to UE sending handover complete message to the eNodeB. This test results were obtained by using Qualcomm MTP

Based on the analysis of coverage capability of TDD and FDD and the handover performance between FDD and TDD, it can be seen that carrying VoLTE service on a TDD/FDD converged network is essentially the same as carrying it on a multi-layer LTE FDD or TDD network.

3.4. Requirements on TDD/FDD Products

Converged products, including converged base stations and converged terminals, lay the foundation of convergence networking. The commonality between LTE FDD and LTE TDD makes it possible that TDD and FDD can share a common eNB hardware platform, thus reducing eNB cost from material purchase and production point of view. From equipment installation and maintenance point of view, a LTE FDD and LTE TDD eNB common platform will be helpful for delivering both CAPEX and OPEX savings for operators.

Mainstream LTE infrastructure vendors have already provided TDD/FDD LTE dual mode eNB on a common platform. For RF part, TDD is generally on separate RRUs and antennas to FDD simply because TDD is in a different frequency band. However, RRU and antennas should also be integrated as multiband RRU and broadband antenna from the cost perspective, but only applied in co-locate scenarios. Dual mode terminals, with capabilities of supporting TDD and FDD as well as interworking, are of great importance.

3.4.1. Convergence of network products

Convergence of network products refers to converged BBU, RRU and antennas.

BBU:

Except for slight differences on physical layer, specifications on other layers are consistent between LTE FDD and LTE TDD. Over 90% of the software protocols for LTE FDD and LTE TDD eNodeB are the same. The commonality on software means the approximately similar hardware processing capability requirements. By using programmable DSP, FPGA and high-end CPU, it’s easier to realize the common hardware platform. BBU convergence can be realized by physical stacking FDD and TDD baseband processing board with common hardware platform and different software in the first stage, where cabinet, power, controlling board and interfaces could be shared. Then a single board with both TDD and FDD modes could be supported later.

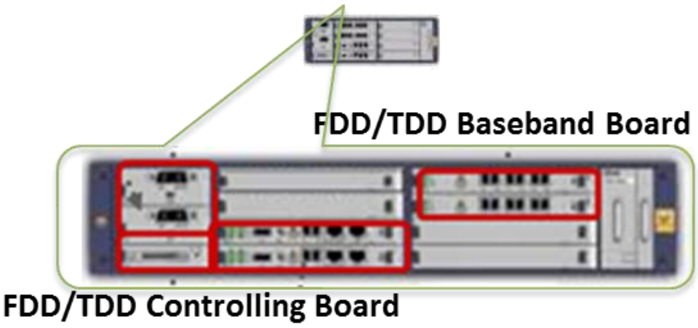


Figure 3.4-1: Converged BBU Product

For 2 path BBU product, baseband processing complexity and interface requirements of LTE FDD and LTE TDD eNodeB are nearly the same. Mainstream LTE vendors now have already supported a common hardware platform for LTE FDD and LTE TDD BBU.

8 path BBU product, currently only LTE TDD has the demand for 8 path BBU, and baseband processing complexity and interface requirements of 8 path BBU are significantly higher than 2 path BBU. If LTE TDD baseband board supporting 8 path can support 3 FDD LTE 2 path processing, then 8 path TD-LTE BBU supporting one sector can support 3 sector 2 path FDD LTE BBU. Thus the processing board of LTE TDD can be kept the same for LTE FDD.

Requirements on TDD/FDD converged BBU products are as follows,

- common HW platform with single design on size, interfaces, management, power and monitoring module
- FDD/TDD baseband processing board could be configured and operated in a BBU
- Controlling board could be configured and operated in a BBU; Furthermore, controlling board could be shared between TDD and FDD for radio resource management.
- Unified interface is shared for TDD/FDD in a BBU.

RRU:

With different frequency bands, RRUs of TDD and FDD are commonly deployed separately. However if multiband RRU are available, converged RRU may be considered in some circumstance, such as where there is only limited space for the radio unit installation. FEM and Transmit/Receive path of RRU are significantly different between LTE FDD RRU and LTE TDD RRU due to difference in duplexer mode. According to present solution, LTE FDD RRU and LTE TDD RRU cannot share a common hardware platform in a cost effective way.

If it is possible to enlarge the bandwidth of Transmit/Receive path to support both FDD and TDD Transmit/Receive frequency bands, for example in 2.6GHz band, and by using a novel duplex mode which can support FDD and TDD duplex mode flexibly, common platform for LTE FDD RRU and LTE TDD RRU is possible. As the Transmit/Receive path bandwidth is mainly limited by PA or ADC, RRU common platform for LTE FDD and LTE TDD working in adjacent frequencies is more feasible.

Antenna:

Similar to converged RRU products, converged antennas are with limited deployment scenario such as co-located TDD and FDD. But converged antenna is a cost effective deployment solution since the site rental is often correlated with the number of antennas and any additional antenna may incur extra OPEX in the long term in some regions. Many operators prefer to deploy a fully converged antenna (multiband wideband antennas) solution.

There are two approaches for TDD/FDD converged antennas. Firstly, the two systems can use different arrays and interfaces while sharing the outer cover, which is suitable when the frequency bands are far away from each other. Alternatively, an inner combiner can be used, so that the antenna arrays can also be shared (see Figure 3.4-2). In this scenario, the insertion loss due to the combiner should be reduced as much as possible. Outer combiner is not recommended.

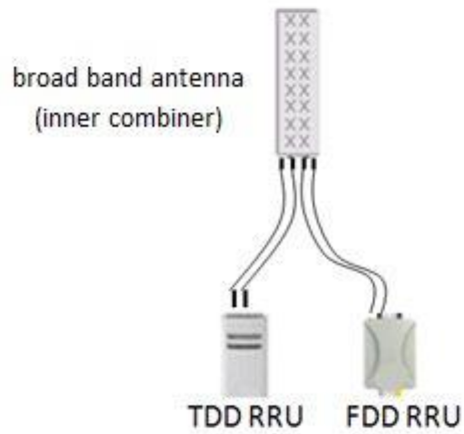


Figure 3.4-2: two path broad band TDD/FDD antenna

3.4.2. Convergence of terminals

As over 90% of the software protocols for LTE FDD and LTE TDD can be reused and considering global roaming/applicability, most of the terminal chipset vendors have developed their LTE TDD/FDD converged chipsets on a unified platform. Terminal baseband chips need to support LTE FDD/TDD dual-mode and multi-mode multi-band for roaming. Requirements on LTE TDD/FDD converged terminals are as follows:

- LTE TDD mode and corresponding bands supported
- LTE FDD mode and corresponding bands supported
- LTE FDD/TDD dual-mode and multi-mode multi-band for roaming supported
- Inter-frequency measurement supported
- Mobility management solutions supported for FDD/TDD interworking, includes
    - Cell reselection in idle mode
    - PS handover in connected mode
    - Redirection in connected mode

Except for supporting multi-mode multi-band interworking, common requirements of TDD/FDD converged terminal are as follows:

- New Call
    - VoLTE terminals, the calling feature are carried by either VoLTE or CS calls depending on network coverage. VoLTE will be first priority and follow by CS.
- New Message
    - Shall support GSMA RCS 5.1 as minimum
    - Shall support SMS over SGs for SMS receiving.
- Service and functionality
    - Shall support multi-party call
    - Able to share and play picture/video during a call. (both terminals of the originator and receiver able to view the same object sharing)
    - Able to receiving/sending messages and accessing the communication history with contact during a call.
- IP Connection Management
    - Concurrent connections of multiple APNs (IMS APN and Internet APN) shall be supported.
    - Concurrent connections of LTE and WiFi shall be supported.
    - Concurrencies of IPv4 and IPv6 in scenario occur on different APNs or WiFi.
    - Packet aggregation of LTE and WiFi base on connectivity quality. User able to select the configuration option.
- Authentication
    - AKA and HTTP Digest authentication mechanism shall supported.
- Terminal Management
    - Shall support mandatory upgrades (with users acknowledgement) and recommended upgrades
    - Shall support rollback features in the update process – cater for in case of failure.
- Global Roaming
    - Support Global Roaming services on both TD-LTE and FDD-LTE

- o Shall use the IMS APN in IMS roaming mode as priority if supported. If not supported, shall use the Internet APN in PS roaming mode.
- Security
  - o Mechanisms prevention of users from attack.

For example, Optus has worked with leading terminal suppliers to bring TD-LTE capabilities to UEs. However, the more challenging task was to have popular handsets support seamless interaction between TDD and FDD layers. The Samsung Galaxy 4 Mini (i9197) was the first phone to achieve this, soon follow by the Galaxy S4 TDD variant (i9507)[4]. Since then several major suppliers have released handsets that support full TDD-FDD interoperation, including LG, HTC, and Nokia.

The key enabler of TDD/FDD convergence is the modem chipset. Once the major chipset suppliers such as Qualcomm, HiSilicon and Marvell supported seamless TDD/FDD convergence, adoption in handset picked up quickly. However it is important to note that full convergence was not achieved immediately. Early chipsets that supported both TDD and FDD modes did not necessarily support the full seamless interaction between them. Some models could only support either TDD or FDD at any single point in time, and needed to fall back to 3G before being able to attach to the other layer. Now that many chipsets support seamless TDD/FDD interaction, network operators are looking forward to this capability being introduced into lower tier devices.

3.5. Independent TDD/FDD vendors in a converged network

In a fully converged TDD/FDD network, it is important to consider advanced traffic and layer management capabilities as well as carrier aggregation potential in order to maximise the benefits of convergence.

While theoretically different vendors could be used for TDD and FDD layers on same site, many advanced network features would not be able to be deployed if different vendors were used.

This is because most traffic, load and layer management capabilities are implemented through vendor proprietary algorithms, and these algorithms rely on network information and measurements collected by eNB or reported by the UE. The way this information is measured differs between vendors (different characteristics are measured in different ways), and this information cannot be shared between different vendors because there is no standardised way of sharing such information. Hence there is no way these advanced layer management features could be implemented.

About the only feature that could be implemented would be signal strength or quality related handovers between the layers, as these are reported by the UE to the eNB, and the eNB would be configured with the IDs of neighbouring cells, which would not necessarily need to be the same vendor.

TDD/FDD carrier aggregation would also be impossible to implement if different vendors were used for the TDD and FDD layers. This is because the eNB needs to assign a Pcell, allocate one or more Scells, and then the eNB scheduler needs to assign user data among these cells. This requires all the relevant cells to be connected to and managed by the same baseband pool which is only possible with a common vendor.

If the TDD network is a different network to FDD, this situation does not apply because the networks do not interact at an RF level. Hence different vendors could be used in this situation.

4. Roadmap of Convergence Networking and Industry Status

4.1. GTI Operator Survey

In order to better understand the intentions of operators around the world regarding TDD/FDD Convergence, the GTI conducted an operator survey in August 2014 seeking information about operators' network plans.

The survey was open from 1st to 10th August and 25 operators responded. At a high level, this survey revealed that:

- 12 operators – just under half of respondents – own both TDD and FDD spectrum
- TDD spectrum existing use is evenly split between WiMax and LTE
- FDD spectrum is predominantly used for 4G LTE
- One operator runs all technologies: 2G, 3G, 4G (TDD and FDD) and WiMax

TDD use	# operators	FDD use	# operators
Not used	1	Not used	1
Tech 4G Trial	5	2G only	1
Live 4G Trial	1	3G only	1
WiMax	9	4G only	3
4G (LTE)	8	2G & 3G	1
4G & WiMax	1	3G & 4G	1
		2G, 3G & 4G	4

Table 4-1 – TDD and FDD spectrum use from GTI operator survey

In terms of spectrum ownership, the survey results showed that

- The most TDD spectrum bands owned by any single operator is 4
- The most FDD spectrum bands owned by any single operators is 5
- The most spectrum bands in total owned by any single operator is 8, with three operators owning 6 bands.
- The most common TDD bands are Bands 38 (2.6 GHz) and 40 (2.3 GHz)

The most common bands in use by the survey respondents is shown in Table 4-2.

TDD Band	# operators	FDD Band	# operators
38 (2.6 GHz)	10	3 (1800 MHz)	7
40 (2.3 GHz)	10	1 (2100 MHz)	6
41 (2.5 GHz)	8	8 (900 MHz)	6
42 (3.5 GHz)	8	5 (850 MHz)	5
33 (1.9 GHz)	4	7 (2600 MHz)	5

Table 4-2 – Most common TDD and FDD bands used from GTI operator survey

One of the objectives of conducting this survey was to identify which TDD/FDD band pairings appear to be more common, which would assist the GTI in driving device manufacturers and network equipment vendors to provide the right capabilities in their products to support converged TDD/FDD operation.

For operators with both TDD and FDD spectrum, the most common band combinations are (by the number of operators with that combination) are shown in table 4-3.

TDD band🡻	FDD 🡺 band	1	3	5	7	8	TOTAL
38		2	2	2	4	2	12
40		2	3	2	1	2	10
41		2	3	1	0	3	9
42		3	3	1	2	3	12
TOTAL		9	11	6	7	10	

Table 4-3 – Most common TDD and FDD band combinations from GTI operator survey

Table 4-3 reveals that the most common combination is Bands 38 & 7, and also that:

- There is a high occurrence of FDD Bands 3, 8 and 1 in combination with TDD bands
- There is a high occurrence of TDD Bands 42, 38 and 40 in combination with FDD bands
- There is only one occurrence of combinations 40 & 7, 41 & 5 and 42 & 5.
- There are no occurrences of 41 & 7 (i.e. no market where the full 2.6 GHz band is licenced to be both TDD and FDD).

Note that band combination 38 & 7 covers the full 2.6 GHz band (i.e. both the duplex pair which and the midband gap).

Finally, the GTI survey asked respondents that own both TDD and FDD spectrum to indicate their TDD/FDD network convergence intentions. While only a few operators are already operating converged TDD/FDD networks, the results revealed that most operators are planning to converge their networks within the next 2 years. Only 2 operators indicated they had no plans to converge their networks. The full results are shown in Table 4-4 below.

Convergence Status today		Convergence Intentions		Timing of Convergence		Timing of TDD/FDD load balancing		Timing of TDD/FDD CA / dual connectivity	
Not converged	2	Partial	2	Already converged	1	Already balancing	0	No plans	1
Planning	6	Complete	6	Within 1 year	1	Within 1 year	2	Within 1 year	2
Converged	2	Already converged	1	Within 2 years	5	Within 2 years	6	Within 2 years	6
				Within 3 years	3	Within 3 years	2	Within 3 years	2
No answer or NA	2	No answer or NA	3	No answer or NA	2	No answer or NA	2	No answer or NA	1

Table 4-4 –TDD and FDD Convergence intentions from GTI operator survey

Hence we expect to see the bulk of convergence activity occurring within the next 2 years and the first TDD/FDD CA network to launch next year. This means that device and network equipment vendors very much need to focus on their development of TDD/FDD convergence capability in their hardware and software product roadmaps in the coming year so that they are ready for converged TDD/FDD operator deployments in 2015/16.

4.2. Industry Status

Shown by the convergence roadmap, although some operators are still on the initial stage of TDD/FDD convergence networking, but the end-to-end industry to support convergence is already maturing for deployment.

Nowadays, coverage-based mobility management functions between LTE FDD and TDD, including idle reselection, redirection and handover, are well supported by both of mainstream network equipment and terminal industry and ready for commercial deployment. Handover of LTE TDD and LTE FDD are well supported by chipset vendors such as Qualcomm, Hisilicon, Marvell as well as MTK. All of the 5-mode or 4-mode smartphones support handover between LTE TDD and LTE FDD since the second half of 2013. Handover between LTE TDD and FDD LTE has already been enabled in more than 6 commercial networks.

Load and traffic balancing functions are well supported by major network equipment vendors. As for the terminal side, no additional requirement is needed as long as the LTE FDD/TDD handover function is already supported.

Considering joint operation solutions, demonstrations on TDD/FDD CA have been demonstrated since 2014 Mobile Asia Expo (MAE), and in August 2015, Optus became the first operator in the world to commercially launch TDD/FDD Carrier Aggregation. Optus in fact commercially launched Cat 9 three-carrier aggregation from the start, using two TDD carriers and one FDD carrier. A number of other operators including Vodafone Portugal, Swisscom Switzerland and China Mobile Hong Kong have announced TDD/FDD convergence trials or launch plans.

From the perspective of converged products, mainstream network product vendors have released TDD/FDD converged BBU in a common hardware platform, where TDD and FDD carriers can be flexibly configured and deployed. Converged TDD/FDD antennas are also supported by mainstream vendors, with multiple FDD and TDD band and path combinations.

Multi-mode Multi-band (MMMB) converged terminals only requires slight increase in cost and complexity compared with FDD only terminal. This slight increase in cost is mainly estimated as $4 on BOM, including PA, Filter and Switch. The increase in complexity is mainly caused by larger area required for PCB. It is challenging for the design when PCB area is limited. There is little influence on RF design and performance of converged antenna compared with FDD only terminals.

As of June 2014, 8 chipset vendors have release 24 commercial chipset platforms, including Qualcomm, Hisilicon, Marvell, MTK and so on. In addition most of terminal companies have released commercial LTE TDD/FDD converged smartphone, such as Samsung, Apple, SONY, HTC, Huawei, ZTE.

5. Case Studies

5.1. China Mobile Hong Kong

China Mobile Hong Kong (CMHK) commercially launched a converged network on 18th December, 2012. CMHK owns totally 96.4MHz spectrum resource, including:

- GSM and LTE FDD (Band 3, 1800MHz): 2*13.2MHz, in which 2*3MHz or 2*5MHz for LTE FDD
- LTE FDD (Band 7, 2600MHz): 2*15MHz + 2*5MHz, currently only 2*15MHz is in used for FDD LTE
- TD-LTE (Band 40, 2300MHz): 30MHz, currently only 20MHz is in used for TDD LTE

In the converged network, since most of the GSM sites have re-farmed to LTE FDD, now LTE FDD on 1800MHz provides full coverage, while LTE TDD on 2300MHz with 20MHz bandwidth and LTE FDD on 2600MHz provides capacity expansion at hotspots. In terms of mobility, LTE TDD has a highest priority than FDD LTE bands, while priority on LTE FDD Band 7 is higher than LTE FDD Band 3. Priority of LTE bands is higher than 3G and GSM.

To deploy a fast and low-cost rollout of TDD/FDD converged network, the core network is shared. Site location, cabinet, power supply and backhaul of TDD and FDD are also shared on RAN side. At the current stage, BBU and RRUs are separate for TDD and FDD deployment: There is LTE TDD BBU and FDD LTE BBU installed in the equipment room; the LTE TDD RRU and FDD LTE RRU connect with their BBU by optical fibre and remotely installed on the tower respectively. For the LTE TDD and FDD LTE co-site scenario, co-antenna solution has been introduced, with the architecture of co-antenna as shown below. By adding combiners, LTE TDD equipment and FDD LTE equipment share the 2-path antenna, which support 2.3G/Hz2.6GHz. The broadband antennas of TDD and FDD have independent electrical tilting.

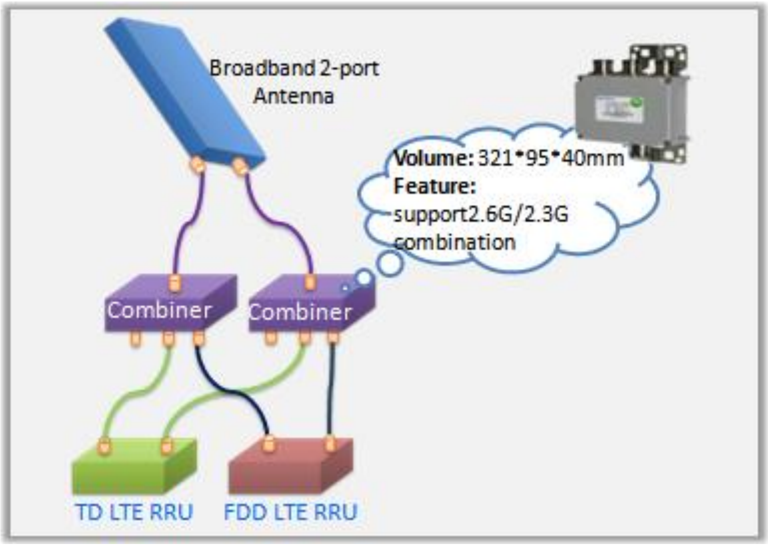


Figure 5.1-1: converged antenna solution

Network planning, optimization and installation of TDD and FDD are also shared.

TDD/FDD interworking is available in converged network of CMHK. China Mobile Hong Kong (CMHK) commercially launched LTE FDD network in April. 2012, and TDD network in December of the same year. According to the field tests, the average latency for idle reselection between TDD and FDD network is around 31 ms, while those of intra-frequency reselection within LTE FDD and TDD are 29 ms and 31.8 ms[3], respectively. It can be seen that the performance of idle reselection between LTE TDD and LTE FDD is at the same level as those of LTE intra-frequency reselection.

According to the test results in CMHK, the average control plane latency of TDD/FDD handover is 17.8 ms[4], while those of intra-frequency handovers within LTE FDD and TDD are 16.6 ms and 17.5 ms, respectively. As for the user plane, the field tests shown that the latency for TDD and FDD handover is 55.9 ms, while those of intra-frequency handovers within LTE FDD and TDD are 53 ms and 60 ms, respectively.

The process of TDD and FDD handover is the same as those of intra-frequency handover within TDD or FDD, therefore, the performance of the former should be at the same level as the latter, as confirmed by the field test results.

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[3] Idle reselection latency is defined as the time difference between the RRC layer of UE receiving measure report from the physical layer and triggering cell reselection to UE decoding MIB/SIB and going to RRC IDLE in the target cell

[4] The handover latency in control plane is defined as the time difference between UE receiving handover command message to UE sending handover complete message to the eNodeB. This test results were obtained by using a MiFi

5.2. **Optus (Australia)**

Optus initially launched 4G in the 1800 MHz band (FDD) in Newcastle on 26 April 2012, followed by Sydney and Perth in July 2012, then Melbourne, Brisbane, the Gold Coast, Adelaide and Wollongong.

Optus followed this up with the launch of 4G (TDD mode) in the 2300 MHz band in Canberra on 20 May 2013, however because Optus does not own 1800 MHz spectrum in Canberra, this 4G TDD network remained separate to the 4G FDD network in the other cities.

4G TDD was launched in Sydney, Melbourne, Brisbane and Adelaide on 13 September 2013, complementing the 4G FDD 1800 MHz network in those cities, thereby creating Australia's first dual-mode, dual-band, converged FDD/TDD LTE network.

This launch was only the 8th known converged FDD/TDD LTE network in the world, following other operators such as Aero2 in Poland, Hi3G Sweden, and China Mobile Hong Kong.

A key collaboration to make this possible was between Optus and Samsung. Samsung used the Optus TDD/FDD network as its global testing ground for the Samsung Galaxy S4 and S4 Mini dual mode FDD/TDD smartphones.

Optus was the first telecommunications carrier in the world to support Samsung's dual-mode 4G devices with seamless TDD/FDD-LTE handover technology.

Optus has continued to seed its customer base with mobile devices which support 4G in both FDD and TDD modes to ensure ongoing uptake of Optus' converged 4G network.

Optus secured additional 4G spectrum at auction in 2013, in 2600 MHz (3GPP Band 7) and 700 MHz (3GPP Band 28). This spectrum became available for use from 1 October 2014 and 1 January 2015 respectively. As Optus rolls out 4G in these bands, co-located with existing 3G and 4G base stations, Optus was one of the first operators in the world to commercially operate LTE over four spectrum bands simultaneously:

- 700 MHz – FDD, 2 x 10 MHz
- 1800 MHz – FDD, 2 x 15 MHz
- 2300 MHz – TDD, initially 40 MHz with ability to increase to 80 MHz
- 2600 MHz – FDD, 2 x 20 MHz.

In September 2014, Optus became the first operator in the world to commercially launch TDD carrier aggregation (20+20 MHz in Band 40) and in August 2015 Optus became the first operator in the world to commercially launch TDD/FDD Carrier Aggregation. Optus in fact commercially launched Cat 9 three-carrier TDD/FDD aggregation from the start, using two

TDD carriers (20+20 MHz in Band 40) and one FDD carrier (15 MHz paired in Band 3). This also supports all 2CC subsets (TDD+TDD and TDD+FDD).

Optus is a strong believer in TDD/FDD convergence and is actively involved in efforts to drive convergence globally.

5.3. Packet One Network (Malaysia)

The plan is to roll-out a LTE network in Frequency Division Duplex mode (FDD) utilizing 3GPP Frequency Band 5 (850MHz) and Time Division Duplex mode (TDD) utilizing 3GPP Frequency Band 38 (2600MHz) and with an option of WiMax TDD currently utilizing the 3GPP Frequency Band 40 (2300MHz) in the future after it has been vacated.

Basically, the approach is the 850MHz band will be utilized as blanket coverage layer due to the spectrum's superior characteristic in terms of link budget and penetration ability. On top of that, the 2600MHz band will be utilized to compliment the LTE rollout as a capacity layer or hotspot areas in areas where/when it is needed.

With only 2x10MHz spectrum in 850MHz band, the network will not able to cater the high growth of data traffic volume. Therefore, 2600MHz sites rollout is projected to increase rapidly from Year 2 onwards as Multi Carrier network to ensure the network capacity is enough to benefit the user experience from the perspective of speed and data quota.

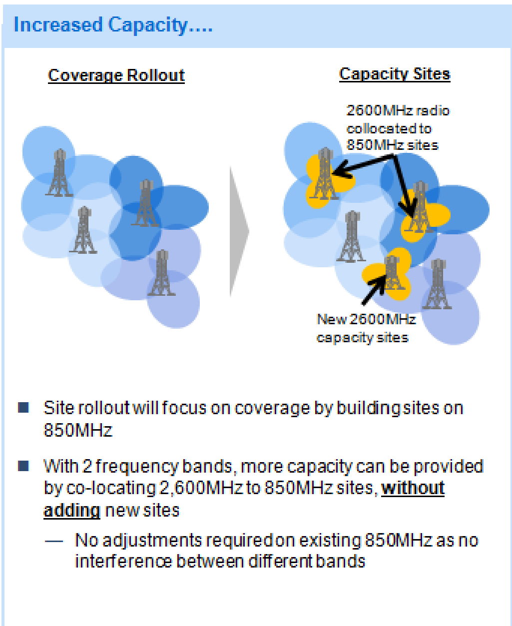

Figure 5.1-2

TDD/FDD converged solutions can be very efficient to handle the explosive LTE traffic growth in years to come. When an operator has both TDD and FDD spectrum, a converged network is an efficient way to fully utilize the available spectrum and meet the increasing data rate requirements.

Carrier Aggregation which will be made available from Release 10 onwards is an important technological need to provide high speed wireless broadband to its customers. It will be implemented when the ecosystem is ready with the additional frequency bands 38 and 40.

Here the bandwidth of both frequency bands will be added and provide higher throughput rates to the customer of up to 150Mbps.

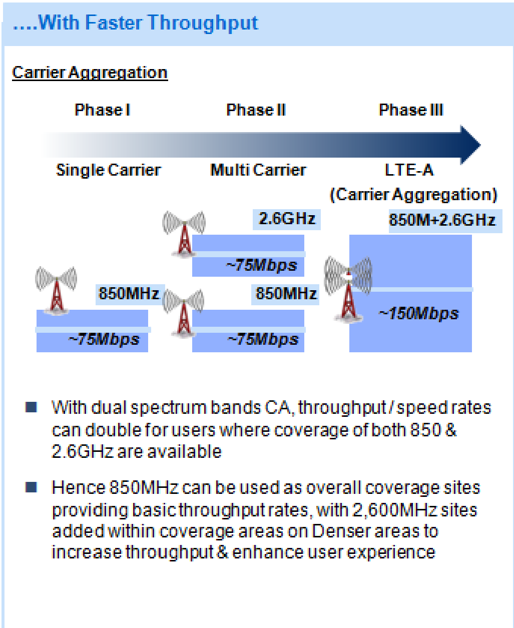

Figure 5.1-3

5.4. Hi3G (Hutchison 3 Sweden)

At the end of 2011, Hi3G implemented TDD/FDD LTE dual-mode network, with approximately 720 sites on 2600MHz TD-LTE and 2600MHz FDD LTE, and 200 sites on 2600MHz TD-LTE and 800MHz FDD LTE.

The usage strategy of LTE frequency bands are:

- LTE 2600MHz, with 2 x 10MHz FDD and 50MHz TDD, used to provide high speed data service.
  - FDD is mainly used in urban area to guarantee continuous coverage
  - TDD is mainly used to improve capacity
- LTE 800MHz, with 2*10MHz FDD, is mainly used for rural area coverage

Hi3G deployed TDD/FDD LTE Dual-mode Network, and requested inter-working with existing UMTS network. There are three major scenarios in the deployed network:

- Suburban and countryside area: coverage provided by UMTS 900MHz and LTE FDD 800MHz, And in some downtown of small cities, TD-LTE 2600M will be used
- Dense Urban area: hot spot coverage provided by 2.6GHz FDD and TDD LTE.
- Hotspot and blind area expansion: TD-LTE 2.6GHz for hot spot coverage capacity expansion

In dense urban areas, FDD and TDD LTE are converged to provide high speed data service. LTE FDD's bandwidth is 2x10MHz; while TD-LTE's bandwidth is 50MHz. LTE FDD and LTE TDD take the same role as both for coverage and capacity. Because TD-LTE has bigger potentiality in spectrum, it is configured with higher priority.

With the development of industry and technology, currently Hi3G TD- LTE and LTE FDD inter-working strategy includes two stages:

- Stage I: Coverage based interworking.
  - Dongles or CPEs are prior to register on TDD LTE network, mobile phone user has priority to register on FDD LTE network.
  - Bi-directional reselection and bi-directional redirection are supported between TD-LTE and LTE FDD
  - Interworking of connected mode between LTE and UMTS adopt redirection.
- Stage II: Load balancing among multi-mode network
  - Bi-directional PS handover between TD-LTE and LTE FDD
  - Load balance among TD-LTE, LTE FDD and TDD/FDD, PRB based and users based are both required.

For the LTE TDD and FDD LTE co-site scenario, the solution is shown by :

- Base station: one BBU with SDR platform including 1 FDD BPL and 1 TDD BPL could be shared by TD-LTE and FDD LTE. BBU could be installed in the equipment room; the FDD RRU and TDD RRU connect with BBU by optical fiber and remote installed on the tower respectively.
- The infrastructure including tower, shelter and power could be shared by TD-LTE and FDD LTE.
- EPC could be shared by TD-LTE and FDD LTE.
- Transmission resource could also be share by TD-LTE and FDD LTE.

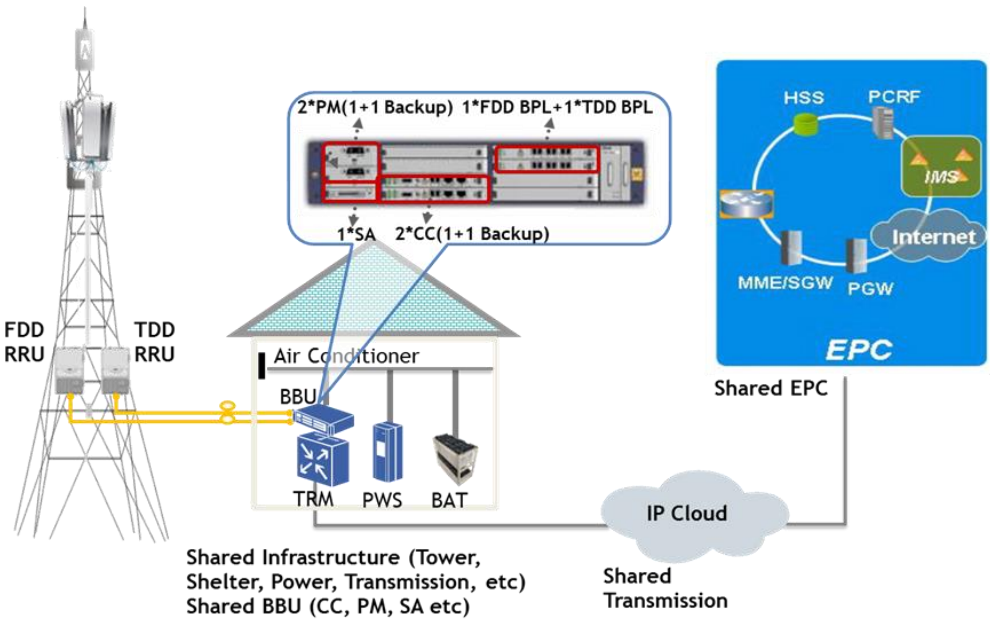

Figure 5.1-4: Network architecture of TD-LTE/FDD LTE Co-site

5.5. **STC (Saudi Arabia)**

STC owns TDD 2.3GHz spectrum with -wide bandwidth (52MHz) which is ideal for both Mobile and Wireless Broadband. Frequency bands for LTE are:

- TDD: 2.3GHz total 52MHz, already used 20MHz with 3:1 configuration, plan to upgrade to 20MHz+20MHz CA in 2014
- FDD: 1.8GHz 2x10MHz provides deep coverage but less capacity

2.3GHz TDD serves as capacity layer for its huge bandwidth and flexible DL:UL configuration, while FDD 1.8GHz serves as coverage layer. Camping on TDD is with higher priority.

STC have started TDD-FDD convergence in three phases:

- Phase 1: Shared antennas, Core Network and billing system for fast deployment. TDD and FDD both serve for Mobile and Wireless Broadband. Coverage based handover and reselection. (2013)
- Phase 2: Shared BBU, TDD/FDD convergence with load balancing for more smartphones and CPEs (2014)
- Phase 3: TDD/FDD deep convergence: carrier aggregation (2015)

At the present stage, coverage based cell reselection, coverage based handover as well as load based handover are applied in convergence network.

6. GTI Observations and Conclusions

As demonstrated in this white paper, TDD/FDD convergence networking has gained growing focus as a promising way to fully utilise limited radio resources for those operators who own both TDD and FDD spectrum. Clear and defined scenarios and solutions are available to meet requirements of TDD/FDD convergence networking. The end to end industry is also focussing growing attention on converged products and solutions.

Eighteen LTE networks are operated in both TDD and FDD modes, with about half operating in a converged configuration. These networks provide much information and significant experience to operators investigating TDD/FDD converged deployment and operation. It also demonstrates that the industry has laid a solid end-to-end foundation and provided choice for operators' varied convergence strategies.

Infrastructure vendors to continue to deliver and evolve converged products and features including common BBU, mobility management, load balancing/traffic management functionality and TDD/FDD carrier aggregation. The latter capabilities are delivering the layer management mechanisms required by operators to deliver a seamless TDD/FDD customer experience.

There is continued growth in the implementation of converged terminals supporting the widest range of both TDD and FDD bands. Some of the most recently released smartphones support as many as 20 LTE bands across TDD and FDD.

There have also been substantial developments in FDD-TDD Carrier Aggregation following the first lab demonstrations being conducted in early 2014. Optus Australia has commercially launched TDD/FDD carrier aggregation, and a number of operators plan to launch it within the next 3 to 6 months, taking advantage of the fact that the newest devices released in Q3 2015 support TDD/FDD carrier aggregation.

3GPP Releases 12 and 13 have a number of TDD-FDD carrier aggregation combinations being defined, however not all of the band combinations identified by GTI operator members are in the process of development, hence more work is required to get additional TDD-FDD carrier aggregation combinations submitted to 3GPP.

The GTI is closely monitoring the development of TDD/FDD convergence networking and is calling for active participation and contribution from industry to develop a mature converged TDD/FDD ecosystem.

7. References

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[2] Global Mobile Suppliers Association (GSA) *"Evolution to LTE"* report, 21 July 2015.

[3] 3GPP RP-142248, "Study on possible additional configuration for LTE TDD", CATT, CATR, NTT DOCOMO

[4] "Samsung Announces GALAXY S4 and GALAXY S4 mini With the world's first TDD-LTE and FDD-LTE Seamless Handover Technology" http://www.samsung.com/us/news/21447