MulteFire Release 1.0 Technical Paper

A New Way to Wireless

MulteFire™

Introduction:

MulteFire™ is a new innovative technology designed to create new wireless networks by operating LTE technology standalone in unlicensed or shared spectrum. The MulteFire Release 1.0 specification was completed in January 2017 by the MulteFire Alliance. The Alliance is an open, international organization dedicated to support the common interests of its members, developers and users in the application of LTE and next generation mobile cellular technology in configurations that use only unlicensed radio spectrum.

With MulteFire, private and public vertical venues, IoT (Internet of Things) verticals, businesses and property owners can create, install and operate their own private or neutral host MulteFire network in the same way that they do with Wi-Fi. MulteFire incorporates high quality LTE services and functionality supporting voice and data IP services locally, either independently as a private network and/or interworking with existing mobile networks to provide secure, seamless service as a neutral host.

Today, in-building neutral host wireless solutions are common in the context of Wi-Fi and distributed antenna system (DAS) deployments and are occasionally employed in macro-cell environments. However, the neutral host option – a common deployment serving subscribers from multiple operators – has rarely been adopted in the deployment of licensed band small cells. MulteFire has the potential to unlock the adoption of small cells and enable neutral host deployments on a much larger scale.

MulteFire creates new business opportunities that allow new market verticals to benefit from the LTE technology and ecosystem. These verticals include large enterprises, sports & entertainment, healthcare, identity management, public venues (malls, airports), hospitality, transportation applications, M2M, IoT, seaport management, gas detection, manufacturing, logistics, and the public sector (first responders, smart grids, military bases and barracks, universities, hospitals, education authorities). Each of these verticals can create customized applications and Quality of Experience (QoE) for its users.

MulteFire is suitable for any spectrum band that requires over-the-air contention for fair sharing, such as the global 5 GHz unlicensed spectrum band or shared spectrum in the upcoming 3.5 GHz CBRS (Citizens Broadband Radio Service) band in the U.S. MulteFire is tightly aligned with 3GPP standards and builds on elements of the 3GPP Release 13[1] and 3GPP 14[2] specifications for Licensed Assisted Access (LAA) and Enhanced Licensed Assisted Access (eLAA), augmenting standard LTE to operate in global unlicensed spectrum. Enhancements such as Listen-Before-Talk (LBT) have been designed to efficiently coexist with other spectrum users, such as Wi-Fi or LAA.

MulteFire enables the full range of LTE services including VoLTE (voice), high-speed mobile broadband (data), user mobility and IoT optimizations. It promises LTE-like performance with the simplicity of Wi-Fi-like deployments. As with mobile networks, MulteFire enables full mobility as a user walks around a building; the technology enables seamless handover between small cells as required. MulteFire will also interwork with external mobile networks to provide service continuity when users leave the area where MulteFire service is available.

MulteFire can operate anywhere, without additional regulatory approval, costly spectrum or specialist expertise. It uses many of the sophisticated features designed into LTE to deliver high performance, seamless mobility and resilience, even in highly congested environments. As with Wi-Fi, multiple MulteFire networks can co-exist, overlap or be friendly neighbors in the same physical space.

MulteFire unleashes enormous potential for the wide adoption of small cells, especially indoors. Additionally, it could form a useful multi-operator solution for building owners at lower cost than today's DAS by acting as a neutral host or single-operator enterprise solution.

The following are MulteFire's key performance advantages thanks to the use of LTE technology:

- End-to-end architecture from general design to support for various deployment modes
- Radio air interface, including frame structure and uplink transmission scheme leveraging eLAA robust anchor carrier design, LBT design, key procedures such as random access procedure, mobility, RRM (Radio Resource Management) measurement and paging
- Better radio coverage
    - Retains LTE's deep coverage characteristics in an unlicensed band
    - Targets control channels to operate at cell-edge SINR of -6 dB
    - Adds a 5-6 dB link budget advantage over carrier-grade Wi-Fi
- Enhanced capacity in denser deployments
    - Significant gains (~2X) over 802.11ac baseline
    - Leverages LTE link efficiency and MAC
- Seamless mobility
    - Brings carrier-grade LTE mobility to unlicensed and shared spectrum
    - Backward and forward handover supported (as Rel. 12)
    - Provides seamless and robust mobility between MulteFire nodes themselves for all use cases and when moving between MulteFire RAN and Macro Network depending on deployment model Network
    - Service continuity to Wide Area Networks (WAN) when moving to/from a neutral host deployment.
- Increased robustness
    - Forward handover enables recovery when radio link failures occur
    - Enhanced radio link failure triggers
    - Leverages LTE mature Self-Organizing Network (SON) techniques

This paper provides technical insights on MulteFire based on the specifications of the MulteFire 1.0 release. Sections 1-3 focus on the network architecture. More details on the radio air interface follow in Section 4. Section 5 presents representative performance evaluation results in different MulteFire deployment scenarios and Section 6 concludes the paper.

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1. Network Architecture for MulteFire

1. General Design Principles

MulteFire network architecture specifications are based on 3GPP Release 13 specifications and inherit valuable properties such as seamless mobility, security, interoperability, support for different Quality of Service (QoS) levels for different IP flows, and different service levels for different users. The design is targeted to minimize the differences between MulteFire and LTE. A MulteFire-based network can be implemented as a single node, or the different functional entities can be implemented as separate nodes. As the interfaces between the core network and radio access network are well specified, multi-vendor MulteFire deployments are also possible.

The MulteFire Release 1.0 specification also takes into account interworking with 3GPP networks. Interworking between 3GPP Public Land Mobile Networks (PLMNs) and a MulteFire Radio Access Network (RAN) does not require any MulteFire-specific features in the 3GPP PLMN. However, some enhanced features or improved performance can only be provided if the 3GPP PLMN supports some MulteFire-specific extensions.

The MulteFire architecture specifications enable access authentication with or without a SIM card to provide services for subscribers from different types of service providers, including traditional mobile network operators as well as non-traditional participating service providers. In order to enable different types of deployments, two reference architectures were developed for MulteFire: PLMN Access Mode and Neutral Host Network Access Mode.

With PLMN Access Mode (Figure 1), the MulteFire RAN is connected to the 3GPP MNO (mobile network operator) Core as an additional Radio Access Network for the PLMN. Mobility with IP address preservation is provided between MulteFire and 3GPP RAN. PLMN Access Mode enables MNOs to extend their network coverage (e.g., where licensed spectrum is not available) or allows MulteFire deployments in venues or other premises to provide mobile service for subscribers from one or more MNOs.

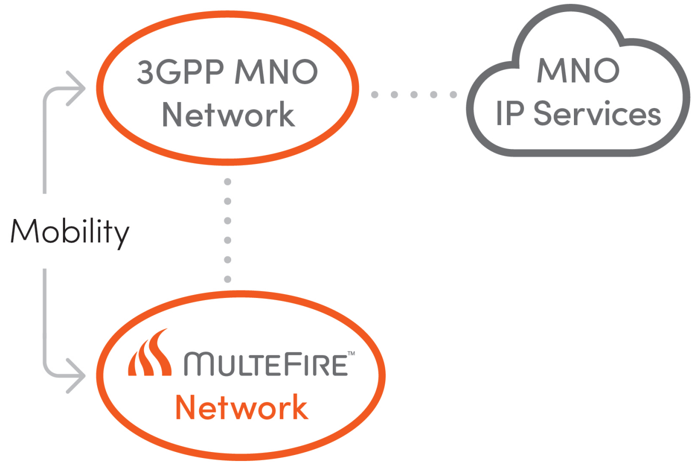


Figure 1. PLMN Access Mode

Neutral Host Network (NHN) Access Mode (Figure 2) is a self-contained network deployment that provides access to local IP networks or to the Internet.

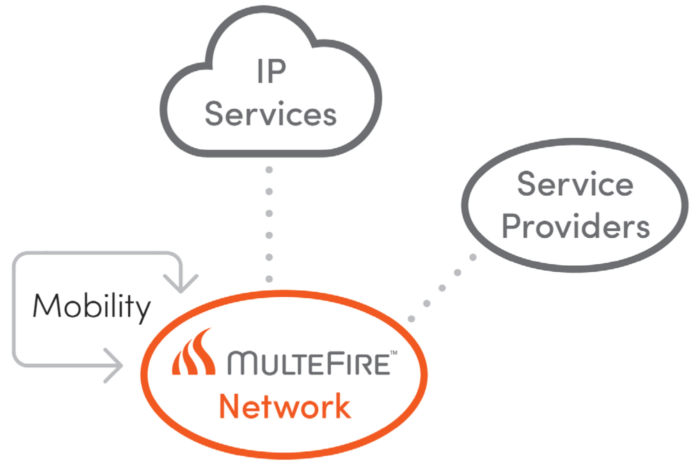


Figure 2. Neutral Host Network Access Mode

Mobility is supported between the MulteFire cells within one NHN. The NHN interacts with external participating service providers (PSPs) to enable services for their subscribers. PSPs provide subscription, billing and the associated Authentication, Authorization and Accounting (AAA) services. PSPs are logically separate from the operator of the NHN. In neutral host networks, an MNO is an example of a PSP.

NHNs can also be deployed as special purpose private networks in isolated environments (e.g., mines, cruise ships, private enterprise, restaurants, hotels), venues or public spaces providing service to subscribers of multiple service providers or enterprises.

The relationship between a MulteFire cell, PLMN and NHN is shown in Figure 3. A MulteFire cell may support PLMN Access Mode for one or more specific PLMNs and NHN Access Mode for a single NHN. When a MulteFire cell supports PLMN Access Mode for a PLMN, it broadcasts the corresponding PLMN ID.

More detail on both architectures is provided in Sections 2 and 3 of this paper.

Figure 3. Relation between MultFire Cell, PLMNs and NHN

2. PLMN Access Mode Architecture

2.1 Architecture Overview

In PLMN Access Mode, the MulteFire RAN is connected to a 3GPP Evolved Packed Core) in a similar manner as an evolved universal terrestrial radio access network (E-UTRAN a.k.a. LTE RAN) is connected to an EPC. Figure 4 presents the reference architecture model for MulteFire PLMN Access Mode. The MulteFire RAN is connected to a 3GPP EPC via S1 and provides functionality similar to E-UTRAN. The only new network element is the MulteFire access point (AP), which plays the role of the LTE eNB (eNodeB). From the EPC's point of view, the MulteFire AP is an eNB. The interfaces reuse existing 3GPP interfaces. There are no changes to S1-MME or S1-U.

The same procedures and identifiers are used in the MulteFire RAN as in E-UTRAN, and the same bearer and Quality of Service (QoS) models are applied. Intra-MulteFire RAN mobility and mobility from a MulteFire RAN to a 3GPP RAN within a PLMN – both in Radio Resource Control (RRC) connected mode and in idle mode – are supported. Mobility can also be supported from a 3GPP RAN to a MulteFire RAN. Network discovery and selection also follows the mechanisms defined in 3GPP.

The architecture supports both roaming and non-roaming scenarios. Multiple EPCs may be connected to a single MulteFire RAN (e.g., RAN sharing is supported). The MulteFire RAN shares the same RAT type as E-UTRAN. The MNO may differentiate a MulteFire RAN from E-UTRAN by allocating different Tracking Area Code (TAC)

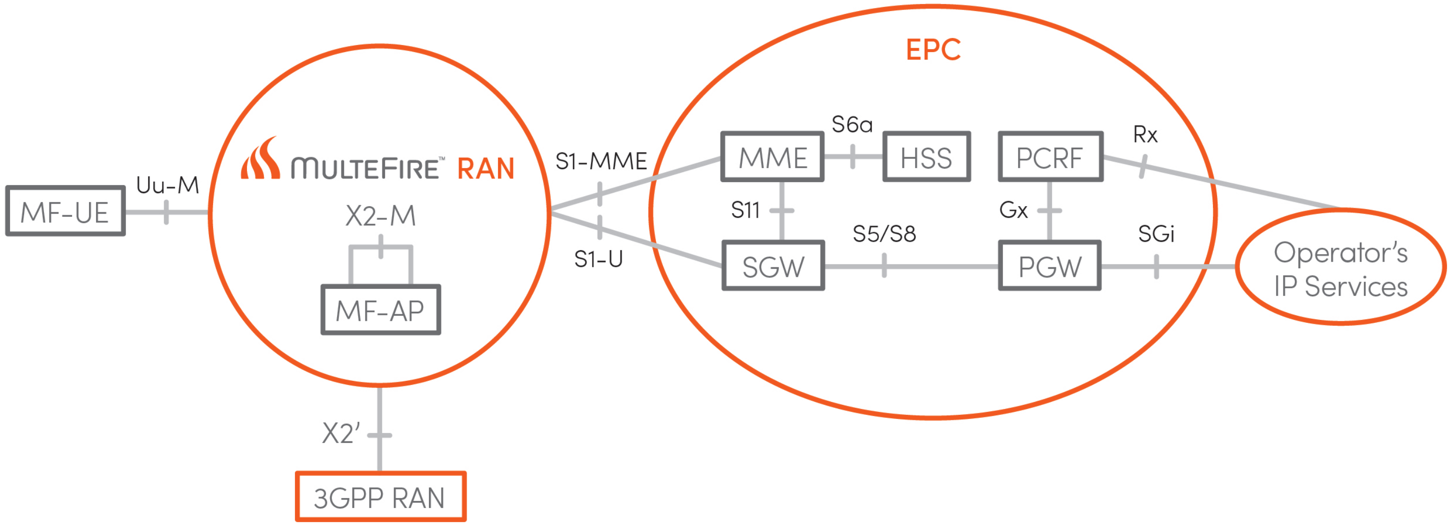


Figure 4. PLMN Access Mode Reference Architecture

values to the two RANs. The EPC can use the TAC value to derive if user equipment (UE) is camping on a MulteFire RAN or E-UTRAN (e.g., charging and policy and charging control (PCC) rules differentiation).

2.2 PLMN Access Mode Use Cases

2.2.1 MulteFire RAN Connected to an Existing Core Network

In this use case, MulteFire is used as an additional RAN to extend an MNO's network coverage (e.g., where licensed spectrum is not available) or/and add capacity leveraging existing core network assets. A MulteFire RAN can also be sold to enterprises to connect it to an existing core. RAN sharing can be used to enable the MulteFire RAN to provide mobile service to multiple MNO cores.

2.2.2 MulteFire-only Network

It is possible that an operator, without using any licensed band, deploys an EPC with a MulteFire RAN in PLMN Access Mode. In this scenario, the operator must have and must advertise its own PLMN ID and also perform USIM-based access authentication. Applications envisioned for this use case are special purpose networks (e.g., industrial, mining, off-shore) or MVNOs without licensed spectrum. In the latter case, the mobile virtual network operator (MVNO) may have roaming agreements with MNOs.

2.3 PLMN Access Mode Functions

There is no new functionality introduced into the EPC for PLMN Access Mode. Different TAC values can be used to differentiate MulteFire RANs from E-UTRAN (e.g., charging and PCC rules differentiation). If TAC differentiation is applied by the MNO, the Mobility Management Entity (MME), SGW and PGW must be configured to differentiate between TAC values used by the MulteFire RAN and those used by E-UTRAN.

3. NHN Access Mode Architecture

Architecture Overview

NHN Access Mode architecture is designed for easy deployment of self-contained MulteFire-based access networks at various locations by various entities. A key design principle is the separation between the access network functions and the service provider functions.

The access network part – NHN – provides UEs with connectivity to an external IP network, typically the Internet. The PSP provides subscription, billing and the associated AAA services. One NHN can serve UEs from multiple PSPs, and one PSP can make its services available via multiple NHNs.

NHN Access Mode Use Cases

3.1.1 Using NHN for Self-contained Wireless Access Service

NHN mode can be used to deploy a self-contained wireless access service which is separate from any mobile service or Wi-Fi service. This use case can also apply in self-contained, isolated deployments where a private service, using the NHN Access Mode architecture, is offered for a specific set of subscribers (e.g., in enterprises or in offshore drilling).

Typically, this use case involves an initial manual PSP selection by the device user, unless the device is pre-associated with a specific PSP. In a case where the UE is not preconfigured with appropriate subscription credentials, an online sign-up process may be used to establish the required wireless access service subscription and also to provision the UE with appropriate credentials for the service. After acquiring the wireless access service from the selected PSP, the UE may be configured to automatically reconnect to the wireless access service whenever the same PSP is available.

Depending on the UE capabilities, it may be possible to simultaneously maintain mobile service via a mobile network and wireless access service via an NHN.

3.1.2 Using NHN for Offloading Mobile Service

3.1.2.1 Offloading Mobile Access Service

In this use case, seen in Figure 5, the mobile operator-provided mobile access service is offloaded to an NHN reusing the mobile operator USIM and the mobile subscription already associated with the USIM. When the UE enters the coverage area of an NHN offering services for the mobile operator PSP, the UE may be configured to automatically connect to the NHN, perform a USIM-based NHN authentication towards the mobile operator AAA server, and upon successful authentication switch some of the data traffic to use the NHN provided IP interface. Similarly, when the UE exits the NHN coverage area, the data traffic can be switched back to use the IP interface provided by the mobile network.

To enable this use case, appropriate policy needs to be present in the UE to control the offloading of the mobile access service. The UE should also be capable of handling both a mobile network and an NHN radio connection either via separate radio hardware resources or by dynamically switching shared radio hardware resources between the two connections.

3.1.2.2 Offloading Mobile Voice Service

Independent of whether the UE has connected to an NHN for self-contained wireless access service or for offloaded mobile access service, the IP interface provided by the NHN can also be used to deliver mobile operator IP services, such as a mobile voice service (i.e., VoLTE). The mechanisms for offloading the mobile voice service to the NHN are similar to those used for Wi-Fi calling.

One option is to use the 3GPP untrusted non-3GPP interworking model. Upon gaining IP connectivity via an NHN, the UE may be configured to automatically use that IP connection for

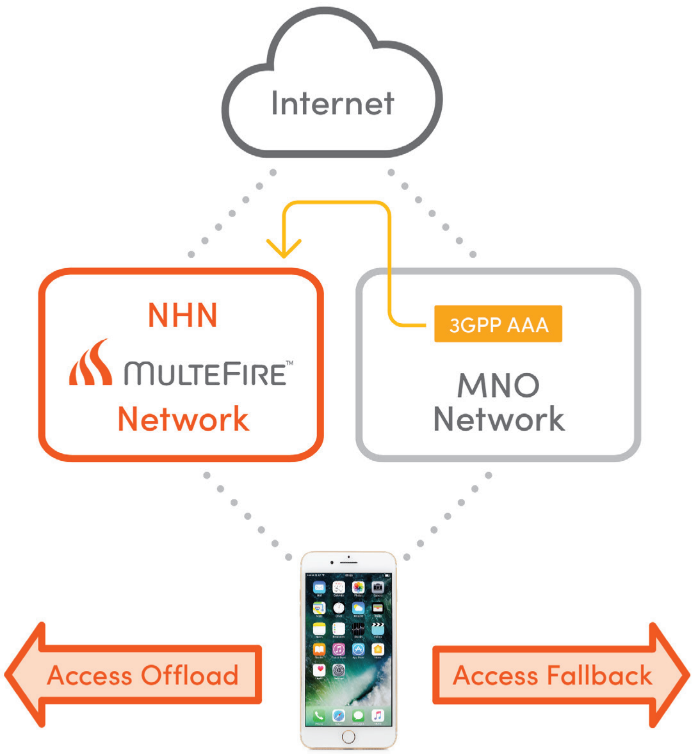


Figure 5. Offloading Mobile Access Service

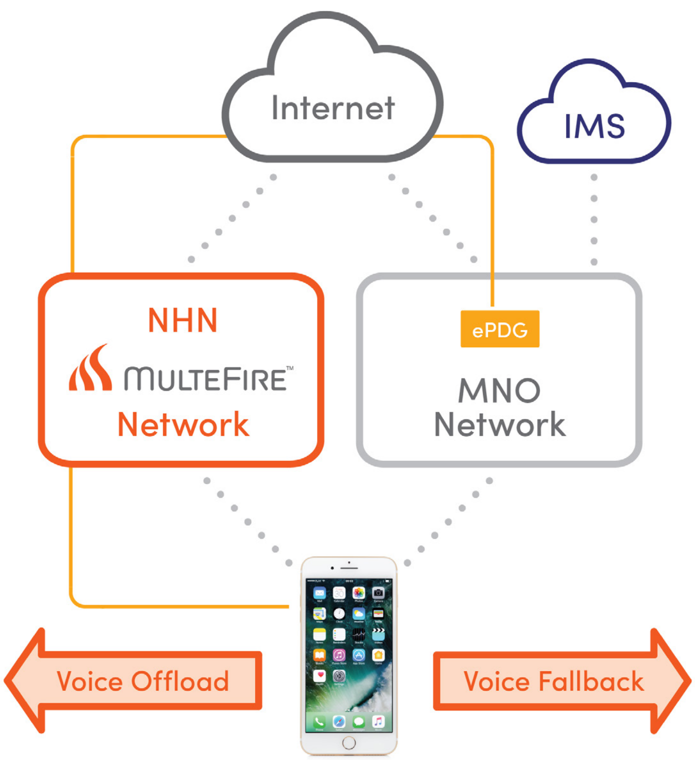


Figure 6. Offloading Mobile Voice Service untrusted non-3GPP

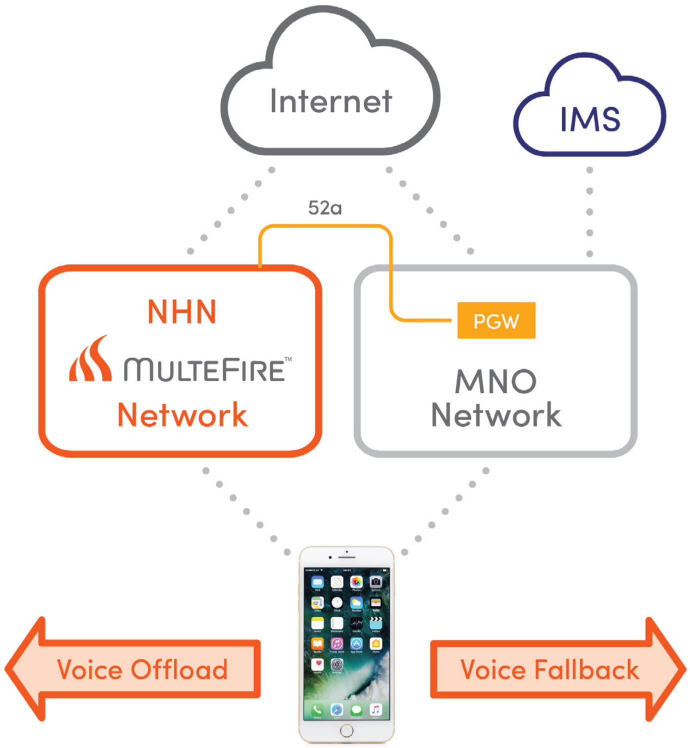


Figure 7. Offloading Mobile Voice Service trusted non-3GPP

reaching out to a mobile operator evolved Packet Data Gateway (ePDG), perform a USIM based authentication with the ePDG and establish an IP security (IPsec)-protected tunnel (a.k.a. SWu reference point) between the UE and the mobile operator ePDG. This secure over-the-top tunnel can then be used as an alternative delivery means for Mobile Operator IP services, such as VoLTE. Setting up and using this SWu tunnel is transparent to the NHN. Extensions to the SWu signaling will be specified to enable establishment of QoS bearers over the MulteFire air interface for the tunneled traffic.

The other option is to consider the NHN as a Trusted Non-3GPP Access Network. In this case the NHN is connected to the EPC (PDN GW) via the 3GPP defined S2a interface. In this way, the UE can access mobile operator IP services such as VoLTE.

To enable this use case, appropriate policy needs to be present in the UE to control the offloading of the mobile voice service.

Architecture Reference Model

Figure 8 represents the reference architecture for NHN Access Mode, e.g., for the use cases where a MulteFire cell is used for PSP services via an NHN.

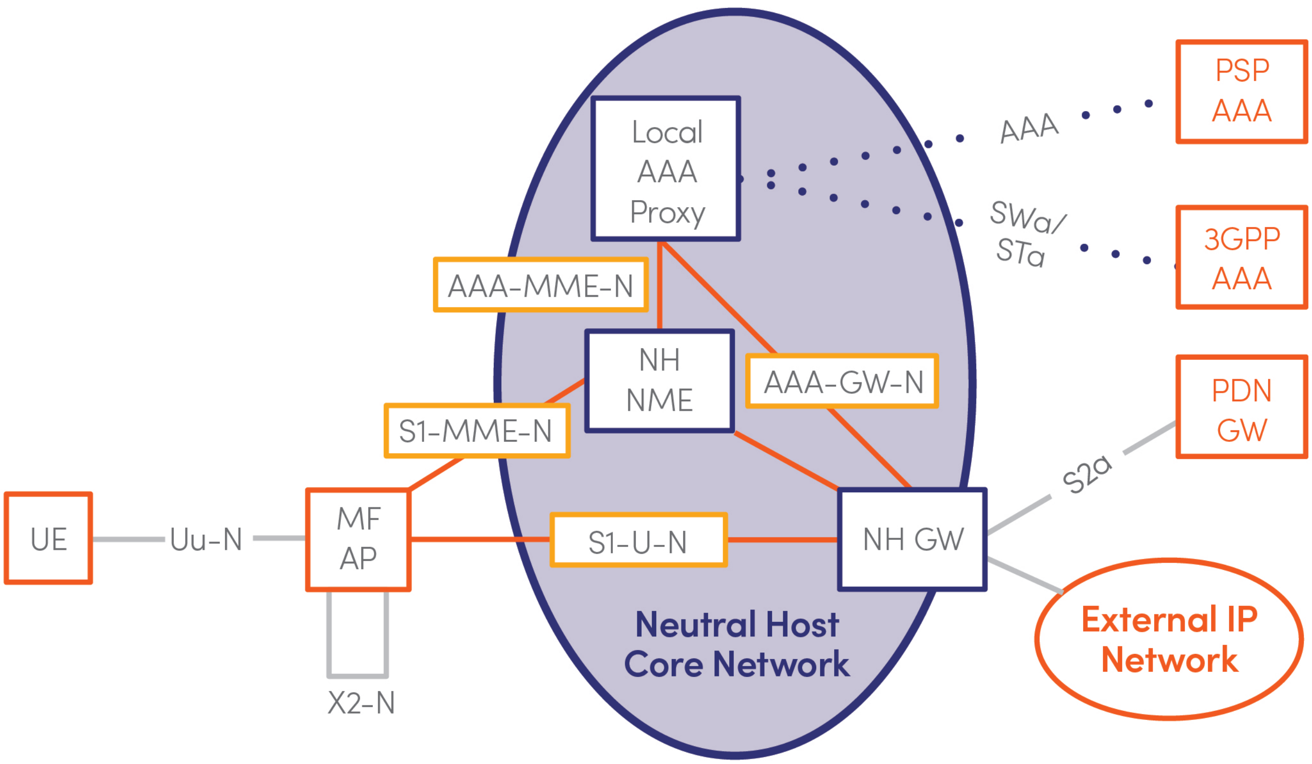


Figure 8. Architectural Reference Model for NHN Access Mode

The functions of the logical entities are as follows:

- MulteFire-AP provides similar functionality to a 3GPP eNB.
- NH-MME provides similar functionality for NHN as the MME provides for a 3GPP PLMN.
- NH-GW provides similar functionality for NHN as a combined SGW/PGW does for offloaded traffic. For EPC routed PDN connections, when S2a is used, the NH-GW functionality is similar to an SGW in interactions with the MulteFire-APs over the S1 interface, and is similar to the Trusted Wireless Access Gateway (TWAG) in interactions with the PLMN PDN-GWs over the S2a interface.
- Local AAA proxy within NHN provides a single point of contact for the external AAA servers.

The neutral host core network architecture has some simplifications compared with the 3GPP EPC architecture. Interfaces within the NHN core (e.g., between the NH-MME and NH-GW) and the related procedures (such as inter-NH-MME procedures) are not specified. The use of policy control is also left to implementation, as dynamic policy control is not included in the NHN Access Mode specifications. Internetworking between an NHN and 2G and 3G networks is also left out.

The key functional differences between NHN Access Mode and LTE/PLMN Access Mode are:

- Network selection – for both NHN and PSP – is defined as a new functionality, separate from PLMN selection
- AAA servers and procedures are used instead of a home subscriber server (HSS) and native LTE authentication
- International mobile subscriber identity (IMSI) is not utilized as UE identification at the non-access stratum (NAS) level
- Support for online signup e.g., the ability to access NHN without a subscription in order to sign up for one

All subscription related functionality, such as authentication, authorization and accounting, are decoupled from the NHN and performed by the PSPs. PSPs may be 3GPP PLMNs (e.g., mobile operators) using 3GPP specified AAA servers (3GPP AAA in Figure 8) and interacting with the NHN using the Non-3GPP access reference points (SWa or STa). PSPs may also be other entities using generic AAA servers (PSP AAA in Figure 8) which interact with the NHN using generic diameter/radius signaling (AAA in Figure 8).

NHN Access Mode Specific Functions

3.1.3 Network Selection

MulteFire cells supporting NHN Access Mode broadcast additional information that enable NHN Access Mode UEs to discover the Neutral Host Network Identity (NHN-ID) and the list of PSP-IDs. NHN-ID is the identifier of the NHN and all of the MulteFire cells of an NHN broadcast the same NHN-ID. The PSP-IDs identify the PSPs that provide services via the NHN. Neutral Host Networks do not have PLMN IDs.

A MulteFire UE autonomously scans applicable frequency bands for MulteFire cells and detects that a discovered MulteFire cell supports NHN Access Mode. Based on the broadcast information, the UE identifies the NHN (NHN-ID) and also discovers the list of available PSPs (PSP-IDs).

When a UE performs automatic network selection, it detects a match between the configured PSP-IDs and the available PSP-IDs and then selects a PSP to use for NHN Access Mode based on priorities in the configured PSP-IDs. After the PSP selection, the UE connects to an NHN serving the selected PSP.

NHN Access Mode also supports manual network selection, where the selection of the PSP and NHN is performed by the device user via the device UI.

3.1.4 Mobility

Mobility is supported between MulteFire cells belonging to the same NHN. The UE performs idle mode cell reselection between the MulteFire cells broadcasting the same NHN-ID. As in E-UTRAN, tracking areas may be defined within an NHN to control idle mode mobility. Active mode mobility among the cells of the NHN is also supported and performed in a manner similar to handovers in E-UTRAN. Mobility is not supported between cells of different NHNs.

3.1.5 Authentication and Other AAA Functions

NHNs rely on external AAA servers for

authentication, authorization and accounting functions. NHNs do not interact with an HSS.

The NHN architecture supports mutual authentication between the UE and the selected PSP. EAP (Extensible Authentication Protocol) is utilized as the authentication protocol. Both the USIM based authentication method (EAP-AKA') as well as non-USIM based authentication methods, e.g., extensible authentication protocol transport security layer (EAP-TLS) and extensible authentication protocol-tunneled transport security layer (EAP-TTLS), are supported. EAP is transported between the UE and the NH-MME using an extended NAS protocol. EAP signaling between the NHN and the external AAA server is transported using the AAA radius/diameter protocol or, in the case of a 3GPP AAA Server, using the SWa or STa reference point.

The EAP layer at the UE and NH-MME is responsible for negotiation of the EAP authentication method to be used. Successful EAP authentication between the UE and AAA server delivers a master session key (MSK) based on which regular LTE style security is established between the UE and NHN. LTE security establishment occurs at the NAS and AS layers in the same way as it is done for PLMN Access Mode. The protocol stack used for authentication is presented in Figure 9.

In NHN Access Mode, the UE handles each NHN-PSP pair separately. For each such pair a separate security context needs to be established. The UE may store security contexts for multiple NHN-PSP pairs and reuse a stored context when reconnecting to an NHN-PSP pair for which a valid security context is still available at the UE. Each NHN Access Mode security context is independent of any other NHN Access Mode security context. Also, the NHN Access Mode security contexts are independent of the PLMN Access Mode security context.

Authorization is done between the PSP and NHN using the AAA interface after successful authentication. The AAA interface between the NHN and PSP may also be used to exchange accounting information for the authorized sessions.

3.1.6 UE Identification

In NHN Access Mode, subscriber identification happens between the UE and PSP at the EAP layer. For this reason no permanent subscriber identity (e.g., IMSI) is used between the UE and NHN at the NAS layer. When an NHN Access Mode UE connects to a new NHN-PSP pair, it uses a common predefined value as the IMSI in its NAS-level Attach Request sent to the NHN. Use of this predefined IMSI value indicates to the network that the UE is attaching for NHN Access Mode. When a security context exists for an NHN-PSP pair, the temporary UE identifier GUTI (globally unique temporary identifier) is used to identify the UE in NAS signaling, similar to how it is done in PLMN Access Mode.

3.1.7 Online Sign Up (OSU)

Access to the NHN may be granted even when the UE does not have a valid subscription with a selected PSP. Subscription for NHN Access Mode can be offered to the MulteFire UE using the OSU system. In order to use OSU, the device needs to have a device certificate.

During this OSU process the UE is authenticated by the OSU provider using the device certificate and subsequently the UE gets connected to the

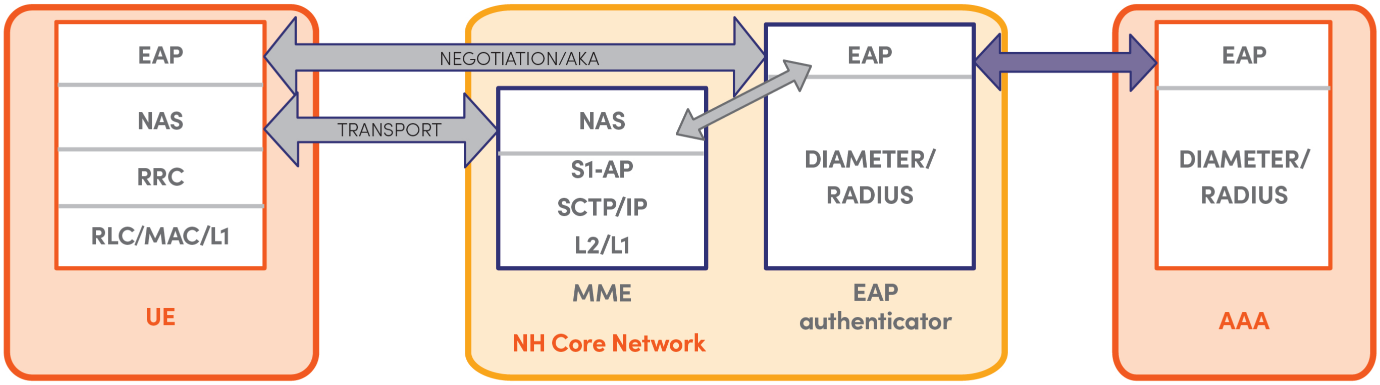


Figure 9. NHN access mode protocol stack for EAP authentication

secure OSU system. The secure connection is used to establish a subscription and to provision all required subscription credentials to the UE. Among those could be a subscription certificate, user ID and password combination, etc. Provisioned subscription credentials can subsequently be used to reconnect to the NHN for regular service.

4. Radio Air Interface

MulteFire builds on the key design features of 3GPP Release 13 LAA and Release 14 eLAA to allow for standalone operation. MulteFire's detailed features are provided in the following sections. Its main objective is to specify LTE enhancements for standalone operation in unlicensed spectrum under the design criteria of a single global solution framework, fair coexistence between Wi-Fi, MulteFire, and LAA, as well as fair coexistence between different MulteFire networks.

The main features that differentiate MulteFire from Release 14 eLAA design include discovery reference signal (DRS) design, support for initial access, control channel design, radio link monitoring (RLM), and mobility on unlicensed small cells to enable standalone operation without access to licensed carrier.

Comparison of MulteFire with LAA/eLAA, LTE-U, LWA

There are multiple LTE-based technologies with different characteristics that will share unlicensed spectrum with MulteFire: LAA/eLAA, LTE Unlicensed (LTE-U) and LTE-WLAN Aggregation (LWA). LAA/eLAA were developed during Rel-13/Rel-14 and are LTE-based unlicensed technologies anchored on licensed spectrum. LTE-U is based on the 3GPP Release 12 LTE technology to be used in unlicensed spectrum. LTE-U uses adaptive on/off duty cycle as a mechanism to share the medium with existing Wi-Fi networks and has an upgrade path to LAA/eLAA. Conversely, LWA was developed as part of Release 13and enables LTE and Wi-Fi link aggregation via dual connectivity. When compared with the current implementation of Wi-Fi deployments of 802.11n/ac, LTE-based unlicensed technologies provides a better user experience thanks to reliable connection management, thereby improving the overall efficiency and especially the quality of service for delay-sensitive applications.

Robust Anchor Carrier Design – Discovery Reference Signals (DRS)

In order to enable reliable synchronization and in turn provide a robust anchor carrier, MulteFire has introduced enhancements to DRS. The design provisions for increased reliability of acquisition for each instance of the DRS compared to LTE as well as reliable transmission of system information.
The components of the DRS are:

- Primary and secondary synchronization signals (PSS/SSS)
- MulteFire primary and secondary synchronization signals (MulteFire-PSS/MulteFire-SSS)
- Cell-specific reference signals (CRS)
- Configurable channel state information reference signals (CSI-RS),
- Master information broadcast (MIB-MulteFire) via the MulteFire PBCH (MulteFire-PBCH) channel
- MulteFire system information broadcast (SIB-MulteFire)
- Serving Cell DMTC: For coexistence with other nodes in the unlicensed band, all downlink transmissions, including the discovery reference signals, are subject to LBT or clear channel assessment (). Since DRS is crucial to synchronization, acquisition of system information and other key aspects of system operation, a transmission window known as the serving cell DRS measurement and timing configuration () window is defined to allow for increased probability of DRS transmission.
    - Serving cell DMTC is a periodic window within which UEs expect to receive DRS transmissions from its serving cell, as shown in Figure 11.
    - Similar to Rel-13 LAA, DRS transmissions within DMTC are subject to short duration of LBT of 25 usec compared to transmissions outside DMTC that are subject to an extended CCA operation.

Opportunistic DRS:

In addition to DMTC, opportunistic transmission of DRS outside the DMTC is only allowed on SF0 if the eNB successfully clears eCCA on those subframes.

- DMTC periodicity is 40, 80 or 160 ms and it may be configured up to 10 ms in length during which UEs expect to receive DRS transmissions.

MulteFire Synchronization Signals (MulteFire-PSS/MulteFire-SSS):

In the frame structure used by Rel-13 LAA, PSS is transmitted on the seventh OFDM symbol of a subframe and the SSS on the sixth OFDM symbol. In addition to the Rel-13 LAA synchronization signals – namely the primary and secondary synchronization signals – the MulteFire DRS includes:

- MulteFire primary synchronization signal (MulteFire-PSS) which is transmitted on the fourth OFDM symbol
- MulteFire secondary synchronization signal (MulteFire-SSS) which is transmitted on the third OFDM symbol

The MulteFire synchronization signals are transmitted on DRS SF within DMTC and also on SF0 outside DMTC. MulteFire synchronization signals help achieve the following objectives:

- Enable fast timing/frequency synchronization and cell search due to additional repetitions via MulteFire-PSS and MulteFire-SSS. Moreover, the MulteFire-PSS sequence provides additional processing gain and robustness to clock frequency offsets during initial acquisition.
- Greater robustness to bursty interference due to multiple synchronization sequences.
- Additionally, signature MulteFire-PSS/MulteFire-SSS sequence can potentially allow UE to distinguish MulteFire eNB from an LAA eNB.

Apart from initial acquisition, DRS is also used for neighbor cell searches as part of radio resource management (RRM) procedures for mobility purposes. MulteFire-PSS/MulteFire-SSS can also improve reliability of RRM measurements.

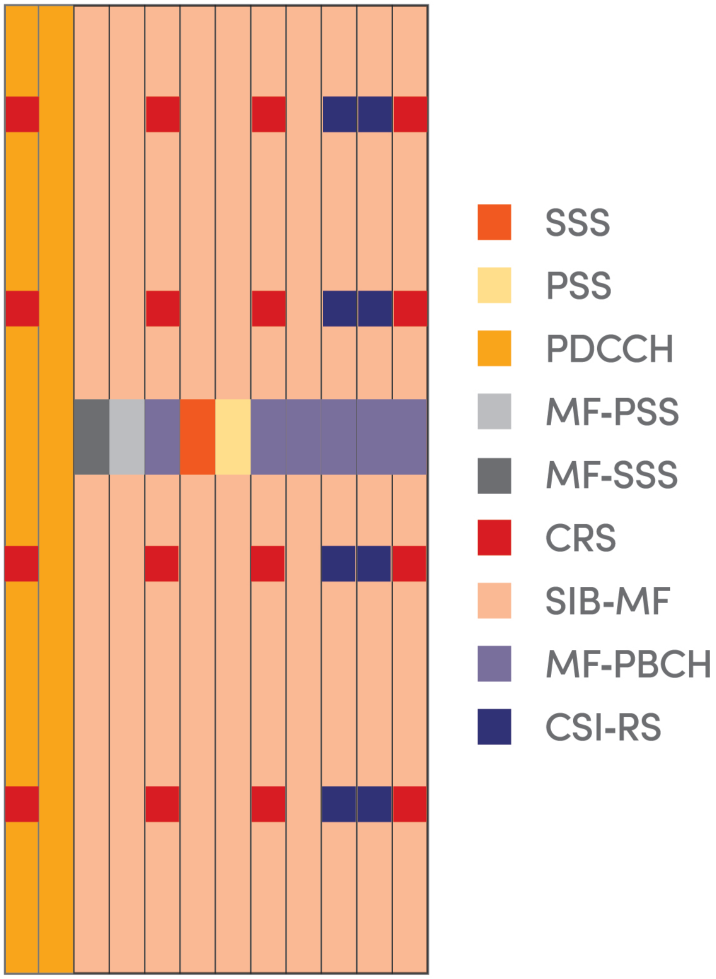


Figure 10. DRS Structure (12 symbol example)

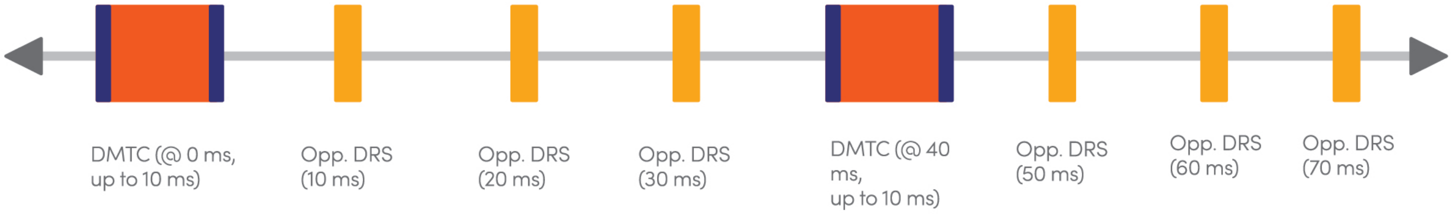


Figure 11. DMTC and Opportunistic Transmissions of DRS & SFN Indication via PBCH

MulteFire Physical Broadcast Channel (MulteFire-PBCH):

In LTE, the MIB is carried on the PBCH physical channel. In Rel-13 LAA, this information is transmitted over the primary licensed carrier. In MulteFire, the transmission of different instances of PBCH in the unlicensed band may not be guaranteed. Therefore, in order to improve the decoding reliability with a single instance of transmission, MulteFire enhanced PBCH (MulteFire-PBCH) is used to transmit the enhanced master information block (MIB-MulteFire).

- o Compared to Rel-8 PBCH, which uses four OFDM symbols, MulteFire-PBCH is transmitted on six OFDM symbols, namely, symbols 4, 7, 8, 9, 10 and 11.
- o DRS transmission within the serving cell DMTC does not necessarily occur on SF0 or SF5. To resolve subframe timing ambiguity during initial acquisition, three bits in the MIB-MulteFire are used to indicate the offset of the current DRS subframe within the DMTC, known as the subframe offset indicator.

- MulteFire System Information Block (SIB-MF): SIB-MF is used to convey system information to the UE and performs the function of Rel-13 SIB1 and SIB2 which is essential for accessing the cell. The SIB-MF is transmitted within the DMTC as part of DRS. In addition, the eNB may transmit SIB-MF on SF0 outside the DMTC opportunistically. SIB-MF is sent as a PDSCH transmission.

Channel Access Procedure

MulteFire follows the Listen-Before-Talk (LBT) principle for channel access procedure. LBT is a procedure whereby radio transmitters first sense the medium and transmit only if the medium is sensed to be idle.

The MulteFire LBT largely uses 3GPP LAA and eLAA LBT procedures as described in 3GPP 36.213[3] as baseline, thereby ensuring fair co-existence with Wi-Fi, LAA/eLAA, and other MulteFire networks. Additional rules are defined for aspects (e.g., UL control channels) that are not covered in LAA/eLAA and are essential for reliable standalone operation.

- Typically, DL and UL data channel transmissions follow Category 4 LBT with Energy Detection (ED) threshold as defined in LAA/eLAA. QoS support for different traffic classes is inherited from LAA/eLAA.
- Similar to LAA, DRS can be transmitted with 25 us single CCA as it is infrequent and critical for standalone operation.
- MulteFire also allows the UL transmission with no LBT within 16 μs after the preceding DL transmission according to the latest European Telecommunications Standards Institute (ETSI) BRAN harmonized standard[4].
- eNB can control and configure LBT type for UL control channels such as short PUCCH and RACH.

Channel Access Priority Class (p)	M_p	$CW_{min,p}$	$CW_{max,p}$	$T_{m\ cot,p}$	allowed CW_p sizes
1	2	3	7	2 ms	{3,7}
2	2	7	15	4 ms	{7,15}
3	3	15	1023	6 or 10 ms	{15,31,63,127, 255,511,1023}
4	7	15	1023	6 or 10 ms	{15,31,63,127, 255,511,1023}

Table 1: LAA UL Category 4 LBT Parameters

Frame Structure: Leveraging LAA with Additional Optimizations

4.1.1 Dynamic UL/DL Configuration

In order to adapt to traffic variations in the uplink (UL) and downlink (DL) dynamically, MulteFire adopts a very flexible frame structure without fixed assignment of DL or UL direction to any subframe a priori.

The eNB signals whether a subframe is DL or UL via the common physical downlink control channel (C-PDCCH). The C-PDCCH indicates the number of OFDM symbols present in a DL subframe. Additionally, the C-PDCCH may signal the presence of the following UL transmission burst within the eNB transmission opportunity at least two subframes before the start of the UL transmission burst. Such signaling enables the use of a short, 25 us LBT process by the UE for the scheduled UL subframes within the eNB acquired transmission opportunity.

MulteFire supports scheduling of UL transmissions within and outside of the eNB transmission opportunity. In addition, MulteFire also supports an enhanced UL scheduling mechanism with reduced UE processing time between the final UL grant and the start of the transmission from the UE, which in practice allows the eNB to shift between very high DL/UL and UL/DL ratios in a flexible manner. In particular, MulteFire can realize significantly higher UL/DL ratios compared to TD-LTE.

To provide periodic UL opportunities (for example for random access and scheduling request), periodic UL allocations are also supported. However, in principle such periodic UL allocations can be overridden by the eNB through DL transmissions as the UE typically has to perform LBT before UL transmissions, and will therefore sense the channel as not being available.

Uplink Transmission Scheme Leveraging eLAA

4.1.2 B-IFDMA Waveform for PUSCH, PUCCH, PRACH, SRS

MulteFire requires support of UL transmissions in unlicensed spectrum subject to LBT requirements. This also includes the specification of a new UL waveform to meet the ETSI regulatory requirements in the 5 GHz band. All this necessitated a partial redesign of the legacy LTE PUSCH for the transmission of UL data, the LTE PUCCH for the transmission of UL control information, the LTE physical random access channel (PRACH) for the transmission of random access preambles during initial connection and at handover, as well as the legacy LTE SRS design.

Block Interleaved FDMA (B-IFDMA) was chosen as the baseline uplink transmission scheme. This choice allows MulteFire to fulfill the ETSI regulatory requirements in the 5 GHz band and at the same time maximize the similarities with 3GPP LAA design. The B-IFDMA design applies to PUSCH, PUCCH, PRACH and SRS. With B-IFDMA, one carrier is divided into N interlaces (N = 10 for 20 MHz carrier, and N = 5 for 10 MHz carrier), each interlace consists of M equally spaced physical resource blocks (M = 10 for both 10 MHz and 20 MHz carrier). The MulteFire physical layer design supports carrier bandwidths of 10 and 20 MHz. Other carrier bandwidths are not supported in current specifications. Note that eLAA uplink also uses identical waveform for PUSCH transmission.

4.1.3 PUCCH/PRACH/SRS High Level Design

Short PUCCH:
A new PUCCH format is introduced called MulteFire short PUCCH (MulteFire-sPUCCH). The MulteFire-sPUCCH is transmitted during the last four symbols of a subframe where the preceding 10 symbols of the subframe are not used for uplink operation. In typical deployments the MulteFire-sPUCCH is transmitted in the ending partial DL subframe used to switch from DL to UL transmission. The benefits of MulteFire-sPUCCH are: 1) it provides an opportunity for the transmission of uplink control information in the beginning of a UL transmission burst so that the eNB will not need to create LBT gaps during the UL transmission burst for UEs that only need to transmit uplink control information and 2) the compact 4 symbol format can carry small control payloads (e.g., few bits of ACK/NACK) more efficiently compared to typical control channel lasting full subframe.

The subframe containing the MulteFire-sPUCCH is either configured to the UE by higher layers, or else it can be identified by the UE by monitoring the content of the C-PDCCH in the previous subframes indicating an ending partial DL subframe.

Extended PUCCH:
Due to its limited duration compared with LTE PUCCH, the MulteFire-sPUCCH format supports limited payload for the transmission of uplink control information. Therefore, the MulteFire-ePUCCH format has also been introduced.

MulteFire-ePUCCH is transmitted in an uplink subframe using the same subframe duration (e.g., 12 to 14 symbols) and interlace structure as the PUSCH. The eNB may schedule different UEs for MulteFire-ePUCCH and PUSCH transmissions in the same UL subframe. In this case, MulteFire-ePUCCH and PUSCH are transmitted on different interlaces by the corresponding UEs.

The UE transmits uplink control information on the assigned MulteFire-ePUCCH resources if the UE receives an indication from the eNB. Such indication to transmit on MulteFire-ePUCCH resources can be carried using a UL grant or the C-PDCCH. In the former case, MulteFire-ePUCCH resources are dynamically scheduled by the eNB. In the latter case, MulteFire-ePUCCH is transmitted on pre-configured resources. Uplink control information consists of HARQ-ACK, channel state information (CSI) and scheduling request (SR).

PRACH:
For small cell operation, the PRACH is transmitted using the same B-IFDMA waveform and duration as MulteFire-sPUCCH. Consequently, a PRACH preamble from one UE can be multiplexed with transmissions from other UEs that use one of the specified MulteFire-sPUCCH formats. The eNB may configure one or more interlaces within a UL subframe as PRACH resources.

SRS:
Two options exist for transmitting SRS. The eNB can trigger SRS transmission along with PUSCH transmission, in which case the last symbol of the corresponding UL subframe, (e.g., symbol 13) will carry the SRS. The triggering for aperiodic transmission of SRS along with PUSCH will occur via a UL grant or a DL grant. The eNB may also configure SRS transmission on the same physical resources as MulteFire-sPUCCH, in which case the SRS is transmitted in the last four symbols of a subframe and can be multiplexed with other UL transmissions using the MulteFire-sPUCCH format.

4.1.4 Uplink Scheduling and HARQ Operation

The UL scheduling framework in MulteFire retains the requirement of a minimum of four subframes between the transmission of a UL grant in the DL and the corresponding potential UL transmission. However, compared with TD-LTE, MulteFire introduces a more flexible timing relationship between the UL grant and the UL transmission through indicating an additional scheduling offset/delay to the UE. It also opens the possibility to schedule a UL transmission spanning multiple UL subframes by using a single UL grant through multi-subframe scheduling. A two-step scheduling approach is introduced where the UE is first provided with an initial UL grant, and then the eNB uses C-PDCCH signaling to trigger the UL transmission. This enhanced UL scheduling flexibility practically allows the realization of a very adaptable UL/DL configuration which is necessary when operating in unlicensed spectrum subject to LBT.

For DL HARQ operation, the same minimum requirements apply as in LTE. This means that upon reception of the DL assignment on PDCCH/EPDCCH and the associated PDSCH in a given subframe 'n', the UE shall have the associated HARQ-ACK feedback ready for transmission in subframe 'n+4'. However, differently from LTE, the timing for transmission of HARQ-ACK feedback is not deterministic due to the flexible MulteFire frame structure. The UE transmits pending HARQ-ACK information at the earliest possible uplink transmission opportunity (following the 'n+4' constraint) where resources for the transmission of uplink control information are available. The uplink transmission opportunity is defined according to the availability of either MulteFire-sPUCCH, MulteFire-ePUCCH or PUSCH resources for the UE.

Since there is no deterministic timing relationship between a DL transmission and the time when the corresponding HARQ-ACK information is transmitted, the HARQ-ACK feedback of all HARQ processes is transmitted in a bitmap using an implicit association between the index in the bitmap and the HARQ process ID.

In MulteFire there is no support for non-adaptive HARQ operation in the UL. UL transmissions only support HARQ operating in an asynchronous manner. Any uplink transmission – new transmission or retransmission – is scheduled through a UL grant via PDCCH/EPDCCH.

Key Procedures

Differently from LAA, and due to the standalone deployment requirement in unlicensed spectrum, MulteFire needs to support key procedures such as random access, mobility, and paging. However, because of the different nature of transmission on unlicensed spectrum which is subject to the LBT requirements, some modifications to the legacy LTE procedures are needed.

4.1.5 Random Access Procedure

The random access procedure in MulteFire is based on the four-step random access procedure specified for LTE. During the random access procedure in MulteFire, the UE and the eNB shall perform the channel access procedures for accessing the channel on which the messages for each step are transmitted. In order to cope with the restriction imposed by the LBT requirements, the UE does not increase the preamble counter when LBT in UL fails. Also, the maximum configurable length for the random access response is increased in order to allow for delays in the eNB response due to LBT in DL.

4.1.6 Mobility and RRM Measurement

Both intra-MulteFire mobility and mobility between LTE and MulteFire – the latter only when operating in PLMN Access Mode – are supported.

Mobility management follows the same principles of LTE, including support for synchronized, loosely synchronized and non-synchronized networks. Similar to LTE Rel-13 LAA, RRM measurements are based on DRS transmissions from neighbor cells, which the UE performs according to the DMTC provided by the network. However, MulteFire introduces a few modifications to the DMTC and measurement gap framework specified for LAA, mainly to cope with potentially non-synchronized neighbor cells for which the serving cell may not necessarily know their DRS transmission timing.

4.1.7 Paging

In MulteFire, the basic LTE paging procedure is reused, though enhanced, by extending the paging occasion to a paging occasion window, to provide the eNB with increased flexibility in the scheduling of paging messages if the channel is not accessible because of LBT failure.

5. Performance Evaluation

Performance with Spectrum Sharing

5.1.1 Evaluation Methodology

The methodology used for evaluating the system level performance of MulteFire closely follows the methodology used in the LAA evaluation undertaken in 3GPP [TR 36889][5]. The objective has been threefold: First, to evaluate the performance of the underlying MAC and PHY features of MulteFire at the system level and to compare it with equivalent Wi-Fi deployments; second, to evaluate coexistence, e.g., performance of a network in an unlicensed channel where nodes of both types, Wi-Fi STAs and APs and MulteFire eNBs and UEs coexist and undergo the LBT mechanism for accessing the medium; third, use the evaluations to identify design enhancements for MulteFire for further performance enhancement. For the remainder of this section, we use 'small cells' to describe APs/MulteFire eNBs and UEs to describe STAs and MulteFire UEs.

The general methodology assumes existence of two operators (OP1 and OP2) deploying small cells in a 20 MHz unlicensed channel in overlapping areas of coverage that serve UEs whose operator choice is predetermined. The two scenarios evaluated are Outdoor Cluster scenario (Figure 12) and Indoor Hotspot scenario (Figure 13).
In the Outdoor Cluster scenario, see Figure 12, 21 clusters of eight small cells, with four small cells per operator are dropped in a seven-cell hexagonal layout, with wrap around mechanism for removing edge effects.

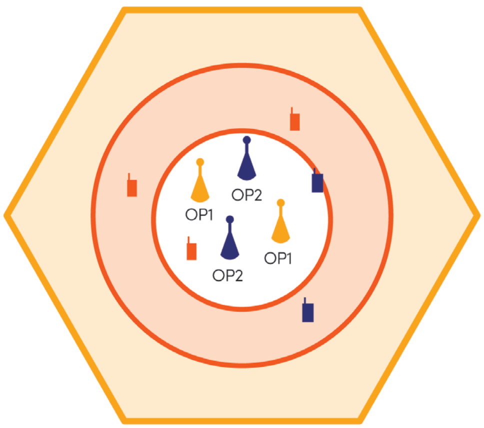


Figure 12. A Cluster of Outdoor Small Cells in a Hexagonal Macrocell Area. Four out of Eight Small Cells Depicted.

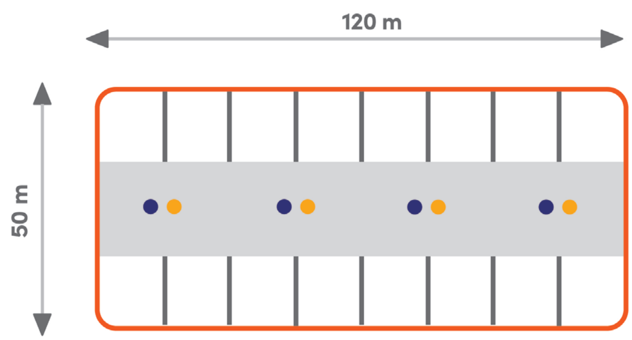


Figure 13. A Building of Indoor Hotspot Model. The Blue and Yellow Dots Represent Small Cells Belonging to Operator 1 and 2 [TR36899]

Each cluster has 10 active outdoor UEs per operator dropped. The detailed assumptions on node locations, antenna patterns, transmit power and pathloss models follow the assumptions of the outdoor scenario in [TR36889] and are captured in Table 2. Similarly, for the Indoor HotSpot scenario, four small cells per operator are systematically placed in a building (hotspot) depicted in Figure 15 and 16 active UEs per operator are dropped indoors. The assumptions follow [TR36889] and are captured in Table 2. For all UEs, it is assumed that the strongest cell for the corresponding operator is selected as the serving cell.

The traffic model used for evaluation is the FTP type 3 model [TR36889], where UEs are downloading and uploading files of fixed size. The files arrive for downloading (DL traffic at the eNBs) and uploading (UL traffic at the UEs) independently following a Poisson process. The time taken for a file to be delivered is noted and used to calculate the user perceived throughput (UPT), equivalently called burst rate. The average UPT is recorded for every UE.

Table 2. Main Assumptions for Performance Evaluation

Category	Model	Description
Deployment	System bandwidth	20 MHz
	Carrier frequency	5 GHz
Indoor Layout	Layout and Pathloss Model: Indoor	Follows 3GPP TR36.889, Table A.1.1
	UEs	20 indoor users per operator, per building
Outdoor Layout	Layout and Pathloss Model: Outdoor	Follows 3GPP TR36.889, Table A.1.2
	UEs	20 Outdoor users per operator, per cluster
Traffic Model	FTP Model 3 (non-adaptive Poisson arrivals), with file size 4 Mb 80:20 DL:UL traffic ratio	
	Inter-arrival rate	Varies
Wi-Fi	Technology	802.11ac
	Wi-Fi TXOP	4 ms
	LBT	CAT4 eCCA: 9 us slots, exponential backoff counter {0,CW} where CW{15,31,63}
	Energy Detection Threshold	-72 dBm
MulteFire	MulteFire MAC	
	MulteFire TXOP	8 ms
	Energy Detection Threshold	-72 dBm
LBT	eNB: CAT4 eCCA: 9 us slots, exponential backoff counter {0,CW} where CW{15,31,63} UE: 25 us one shot CCA	

Three different deployment scenarios are evaluated:

1. "W+W": Both OP1 and OP2 deploy Wi-Fi nodes
2. "W+M": Op1 deploys Wi-Fi, OP2 deploys MulteFire
3. "M+M": Both OP1 and OP2 deploy MulteFire nodes.

The system level performance is evaluated in terms of the gain in UPT for different deployment scenarios considering the 'W+W' scenario as the baseline. The gain in median and tail (bottom 10 percent) is reported for varying traffic offered load.

Results are presented in the form of gain in average DL/UL user perceived throughput (e.g., burst rate) for each scenario relative to the baseline 'W+W', e.g., two Wi-Fi operators, scenario.

Spectrum Sharing with Wi-Fi: Co-existence and Performance

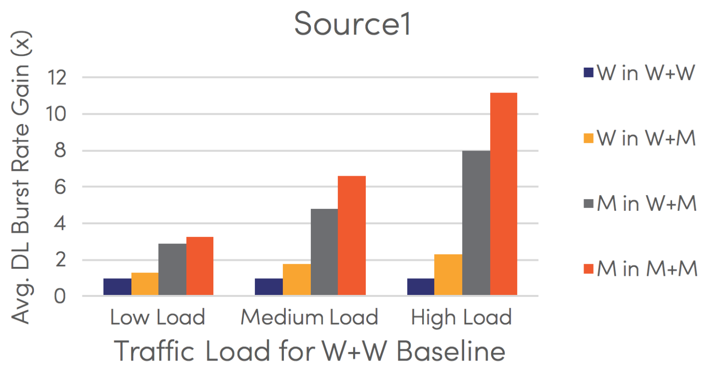
Outdoor Deployment

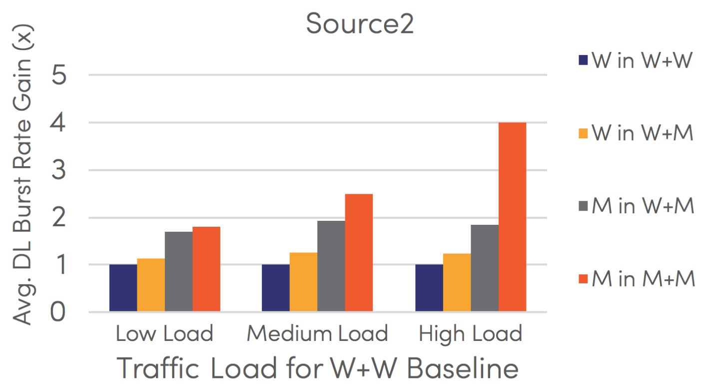
The DL and UL performance for different outdoor deployment scenarios and for different offered traffic loads is provided in Figure 16 and 17, respectively. Traffic loads are broadly characterized as low, medium and high corresponding to average buffer occupancy (DL+UL) of <15%, 15-50% and greater than 50%, respectively, for the baseline W+W scenario. Results from three different source companies are provided. While the general simulation assumptions are similar for all sources, as listed in Table 2, the performance can be different due to differences in additional aspects like rate control, Wi-Fi and MulteFire link modeling, etc particularly Wi-Fi performance. Note that sources 1 and 3 results do not model RTS/CTS for Wi-Fi, while source 2 results include RTS/CTS for Wi-Fi modeling.

1.) For each user, the rate for each file delivery is computed and the average value across all files delivered is termed as UPT. Average or tail (10%) UPT across users is used for computing the performance gain relative to the baseline Wi-Fi+Wi-Fi scenario.

Comparing MulteFire and Wi-Fi operator performance in the 'W+M' scenario relative to the 'W+W' scenario, the following key observations can be made:

- MulteFire provides gain of 1.5-4x in DL and 1-1.7x on UL over Wi-Fi in baseline 'W+W', with gain being higher at higher traffic load.
  - MulteFire gain can be attributed to better link efficiency achieved due to better link curves (e.g., owing to channel estimation, HARQ) and rate adaptation.
  - Gains are generally higher at higher loads, suggesting MulteFire can handle higher loads better. As load increases, Wi-Fi baseline performance reduces due to more contention in the medium. MulteFire provides better link and less contention with scheduled access and therefore performs better.
- Regarding co-existence, comparing the Wi-Fi performance in 'W+M' vs. 'W+W', replacing a Wi-Fi operator with a MulteFire operator improves the Wi-Fi operator performance. Gains range from 1.5-4x in DL and 1.1-1.8x in UL and are higher at higher loads in some cases.
  - MulteFire LBT design, which is largely inherited from 3GPP LAA/eLAA LBT design, ensures good co-existence with Wi-Fi.
  - In addition, by introducing MulteFire with better link efficiency, the overall interference in the network is reduced, which benefits Wi-Fi. In this sense, MulteFire's link efficiency has a compounding effect. For example, the MulteFire operator not only delivers its packets faster, but in addition it reduces interference thereby resulting in higher data rates for other nodes.
- Comparing MulteFire performance vs. Wi-Fi performance in the 'W+M' scenario:
  - In DL, MulteFire provides 1.5-2x gain even over the improved Wi-Fi operator performance.
  - In UL, although MulteFire performs significantly better than Wi-Fi in the 'W+W' scenario, MulteFire performance is comparable to Wi-Fi in the 'W+M' scenario. In some cases, the MulteFire gain is lower than the Wi-Fi gain, primarily due to Wi-Fi with contention based access getting higher share of medium compared to MulteFire with scheduled access. With scheduled access, for UL transmissions both eNB and UE have to contend and win the medium in MulteFire. For Wi-Fi, only the UE needs to contend for the medium and therefore MulteFire UL can be starved in some scenarios. MulteFire UL performance can be improved by enabling 'autonomous UL' operation (e.g., similar to Wi-Fi, MulteFire UEs can contend and transmit on winning the medium). Autonomous UL is targeted for MulteFire 1.1 specification to further enhance MulteFire performance.





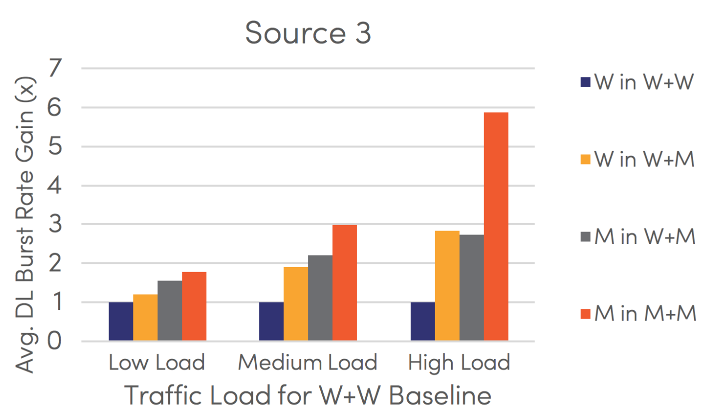
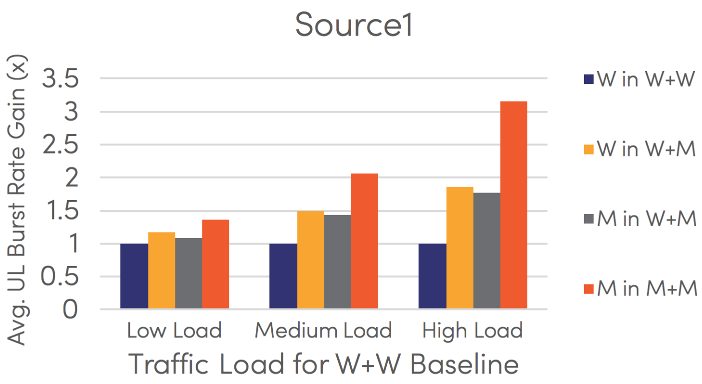
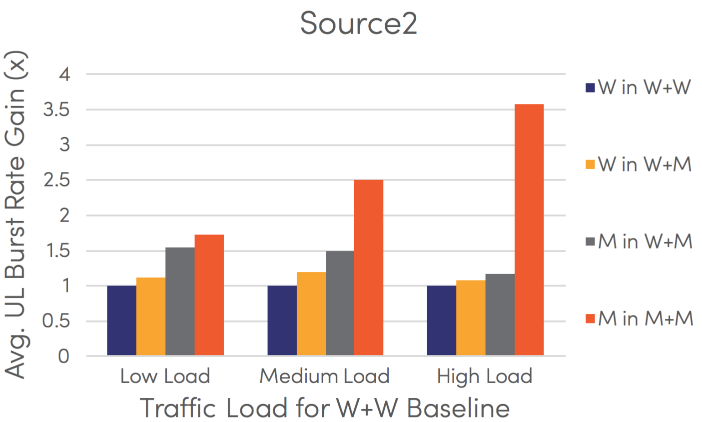


Figure 14. (Top) Source1, (Middle) Source2, (Bottom) Source3: DL Avg. Burst Rate Gain for Different Outdoor Deployment Scenarios. Gain is relative to 2-operator Wi-Fi baseline deployment (i.e., UPT in scenario(x) / UPT in W+W scenario). Different traffic loads are characterized based on DL+UL buffer occupancy (BO) for the baseline W+W scenario, Low load: BO < 15%, Medium load: 15<BO<50%, High load: BO > 50%.





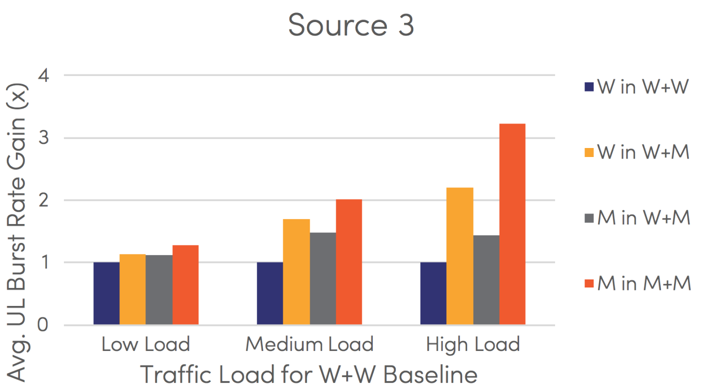


Figure 15. (Top) Source1, (Middle) Source2, (Bottom) Source3: UL Avg. Burst Rate Gain for Different Outdoor Deployment Scenarios. Gain is relative to 2-operator Wi-Fi baseline deployment (i.e., UPT in scenario(x) / UPT in W+W scenario). Different traffic loads are characterized based on DL+UL buffer occupancy (BO) for baseline W+W scenario, Low load: BO < 15%, Medium load: 15<BO<50%, High load: BO > 50%.

Indoor Deployment

The DL and UL performance for different indoor deployment scenarios and for different offered traffic loads is provided in Figure 18 and 19, respectively.

Similar to the outdoor scenario, MulteFire co-exists with Wi-Fi and even enables higher data rates for Wi-Fi due to MulteFire's better link efficiency. Compared to Wi-Fi in the 'W+W' baseline scenario, MulteFire provides gains of 1.5-4x in DL and 1-1.5x on UL.

In contrast to the outdoor scenario, MulteFire UL starvation is more prominent in the indoor scenario as evidenced by no or low gain of MulteFire over Wi-Fi in the 'W+M' scenario. In the indoor scenario, several eNBs/UEs are within ED range of each other and therefore medium contention by Wi-Fi UEs can more prominently reduce medium access for MulteFire UL transmissions compared to the outdoor scenario. MulteFire UL performance can be improved by enabling autonomous UL transmission, a design enhancement targeted for the next MulteFire specification. It is also worth noting that UL performance can be improved by trading off DL performance. For example, source 1 results show significant MulteFire gain in DL, both over Wi-Fi in 'W+W' and Wi-Fi in 'W+M' scenario, while no gain is shown for MulteFire over Wi-Fi in the 'W+M' scenario. The DL gains can potentially be traded off of for better UL performance by adapting the TDD configuration within Tx bursts more appropriately, (e.g., making it more UL heavy).

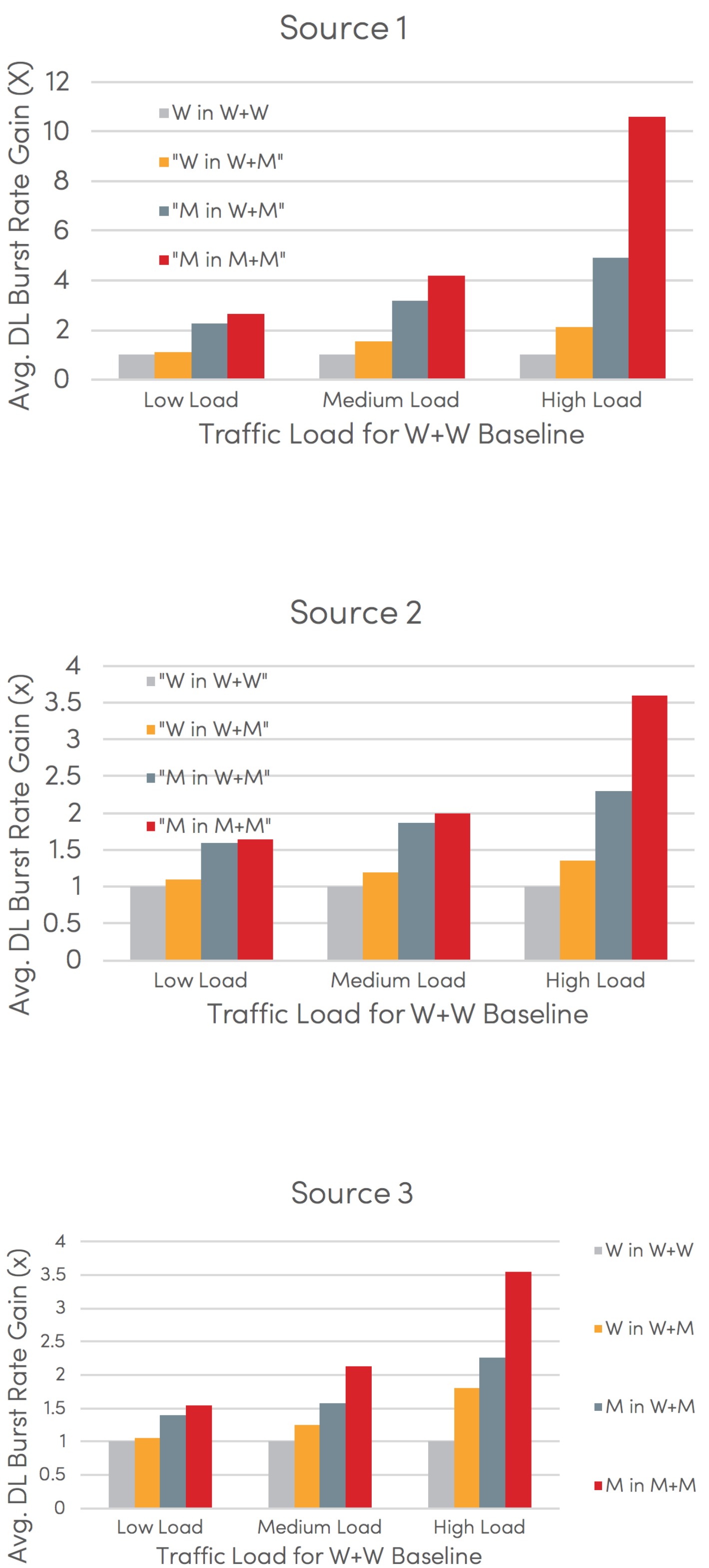


Figure 16. (Top) Source1, (Middle) Source2, (Bottom) Source3: DL Avg. Burst Rate Gain for Different Indoor Deployment Scenarios. Gain is relative to 2-operator Wi-Fi ('W+W') baseline deployment (i.e., UPT in scenario(x) / UPT in W+W scenario). Different traffic loads are characterized based on DL+UL buffer occupancy (BO) for the baseline W+W scenario, Low load: BO < 15%, Medium load: 15<BO<50%, High load: BO > 50%.

Figure 17. (Top) Source1, (Middle) Source2, (Bottom) Source3: UL Avg. Burst Rate Gain for Different Indoor Deployment Scenarios. Gain is relative to 2-operator Wi-Fi baseline deployment (i.e., UPT in scenario(x) / UPT in W+W scenario). Different traffic loads are characterized based on DL+UL buffer occupancy for baseline W+W scenario, Low load: BO < 15%, Medium load: 15<BO<50%, High load: BO > 50%.

Performance in Shared vs. Separate Deployments

In the previous section, we compared MulteFire and Wi-Fi performance in mixed MulteFire + Wi-Fi deployment scenarios. Figures 14, 15, 16 and 17 also provide DL & UL performance for the two operator MulteFire-only deployment scenario. As shown, MulteFire + MulteFire deployments significantly outperform Wi-Fi + Wi-Fi deployments in both DL and UL for indoor as well as outdoor environments. Compared to 'W+W', in 'M+M' both MulteFire operators have high link efficiency and lower contention due to scheduled access for both operators. This results in significantly improved interference and higher spectrum efficiency resulting in high gains in user experience. It is worth noting that the 'M+M' scenario DL & UL gains are highest at high offered traffic load relative to the 'W+W' baseline. This suggest that MulteFire can handle high data demand, making it ideal choice for dense venues and public hotspot type of deployments.

6. Conclusion

Owning and operating a MulteFire network that uses unlicensed spectrum has many benefits, whether it is deployed as a standalone network or interworks with existing mobile networks. MulteFire provides secure, seamless service and can act as a neutral host offering VoLTE, high speed mobile broadband, and LBT, all with LTE-like performance. Additionally, its Wi-Fi-like simplicity makes it a powerful tool for any organization that does not require hiring expert implementers.

MulteFire can operate anywhere, even in congested Wi-Fi and LTE environments where it can co-exist and overlap. It seamlessly hands over between small cells as necessary to provide users with better mobility and to ensure that they stay connected to their information. When a user leaves the MulteFire network area, MulteFire interworks with external mobile networks to provide service continuity.

Moreover, there are a number of verticals that require high reliability, safety and mass connections with ubiquitous coverage. MulteFire will build a solid foundation for future smart connection in vertical scenarios including broadband and IoT. The first specification release, Release 1.0, is a testiment to the merits of deploying cellular technologies in unlicensed and shared spectrum. MulteFire Release 1.1 is expected to be released in late 2017 with new features for optimized IoT and further enhancements for coverage, spectrum efficiency, mobility and shared spectrum. Looking ahead, MulteFire will continue to be enhanced with new features introduced in a phased approach, targeting enriched scenarios, services and additional spectrums.

MulteFire truly is a new way to wireless.

7. References

[1] 3GPP Release 13
[2] 3GPP Release 14
[3] 3GPP 36.213: Terrestrial Radio Access (E-UTRA); Physical Layer Procedures
[4] European Telecommunications Standards Institute (ETSI) BRAN harmonized standard
[5] 3GPP 36.889: Feasibility Study on Licensed Assisted Access to Unlicensed Spectrum

Glossary of Terms

3GPP – Third Generation Partnership Project
AAA – Authentication, Authorization and Accounting
B-IFDMA – Block Interleaved FDMA
BO – Buffer Occupancy
CAT4 – Category 4
CBRS – Citizens Broadband Radio Service
CCA – Clear Channel Assessment
C-PDCCH – Common Physical Downlink Control Channel
CSI – Channel State Information
CWS – Contention Window Size
DAS – Distributed Antenna System
DL – Downlink
DMTC – DRS Measurement Timing Configuration
DRS – Discovery Reference Signal
DTxW – Discontinuous Transmission
EAP – Extensible Authentication Protocol
EAP-TLS – Extensible Authentication Protocol-Transport Layer Security
EAP-TTLS – Extensible Authentication Protocol-Tunneled Transport Layer Security
ECP – eNB Channel Processor
ED – Energy Detection
eDRS – Enhanced Discovery Reference Signal
eLAA – Enhanced Licensed Assisted Access
eNB – eNodeB
EPC – Evolved Packet Core
ePDG – Evolved Packet Data Gateway
ePUCCH – Extended PUCCH
ETSI – European Telecommunications Standards Institute
E-UTRAN – Evolved UTRAN
GUTI – Globally Unique Temporary Identifier
HARQ – Hybrid Automatic Repeat Request
HSS – Home Subscriber Server
IMSI – International Mobile Subscriber Identity
IoT – Internet of Things
IPSec – IP Security
LAA – Licensed Assisted Access
LBT – Listen-Before-Talk
MCOT – Maximum Channel Occupancy Time
MIB – Master Information Block
MME – Mobility Management Entity
MNO – Mobile Network Operator
MSK – Master Session Key
MVNO – Mobile Virtual Network Operator
NAS – Non-Access Stratum
NHN – Neutral Host Network
NHN-ID – Neutral Host Network Identity
OFDM – Orthogonal Frequency Division Multiplexing
OSU – Online Sign Up
PCC – Policy and Charging Control
PGW – Packet Data Gateway
PLMN – Public Land Mobile Network
PRACH – Physical Random Access Channel
PSP – Participating Service Providers
PSS/SSS – Primary and Secondary Synchronization Signals
PUCCH – Physical Uplink Control Channel
PUSCH – Physical Uplink Shared Channel
QCI – QoS Class Identifier
QoE – Quality of Experience
QoS – Quality of Service
RAN – Radio Access Network
RAT – Radio Access Technology
RLM – Radio Link Monitoring
RRC – Radio Resource Control
RRM – Radio Resource Management
S1 – Interface between an eNodeB and the Core Network (CN)
S1-MME – Reference point for the control plane protocol between E-UTRAN and MME
S1-U – Reference point between E-UTRA N and Serving GW for the per bearer user plane tunnelling and inter eNodeB path switching during handover.
S2a – Reference point providing the user plane with related control and mobility support between trusted non 3GPP IP access and the Gateway
SF0 – Subframe 0
SGW – Serving Gateway
SIB1 – System Information Block 1
SIB2 – System Information Block 2
sPUCCH – Short Physical Uplink Control Channel
SR – Scheduling Request
SRS – Sounding Reference Signal
STa – Reference point connecting the Untrusted non-3GPP IP Access with the 3GPP AAA Server/Proxy and transports access authentication, authorization and charging-related information in a secure manner
SWa – Reference point connecting the Trusted non-3GPP IP Access with the 3GPP AAA Server/Proxy and transports access authentication, authorization, mobility parameters and charging-related information in a secure manner
SWu – Reference point between the UE and the ePDG that supports handling of IPSec tunnels
TAC – Tracking Area Code
TWAG – Trusted Wireless Access Gateway
UCI – Uplink Control Information
UE – User Equipment
UL – Uplink
UPT – User Perceived Throughput
USIM – Universal Subscriber Identity Module
VoLTE – Voice Over LTE

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