MulteFire Release 1.1 Enhancements

A. Overview of MulteFire 1.0

a. Existing Unlicensed Band Technology

In the unlicensed 5 GHz band, Wi-Fi is a popular technology for wireless networks. Licensed Assisted Access (LAA) and Enhanced Licensed Assisted Access (eLAA) from the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) Release 13/14 augment standard LTE to operate in global unlicensed spectrum, offloading mobile data at lower cost.

b. Role of MulteFire 1.0 in Unlicensed Band Technology Evolution

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 MulteFire 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 technologies – such as 5G NR – in configurations that use only unlicensed or shared radio spectrum.

MulteFire 1.0 [1] 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 3.5 GHz Citizens Broadband Radio Service (CBRS) band in the U.S. MulteFire 1.0 is tightly aligned with 3GPP standards, and builds on elements of the 3GPP Release 13 and 3GPP Release 14 specifications for LAA and eLAA, respectively, 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 1.0 enables the full range of LTE services including voice over LTE (VoLTE), high-speed mobile broadband (data), user mobility and Internet of Things (IoT) optimizations. It promises LTE-like performance with the simplicity of Wi-Fi-like deployments. As with mobile networks, MulteFire

1.0 enables full mobility as a user walks around a building; the technology enables seamless handover between small cells as required. MulteFire 1.0 will also interwork with external mobile networks to provide service continuity when users leave the area where MulteFire 1.0 service is available.

MulteFire 1.0 can operate anywhere, without costly spectrum or without specialists with expertise in the area of network deployments. 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 1.0 networks can co-exist, overlap or be friendly neighbors in the same physical space.

c. Deployment Use Cases for MulteFire

With MulteFire 1.0, private and public vertical venues, IoT verticals, businesses and property owners can create, install and operate their own private or neutral host network in the same way that they do with Wi-Fi. MulteFire 1.0 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 1.0 has the potential to unlock the adoption of small cells and enable neutral host deployments on a much larger scale. 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.

MulteFire 1.0 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, mobile-to-mobile (M2M), IoT, 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.

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:*
    - o Retains LTE's deep coverage characteristics in an unlicensed band.
    - o Targets control channels to operate at cell-edge SINR of -6 dB.
    - o Adds a 5-6 dB link budget advantage over carrier-grade Wi-Fi.
- *Enhanced capacity in denser deployments:*
    - o Significant gains (~2X) over 802.11ac baseline.
    - o Leverages LTE link efficiency and MAC.
- *Seamless mobility:*
    - o Brings carrier-grade LTE mobility to unlicensed and shared spectrum.
    - o Backward and forward handover supported (as in 3GPP Rel. 12).
    - o Provides seamless and robust mobility between MulteFire 1.0 nodes themselves for all use cases and when moving between MulteFire 1.0 RAN and Macro Network depending on deployment model Network.
    - o Service continuity to Wide Area Networks (WAN) when moving to/from a neutral host deployment.
- *Increased robustness:*
    - o Forward handover enables recovery when radio link failures occur.
    - o Enhanced radio link failure triggers.
    - o Leverages LTE mature Self-Organizing Network (SON) techniques.

II. MULTEFIRE 1.1 ENHANCEMENT OVERVIEW.

As mentioned above, MulteFire 1.0 [1] is a novel technology designed to create new wireless networks by operating LTE technology on unlicensed or shared spectrum. MulteFire 1.1 represents an evolution of this technology with the aim to further improve its performance, and enhance its potential, while maintaining backwards compatibility with MulteFire 1.0. In MulteFire 1.1, four new features are defined to further enhance MulteFire 1.0: i) grantless uplink transmission (GUL); ii) wide-coverage enhancement (WCE); iii) autonomous user equipment (UE) mobility (AUM); iv) self-organized network (SON). This section provides an overview of each of these features, in the order they have been listed.

A. GUL

A scheduling-based system promises in general better uplink (UL) performance than an asynchronous and autonomous random access system such as Wi-Fi, when the system has exclusive rights to use the medium. In fact, in Fig. 15 and Fig. 16 of [1] it was shown that a MulteFire 1.0 system over-performs Wi-Fi baseline by providing a better link, and less contention through a scheduled access. However, during the same simulation campaign it was also noted that the UL performance of MulteFire 1.0 are highly degraded when this is operating with another incumbent technology such as Wi-Fi, which is characterized by a decentralized and asynchronous random access to the radio channel for data transmission, rather than a scheduled access. In this scenario, the UEs in the MulteFire 1.0 system have a disadvantage compared to Wi-Fi technologies in accessing the channel as they need to go through the following contentions:

1. When the UE has data to transmit, the UE must send first a scheduling request (SR) to the serving eNodeB (eNB) to request UL resources. In order to do so in the MulteFire 1.0 system, the UE has to first perform LBT to acquire the medium, before it can transmit the SR.

2. Once the SR is received, the eNB prepares an UL grant for certain subframe(s) to the UE, and the eNB shall acquire the channel by means of LBT again.

3. After receiving an UL grant, the UE needs to acquire the channel for UL data transmission by means of LBT, unless the switching gap is less than 16us within one MCOT.

In case a UE has received an UL grant, if LBT is needed but fails the UE loses its opportunity to transmit, and the related frequency/time domain resources for the SR and UL grant transmission are wasted. The UE can perform a transmission for the same data only after the eNB detects that the expected transmission failed, and re-schedules the same data transmission, which leads consequently to increasing overhead and the delay to get data packets transferred over the uplink.

On the other hand, Wi-Fi operates asynchronously and autonomously where the nodes are not restricted by grant assignments for transmissions at specific intervals. This allows a Wi-Fi node more flexibility in contending the channel and acquiring it for transmission access. In fact, as shown in [1] Wi-Fi terminals have indeed a natural advantage over MulteFire 1.0 terminals in UL data transmission, since multiple contention operation within one data transmission procedure significantly limits the UL access opportunity for MulteFire 1.0 systems.
To improve the UL performance, a GUL transmission procedure is introduced in MulteFire 1.1. GUL provides an effective way in improving the MulteFire 1.0 UL performance, since it has an advantage in the following aspects:

1. GUL is an evolution of MulteFire 1.0, and it inherits all its benefits, while maintaining backwards compatibility;

2. The UL autonomous transmission does not rely on a SR request. Therefore, if within a predefined set of radio resources, which are configured on a per-cell basis, a UE succeeds LBT, then it can start transmitting immediately as Wi-Fi. Thus, it does not suffer from the multiple contentions imposed on the scheduled UL access.

3. It will naturally well-coexist with Wi-Fi as the UE behavior is not different from Wi-Fi stations.
As mentioned, GUL is expected to operate with other incumbent technologies, such as Wi-Fi deployments of 802.11n/ac. It is also expected to operate with 3GPP

Further Enhanced Licensed Assisted Access (feLAA) networks, which have introduced autonomous uplink access. The design of this autonomous UL for feLAA has high resemblance with GUL, and the differences between the two features are minimum. A thorough description of the GUL design is provided later in this paper in Section III.

B. WCE

In the past few years, with the advent of low-power processors, low-power sensors, and intelligent wireless networks, there has been an increasing interest in industrial IoT, especially in the enterprise market. In this matter, a typical scenario is for instance a maritime port, where many automated guided vehicles (AGVs) are used to enable faster delivery of goods and products in warehouses and manufacturing units, and move around the whole area, while they are controlled and may communicate with each other wirelessly. In this context, a high attenuation of the wireless signals is expected due to unavoidable blocking between AGVs or containers, which might obstruct the safe and correct operation of these devices. To this end, a robust wireless connection is required to support continuous connectivity in this typical scenario. Furthermore, in this context apart from eliminating the problem related to the robustness of the wireless signal, better coverage can help to substantially reduce the cost for deploying such a network from a customer point of view.

MulteFire 1.0 has enabled an LTE cellular system to operate solely on unlicensed bands, and therefore allows to completely cut any costs related to the use, and management of the licensed spectrum. While the design of MulteFire 1.0 is able to provide better and more robust links than competing technologies, due to the limitations imposed by the regulatory requirements on the unlicensed bands, this design does not offer the necessary coverage to address deployments as those mentioned above. To overcome this issue, the WCE enhancement is introduced in MulteFire 1.1 with the aim to improve the downlink (DL) link budget for this type of system. According to the maximum coupling loss (MCL) evaluations performed during this work item (WI), WCE allows to improve the DL performance by nearly 8 dB compared to MulteFire 1.0. A thorough description of the WCE design is provided later in this paper in Section III.

C. AUM

When operating a network with mobility in the unlicensed or license-exempt bands, there are several potential challenges which are arising from the combination of low transmit power, coexistence requirements and device mobility. The low transmit power of all nodes will cause the cell sizes to become relatively small, while device mobility might cause the system to have a short time to handle the entire handover procedure when UEs move towards a cell having better link conditions. On top of this, the LBT procedure that is required for coexistence may cause a blocking of the transmission from either the eNB or the UE, which results in lost or delayed messages and delayed/outdated measurement reports. Having delays during the handover procedure in such small cells can potentially cause the UE to be out of coverage of its original source cell before it is able to complete the handover towards a target cell.

To address this problem, MulteFire has introduced Autonomous UE Mobility (AUM), which is a new feature to complement the normal eNB controlled handover procedure. When a UE is being configured for AUM mode, it is pre-configured with one or more potential target cells, and upon certain conditions being met, the UE may autonomously contact the target cell without informing the source cell, thereby reducing the vulnerability of the aforementioned mobility challenges. The pre-configuration of the UE for AUM mode may be based on reported measurements or the eNB might configure UEs blindly for AUM operation. In short, a UE can be configured on a per-cell basis by the source cell to autonomously trigger and perform handover, without receiving an explicit handover command or informing the source cell.

D. SON

SON encompasses solutions to self-configure and self-optimize a network. It was introduced in LTE to facilitate the deployment of a system, and to allow for further performance optimization. The first SON features, i.e. Physical Cell Identity (PCI) allocation and Automatic Neighbor Relation (ANR), were introduced in 3GPP Release 8, while the term “SON” was introduced in 3GPP Release 9. The success of these two features encouraged further study on this topic, and lead to a WI in 3GPP Release 9 that enabled three more SON features: Mobility

Robustness Optimization (MRO), Mobility Load Balancing (MLB) and RACH optimization. Among these new SON features, MRO and MLB turned out to be some of key enablers for LTE, and they were further enhanced in the following releases to match the increasing complexity of the LTE design. Besides the aforementioned features, other SON related features were discussed and enabled in subsequent 3GPP study items (SIs) and WIs, such as Energy Saving (ES), inter-cell interference coordination (i.e., ICIC), enhanced interference mitigation and traffic adaptation (eIMTA), and coordinated multi-point (CoMP) operation.

Considering the role that SON has played in LTE in helping operators deploying and increasing the robustness of the LTE networks, this feature is introduced in MulteFire 1.1 as well. In MulteFire 1.0, two separate network architectures were developed: i) a Public Land Mobile Network (PLMN) Access Mode, and ii) a Neutral Host Network (NHN) Access Mode. While the PLMN access mode uses the legacy LTE network architecture, the NHN Mode is a new self-contained network, which enables 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 MulteFire 1.1, SON features have been introduced focusing on the network self-configuration or the network optimization of stand-alone networks operating in unlicensed spectrum and networks deployed with the NHN architecture. More details regarding the SON features enabled in MulteFire 1.1 are provided later in this paper in Section III.

III. TECHNICAL FEATURES OF MULTEFIRE 1.1

A. GUL design

GUL reuses a similar activation/release procedure as that defined in LTE for SPS (semi-persistent scheduling). In particular, as illustrated in Figure 1, the procedure includes the following steps:

- The eNB configures the essential GUL parameters (i.e., time domain resources) through Radio Resource Control (RRC) signaling, and activates this feature by a dedicated DCI, called activation/release DCI.

- Once activated, the UE transmits one or multiple GUL Physical Uplink Shared Channel (PUSCH) bursts according to configured resources after it successfully acquires the medium. To assist the eNB in decoding the GUL data burst, the corresponding control information, e.g. UE-ID, and HARQ process ID, are carried within a new UCI, called GUL-UCI, which is transmitted in every GUL PUSCH subframe.

- The eNB performs the GUL PUSCH presence detection to detect GUL UE presence, and its GUL data burst, and then feedbacks to it the acknowledgment/negative acknowledgment (A/N) accordingly by using a new GUL-DCI or the legacy DCI grant.

- The UE may perform a new GUL or a new scheduled transmission (SUL) or retransmission depending on eNB's scheduling.

- Finally, the eNB deactivates this feature by transmitting the activation/release DCI with its fields opportunely set.

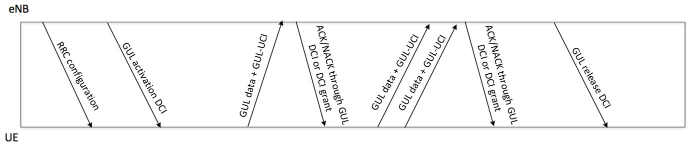


Figure 1- GUL activation/deactivation procedure.

a. RRC configuration and activation/release DCI

As mentioned above, the first step to activate the GUL feature consists in the eNB configuring some long-term parameters through RRC signaling, which include:

- GUL C-RNTI, which is used to identify GUL control and data transmission;
- DMRS related configuration for GUL PUSCH;
- GUL HARQ IDs pool and HARQ timer;
- Time domain resource allocation configured, using a 40-length bitmap;
- Power control related parameters.

In the context of activating/releasing the GUL feature, a new DCI is defined. The activation/release DCI reuses the bit-length of the legacy DCI format 0A in order to reduce UE's blind detection complexity. The activation/release DCI carries among others resource blocks assignment, MCS, PMI and some validation bits, used to discern on whether activation or release is performed: if validation bits are set to all "1"s, the GUL feature is activated, while if validation bits are set to all "0"s, the GUL feature is released. The resource block assignment is used to configure the frequency domain resource used for GUL transmission. Both full bandwidth and partial bandwidth resource allocation is allowed. GUL transmissions are not allowed in the subframes belonging to the DRS Measurement Time Configuration (DMTC) window of the serving cell irrespective of the RRC configured bitmap.

b. Channel access and starting position

For GUL UEs configured to occupy full bandwidth mode, there is a high likelihood that multiple of these UEs start simultaneous transmission and collide with each other. In order to reduce intra-cell collisions, UEs can be configured with random GUL-specific start offsets, which provide the UEs with different priority to access the channel mitigating the change of colliding with each other. When GUL UEs are instead configured to occupy partial bandwidth, in order to better utilize the frequency/time resources available, an exact start offset is more appropriate. In both cases, the PUSCH starting position is aligned for different GUL UEs, and a CP extension is used for transmissions before the next allowed transmission boundary where the PUSCH transmission starts.

When a GUL transmission occurs outside the eNB acquired MCOT, Cat.4 LBT is performed, where the priority class depends on the UL traffic type. Furthermore,

- for full bandwidth mode, the UE randomly chooses a UE specific start position from {16us, 25us, 34us, 43us, 52us, 61us, orthogonal frequency-division multiplexing (OFDM) symbol #1} to reduce the risk of collisions and thereby mutual interference;

- for partial bandwidth mode, the start position

is configured by the eNB from {16us, 25us, 34us, 43us, 52us, 61us, OFDM symbol #1}, so that UEs can be multiplexed in the frequency domain. When GUL happens inside the eNB acquired MCOT, 25us LBT is performed. Furthermore,

- for full bandwidth mode, the start position is randomly chosen by the UE from {34us, 43us, 52us, 61us, OFDM symbol #1};

- for partial bandwidth mode, the start position

is configured by the eNB from {34us, 43us, 52us, 61us, OFDM symbol #1}, and the ending OFDM symbols of every GUL subframe is fixed to 12.

- Since according to the above configuration options the starting time of GUL transmissions is always delayed compared to the starting time of scheduled uplink transmissions, these ensure that precedence is always given to scheduled transmissions over GUL transmissions.

c. GUL-UCI

As mentioned above, in order to assist the eNB in the detection and decoding a GUL PUSCH burst, the GUL-UCI is defined, which is used to carry some essential information, e.g. HARQ ID, UE-ID, RV, channel access priority class, and sharing COT related information. The physical channel of GUL-UCI reuses the MulteFire 1.0 procedure, and the GUL-UCI is mapped into the ACK/NACK and CSI resources, while UL-SCH is rate matched around it. Due to the critical importance of the GUL-UCI, it is transmitted in every GUL subframe. Since the GUL-UCI contains the UE-ID, in order to avoid the chicken-and-egg issue, the GUL-UCI is scrambled independently from the GUL PUSCH, and uses a cell specific RNTI.

d. GUL-DCI

In order to provide HARQ-ACK feedback to the GUL UEs, a new DCI is introduced in MulteFire 1.1, which is called GUL-DCI. This DCI carries among others the following information: TPC, MCS, PMI and an explicit HARQ bitmap with one HARQ-ACK-bit per each GUL-configured HARQ process.

e. GUL HARQ process IDs configuration and GUL retransmission procedure

As for MulteFire 1.0, 16 HARQ process IDs are supported, and the HARQ process IDs that can be used for GUL transmission can be configured by the eNB through RRC signaling using a length-16 bitmap. An HARQ process ID configured for GUL, can be also used for SUL. For one specific GUL HARQ process ID:

- If it is explicitly marked as ACK in the GUL-DCI, the eNB can transmit a DCI grant for SUL initial transmission, where the DCI grant is transmitted in the same subframe or the subframe before the GUL-DCI. Otherwise, a GUL UE can utilize this HARQ process ID for a new GUL transmission;

- If it is explicitly marked as NCKed in the GUL-DCI, the eNB can schedule a retransmission DCI grant, where the DCI grant is transmitted in the same subframe or the subframe before the GUL-DCI. Otherwise, a UE performs GUL retransmission;

- If neither a DCI grant nor a GUL-DCI is received after an RRC configured timer has elapsed, then a new GUL transmission attempt is started.

B. WCE design

Unlike in traditional LTE systems, which are deployed by mobile network operators (MNOs) in licensed bands, and where typically the eNB transmits with higher power than the UE, in a MulteFire system both the eNB and the UE have to comply with the regulatory requirements, which limit their maximum transmission power. In order to cope with this issue, MulteFire 1.0 introduced a block interleaved FDMA (B-IFDMA) waveform for the UL. While this feature has increased the performances for the UL, no enhancements have been introduced in this matter for the DL. However, after a comprehensive MCL study of the design of MulteFire 1.0, it has been found that the DL channels represents the performance bottleneck of this system: for example, 1% BLER is achieved by the MF-PBCH at a signal-to-interference and noise ratio (SINR) of -2.5 dB. Motivated by this, MulteFire 1.1 has introduced the WCE feature, which consists of the DL enhancements discussed in detail in this section with the aim to enhance the DL coverage of MulteFire 1.0 by nearly 8 dB.

a. WCE DRS

In order to improve the link budget performance of the discovery reference signal (DRS), a WCE DRS is introduced, which is composed by two consecutive subframes. In order to maintain backward compatibility with MulteFire 1.0, the first subframe of the WCE DRS has the exact same physical structure, and it carries the same physical signals as the MulteFire 1.0 DRS, while in the second subframe 10 OFDM symbols are used for additional MF-PBCH, and the remaining four carry synchronization signals (i.e., PSS\SSS and MF-PSS\SSS) with the physical structure illustrated in Figure 2. In the second subframe of the WCE DRS, the position of the legacy, and the MulteFire synchronization signals as well as the position of the primary and secondary synchronization signals (PSS/SSS) for both legacy and MulteFire signals are swapped compared to the first subframe, with the aim to distinguish the DRS for MulteFire 1.0 and the WCE DRS, and to avoid any false alarm when acquiring the PCI in initial access. In MulteFire 1.1, the first two symbols of the WCE DRS are used by the eNB to initiate the LBT procedure with priority class 1, and to perform the transmission of the whole WCE DRS in case the LBT procedure succeeds. Through the use of the WCE DRS, a MulteFire 1.1 UE is able to keep a stable wireless connection in initial access, radio link monitoring, and RRM measurement procedure, even with poor link quality.

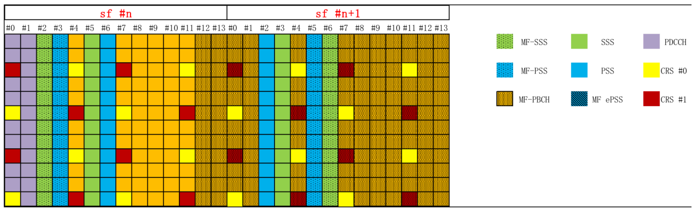


Figure 2 - Illustration of the WCE DRS physical structure.

b. WCE ePDCCH

To enhance the performance of the PDCCH reception for WCE UEs, an enhanced DL control channel is introduced. Due to the limited DL subframes available within one transmission opportunity (TxOP) and due to the difficulties in combining PDCCH transmissions across TxOPs, the WCE DL control channel is designed based on the legacy enhanced physical DL control channel (ePDCCH). In order to allow WCE UEs to decode the control information within one subframe, the maximum aggregation level of ePDCCH is extended up to level 64 for all the DCI formats except for DCI format 1C. For this specific DCI format, which has the smaller payload size among all the DCI formats, a lower maximum aggregation level is required to achieve the target MCL set for WCE, and a maximum aggregation level of 32 is agreed. Apart from a UE specific search space, a common search space is also defined for a WCE UE for system information broadcasting.

c. WCE PDSCH

In order to enhance the coverage of PDSCH to meet the target MCL for WCE, TBS scaling and time-domain repetitions may be jointly applied. TBS scaling allows to utilize a lower coding rate for PDSCH by introducing a scaling factor, which can be equal to 1/2, or 1/4. As for the time-domain repetitions, PDSCH may be repeated 2, 3, or 4 times. In order to support lower coding rates for Channel Quality Indicator (CQI) reports, a new corresponding CQI table characterized by a scaling factor is also introduced.

d. WCE mode management

In order to manage the WCE mode for MulteFire 1.1 UEs, the transition between WCE mode and normal mode (i.e., acting as a MulteFire 1.0 UE) is defined. During initial acquisition, a MulteFire 1.1 UE informs the eNB of its mode of operation (normal mode or WCE mode) through a specific random access preamble, which is chosen from a dedicated group of random access preambles (preamble index 64 to 95), if the measured reference signal received power (RSRP) is below a configured threshold value, which is broadcasted in the SIB-MF1. When the UE is in RRC connected state, the eNB configures through the RRCConnectionReconfiguration message whether the UE operates in normal mode or WCE mode, and the decision is made based upon the ACK/NACK feedback, and the channel quality report provided by the UE.
Handover and mobility management are also supported for MulteFire 1.1 UEs in WCE mode, and a UE with WCE capability can move from a serving cell to the target cell, and operate in either WCE mode or normal mode depending on the measurement results.

C. AUM design

The overall concept of AUM for MulteFire 1.1 has been based on the source eNB acting as an aggregation node. Upon deciding that a connected UE should be configured for AUM (for example following a measurement report from the UE indicating that it is approaching a target cell), the source eNB will contact one or more potential target eNBs for this UE. When receiving the configurations from the potential target eNBs, the source eNB will aggregate the information and feed this to the UE. Such approach is in contrast to existing handover procedures from MulteFire 1.0 and for LTE, where the source eNB transparently forwards handover related information from the target eNB to the UE in the handover command. For the AUM design it was decided to introduce two modes of operation, which allow the target eNBs to choose the amount of information to be exchanged as well as of the amount of resources committed towards the feature. The two main modes are distinguished by their different levels of commitment of resources.

a. Operation without allocation of dedicated resources.

In this mode, there are two possibilities: (a) The target eNB will provide no information on configuration, except information on candidate cells to which UE may trigger cell re-selection even if there is no radio link failure. This is the case when there is no AUM mobility information provided by the target cell. (b) The target eNB will provide information on its configuration, but without any allocation of dedicated resources. That is, the eNB will not commit to reserving any physical resources towards the incoming UE, and the UE will have to access the cell similarly as in the LTE re-establishment procedure. This mode allows for the UE to obtain relevant system information blocks (SIBs) of the potential target cell beforehand. When approaching a new configured potential target cell in this mode, the UE will have to synchronize to the new cell and read the master information block (MIB) to obtain system timing with the new cell. However, further reading of SIBs can be skipped, as the UE already has this information available, and the UE may perform random access procedure faster compared to the situation where there was an RLF. When connecting to the target cell, the UE will perform an RRC connection re-establishment procedure and rely on the eNB to perform a context fetch from the source cell, followed by data forwarding and data path switch from the core network prior to completing the handover procedure. The context fetch procedure will ensure that necessary information related to UE capability and setup towards network operation is transferred from a source eNB to a new serving eNB.

b. Operation with allocation of dedicated resources.

When assigning dedicated resources in the potential target eNB the information provided to the source eNB will contain additional information that will help the UE in attaching faster to the target eNB in case of AUM being triggered. The additional information that is provided to the UE in case of the dedicated configuration will be the full RRC configured resources, meaning that after obtaining synchronization to the new target cell the UE will be able to establish direct contact to the cell, as it already has a configuration for scheduling request as well as a cell-specific RNTI. On top of this the potential target cell will have obtained the UE context as part of the configuration procedure. When configured in this mode, the UE will send an RRC reconfiguration complete message to the target cell, and the target cell will use legacy procedures to trigger data forwarding and data path switch from the core network. This mode of operation will allow for faster completion of the handover, but it will also require the potential target eNBs to reserve resources for UEs that may or may not establish connection. Additionally, for the case where multiple potential target eNBs are configured with dedicated resources for a single UE, there will be some additional network operations for releasing resources in the candidate eNBs that were not selected when the UE performed the AUM. Part of the signaling for this mode of operation is shown in Figure 3.

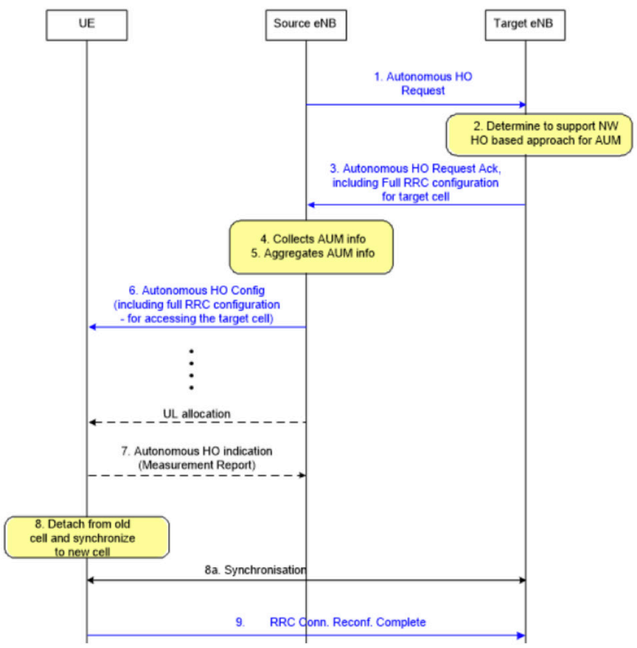


Figure 3 - Illustration of part of the signaling flow when successfully completing an AUM based handover with full RRC configuration. The UE has been configured for AUM operation and has obtained full RRC configuration from the potential target eNB. Since the UE has obtained information on the dedicated resources, it is possible to have contention-free RACH procedure with the target eNB prior to step 9 in the figure.

c. UE operation when configured for AUM

When a UE is configured for AUM, it will receive a configuration message, which will contain the information related to the potential target cells as well as further information related to when and how the UE may trigger an autonomous handover. The configuration also contains a specific AUM timer, which will control the delay between the triggering of a measurement report, and the time UE is expected to perform the autonomous handover. The timer may be configured with values between 0 ms (immediate AUM based handover without measurement report) and 500 ms.

When an AUM measurement event is triggered, the UE will create a measurement report similar to a normal measurement event triggered for regular handover. In case the AUM specific timer is non-zero, the UE will trigger a measurement report to the source eNB, which (in case the measurement report is received) will have some time to perform the normal handover preparation towards the target cell that triggered the measurement report or even cancel the AUM based handover by stopping the AUM specific timer. If the target cell is able to provide the handover message to the UE via the source cell while the AUM timer is still running, the UE will perform a traditional handover. For cases where the AUM specific timer expires prior to the UE receiving a handover message, the UE will autonomously disconnect from the source cell and establish connection to the target cell, according to the configuration that is available.

D. SON design

Considering the role that SON has played in the 3GPP LTE in helping operators deploying and increasing the robustness of the LTE networks, some SON features have been enabled in MulteFire 1.1 as well focusing on the MulteFire network self-configuration and optimization.

a. Self-configuration

NHN-ID is the identifier of a specific NHN, and all the MulteFire cells belonging to that NHN broadcast the same NHN-ID. In this case, it is beneficial for an eNB to automatically provide and share the relevant configuration information related to its NHN network with the newly deployed eNBs. In MulteFire 1.1, an eNB can share the NHN-ID during the X2 setup or the eNB configuration update procedure through X2, if the newly deployed eNB belongs to the same NHN. Automatic neighbor relationship (ANR) procedure is then used to relieve the operator from the burden of manually managing the Neighbor Relations (NRs). However, through this procedure alone it is not possible to guarantee that an eNB would always setup NR correctly, since the PCIs are not unique among different NHN networks. To cope with this issue, in MulteFire 1.1 a UE is in charge of indicating the unique cell identity of a specific NHN to the serving cell eNB. In other words, if the newly deployed cell is a MulteFire cell, and it broadcasts NHN-ID, the UE reports that NHN-ID to the serving cell, so that the serving cell gets updated about the PCIs related to its same NHN.

The DMTC information is a periodic time window within which the DRS is transmitted by the network once in any of its subframe, and this configuration is done in MulteFire 1.0 independently from the neighbor cells. In order to prevent DMTC overlaps among neighbor cells, in MulteFire 1.1, the DMTC information can be exchanged between neighbor eNBs during the X2 setup or eNB configuration update procedure through the X2 interface.

b. Self-optimization

In LTE, the RACH procedure is optimized through the support of UE's reported information and Physical Random Access Channel (PRACH) parameters, which are exchanged among eNBs. In MulteFire 1.0, a short PRACH (sPRACH) was supported together with the legacy RACH procedure. Therefore, the legacy RACH procedure optimization should be taken into consideration as well. For this reason, in MulteFire 1.1 eNBs can exchange the sPRACH parameters through X2 interface within the serving cell information. Furthermore, the UE can report the number of RACH preamble transmission failures due to LBT that occur until the successful RACH completion.

Another useful optimization for the network regards the load balancing. In fact, it is beneficial to distribute evenly the load among cells and/or redirect part of the traffic from congested cells to low loaded cells, and this is achieved in MulteFire 1.1 by load information exchange on X2 interfaces. In this regard, in MulteFire 1.1 the load information of a specific cell operating in unlicensed spectrum is given by the time domain ratio of the channel used for DL and UL transmissions within that MF cell, and the estimated time domain ratio when the channel is considered busy.

The RLF report from a UE can be used for both coverage optimization and mobility robustness optimization. For this purpose, it is necessary to obtain the RLF report within the same network. In this context, in MulteFire 1.1 the UE only indicates RLF report availability, and only provides the RLF report to the network, if the current registered NHN ID was the same as the NHN ID at the time the RLF or handover failure was detected in NHN mode.

IV. PERFORMANCE OF MULTEFIRE 1.1 ENHANCEMENT

This section provides a detailed evaluation of the performance of two features introduced in MulteFire 1.1. In particular, it provides a performance assessment for GUL and WCE, in order to prove the effectiveness of these enhancements.

A. GUL performance

The methodology used for evaluating the system level performance of the GUL design closely follows the methodology used in the LAA evaluation undertaken in 3GPP [2], and the methodology used in [1] to evaluate the performance of MulteFire 1.0. The objective has been twofold: First, 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 GUL UEs coexist and undergo the LBT mechanism for accessing the medium. Second, to compare the performance of MulteFire 1.0, which operates the UL in a scheduled manner, and MulteFire 1.1, while operating in GUL mode.

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 simulation assumptions used in this section are captured in Table I. The indoor Hotspot scenario depicted in Figure 4 has been considered. 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 [2], where UEs are downloading and uploading files of fixed size (0.5 Mbytes). 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.

Parameters	Value
Deployment	Indoor scenario follows 3GPP TR36.889 20 indoor UEs
Bandwidth	20MHz
Traffic model	FTP traffic model 3, (non-adaptive Poisson arrivals), with file size 0.5 MB Model 1: 100% UL Model 2: 50% UL + 50%DL
Operators Type	Case 1: operator 1 is Wi-Fi, operator 2 is MF SUL Case 2: operator 1 is Wi-Fi, operator 2 is MF GUL
Tx Power	18dBm
MF Operator Bandwidth	Full bandwidth: 100 RBs
TxOP length	6ms both MF and Wi-Fi
Cat. 4 LBT, AP in Wi-Fi	9 us slots, exponential backoff counter {0, CW}, where CW{15,31,63}
Cat. 4 LBT, STA in Wi-Fi	9 us slots, exponential backoff counter {0, CW}, where CW{15,31,63, 127, 255, 511, 1023}
Cat..4 LBT, eNB in MF	9 us slots, exponential backoff counter {0,CW} where CW{15,31,63}
Cat. 4 LBT, UE in MF	9 us slots, exponential backoff counter {0,CW} where CW{15,31,63, 127, 255, 511, 1023}
Energy Detection Threshold	-72dBm

Table I- Main Assumptions for Performance Evaluation.

Three different deployment scenarios are evaluated:

1. "W+W": Both OP1 and OP2 deploy Wi-Fi nodes;

2. "W+SUL": OP1 deploys Wi-Fi, OP2 deploys MulteFire 1.0;

3. "W+GUL": OP1 deploys Wi-Fi and OP2 deploy MulteFire nodes that operates GUL.

The system level performance is evaluated in terms of the gain in UPT considering the 'W+W' scenario as the baseline for two different traffic models: i) model 1- 100% UL traffic; ii) model 2 - 50% UL and 50% DL traffic. For each traffic model the system level performance is evaluated for different offered loads. For each model and offered load, results are provided from three different source companies under the same general simulation assumptions listed in Table I.

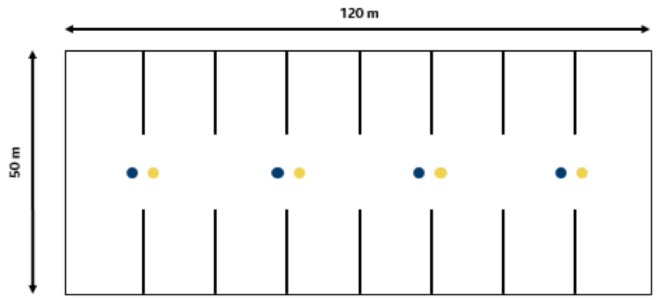
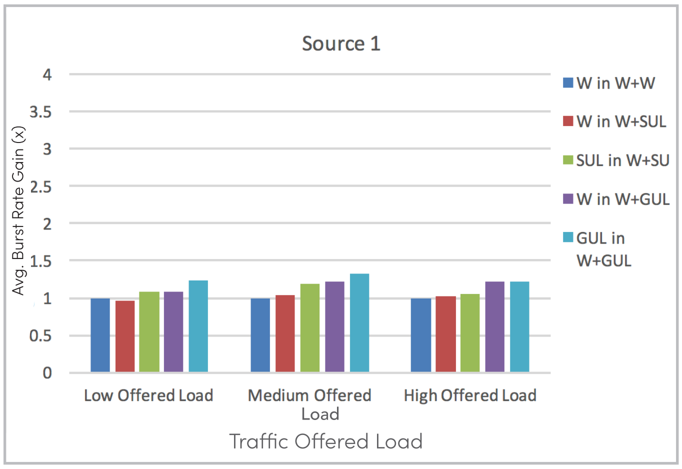


Figure. 4 - A building of Indoor Hotspot model. The blue and yellow dots represent small cells belonging to OP1 and OP2 [2].

Figure 5 provides the gain in UPT considering the 'W+W' scenario as the baseline for traffic model 1 for the UL. Figure 6 and Figure 7 provide the gain in UPT considering the 'W+W' scenario as the baseline for traffic model 2 for UL and DL, respectively.



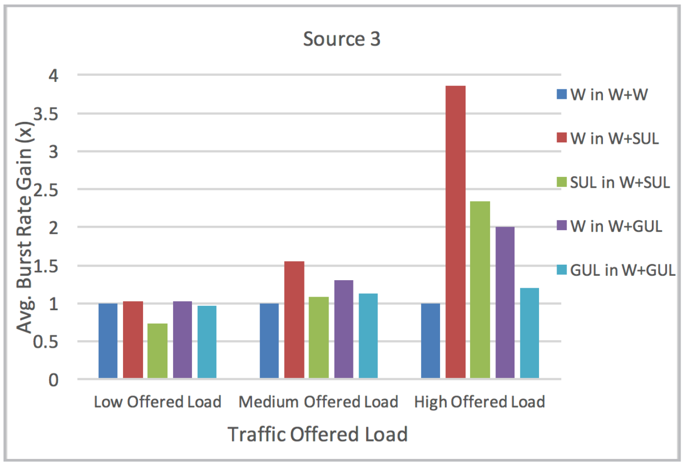


Figure. 5 - (Top) Source1, (Middle) Source2, and (Bottom) Source3: UL Avg. Burst Rate Gain for traffic model 1 for different traffic loads. Gain is relative to 2-operator Wi-Fi baseline deployment (i.e., UPT in scenario(x) / UPT in W+W scenario).

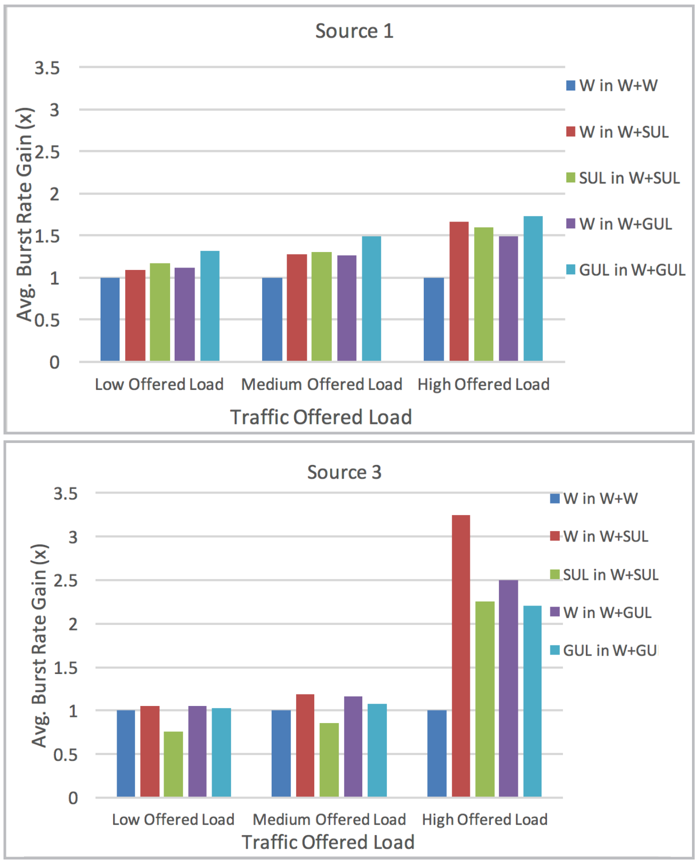


Figure 6 - (Top) Source1, and (Bottom) Source3: UL Avg. Burst Rate Gain for traffic model 2 for different traffic loads. Gain is relative to 2-operator Wi-Fi baseline deployment (i.e., UPT in scenario(x) / UPT in W+W scenario).

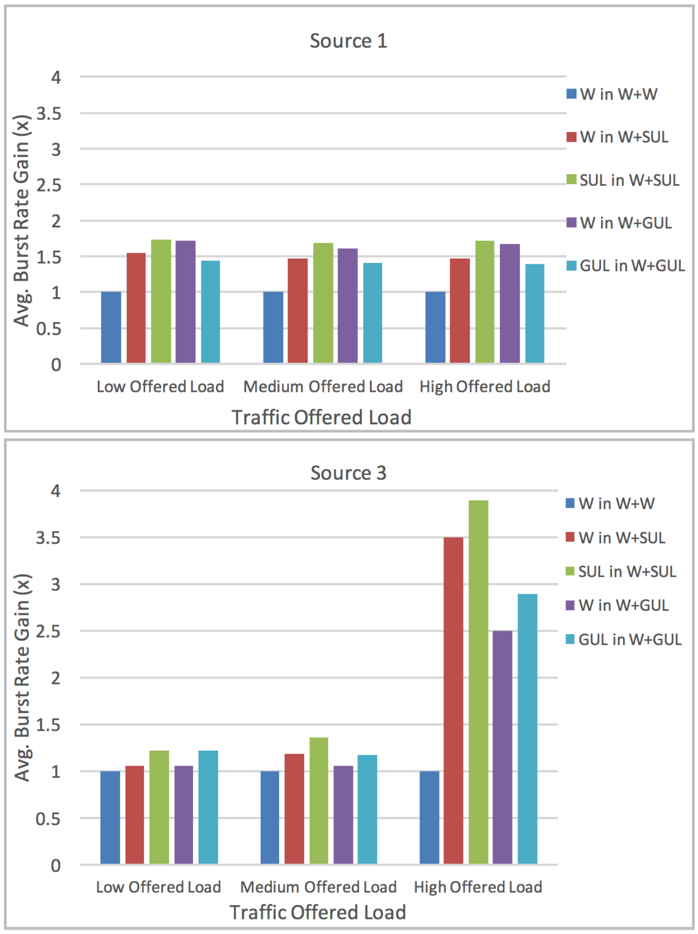


Figure 7 - (Top) Source1, and (Bottom) Source3: DL Avg. Burst Rate Gain for traffic model 2 for different traffic loads. Gain is relative to 2-operator Wi-Fi baseline deployment (i.e., UPT in scenario(x) / UPT in W+W scenario).

For Figure 5, simulation results were collected from three sources: Source 1, Source 2, and Source 3. Figure 5 shows that for all the three sources and for any offered traffic load conditions, GUL coexists well with a Wi-Fi network for UL only traffic. Furthermore, Figure 5 highlights that for both Source 1 and Source 2, the UL performance of GUL outperforms that of SUL, and the gain is inversely proportional to the offered load and is in the range of 1.2-1.4.

For Figure 6 and Figure 7, simulation results were collected from two sources: Source 1 and Source 3. Figure 6 and 7 indicates that for both sources, and all traffic load conditions, GUL coexists well with a Wi-Fi network for both UL and DL in a mixed traffic scenario. Figure 6 highlights as in Figure 5 that for a mixed traffic scenario the UL performance of GUL outperforms that of SUL, and the gain decreases as the offered load increases. Figure 7 highlights instead that for a mixed traffic scenario, the DL performance of SUL outperforms that of GUL, and the gain is proportional with the offered load.

B. WCE performance

During the MulteFire 1.1 WI a detailed and exhaustive link-level performance evaluation was performed for the DL channels in order to verify the impact of the enhancements introduced in the design of WCE. However, for conciseness in this section only the performance of the DRS is provided, which, as stated along this paper, represents the bottleneck of the MulteFire 1.0 performance, and where most of the effort has been spent. For this reason, in the following only the link-level performance for WCE PBCH and PSS/SSS are provided based on the physical structure illustrated in Figure 2.

Fig. 8 provides the required SINR to achieve a target BLER of 10%, which are provided by two different source companies under the same general simulation assumptions listed in Table II. Fig. 8 highlights that the PBCH for WCE can be successfully decoded with a 10% BLER when the SINR is as low as -10 dB, which is equivalent to nearly 8 dB gain compared to MulteFire 1.0.

Table II – Main Simulation assumptions for WCE

Parameters	Value
Carrier Frequency	5 GHz
System Bandwidth	20 MHz
Antenna Configuration of eNB	2 Tx, 2 Rx
Antenna Configuration of UE	1 Tx, 2 Rx
Channel Model	EPA 5Hz
Target BLER	10%

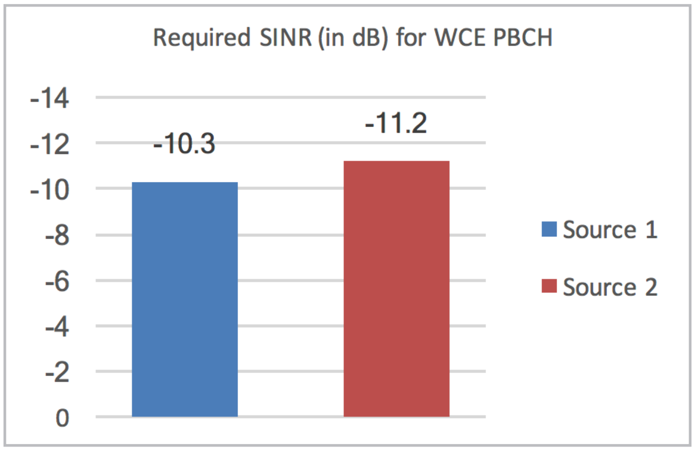


Figure 8 – Performance of WCE PBCH.

Fig. 9 provides the required SINR to achieve a target misdetection of 50% (or equivalently a 10% misdetection after four independent occasions), which are provided by three different source companies under the same general simulation assumptions listed in Table III. Fig. 9 highlights that time and frequency synchronization can be successfully acquired together with the PCI with a misdetection probability of 50% when the SINR is as low as -10 dB.

Table III – Main Simulation assumptions for WCE

Parameters	Value
Carrier Frequency	5 GHz
System Bandwidth	20 Mhz
Antenna Configuration of eNB	2 Tx, 2 Rx
Antenna Configuration of UE	1 Tx, 2 Rx
Channel Model	EPA 5Hz
Frequency Offset	5 ppm
False Alarm	1%
Target Misdetection	50%

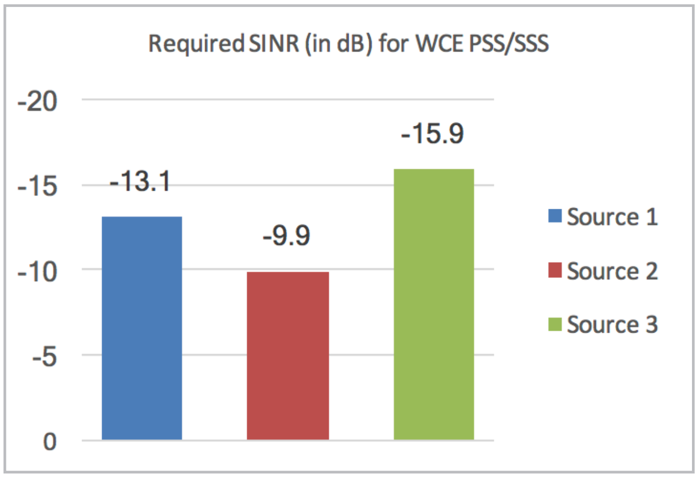


Figure 9 – Performance of WCE synchronization signals.

V. CONCLUSION

MulteFire 1.0 is an innovative technology designed to create new wireless networks by operating LTE technology on unlicensed or shared spectrum. MulteFire provides secure, seamless service and can act as a neutral host. Its Wi-Fi-like simplicity makes this technology a powerful tool for any organization that does not require hiring specialists in the area of network.

MulteFire 1.1 represents an evolution of this technology with the aim to further improve its performance, and enhance its potential, while inheriting all its benefits. In particular, MulteFire 1.1 has introduced four new features to enhance the UL, and DL transmission (i.e., GUL, WCE), improve the handover and mobility (i.e., AUM), and further help operators deploying and increasing the robustness of the network by enabling some important SON features.

Moving forward, there are a number of verticals that require support of massive number of low-throughput devices, reduce complexity, and improve power efficiency. In this matter, MulteFire 1.1 is releases new features for optimized IoT and will continue to be enhanced with new features introduced in a phased approach, targeting enriched scenarios, services and additional spectrums.

MulteFire is a new way to wireless.

REFERENCES

[1] "MulteFire Release 1.0 Technical Paper: A new way to wireless". https://www.multefire.org/wp-content/uploads/MulteFire-Release-1.0whitepaperFINAL.pdf.

[2] 3GPP 36.889: Feasibility Study on Licensed Assisted Access to Unlicensed Spectrum

GLOSSARY OF TERMS

3GPP – Third Generation Partnership Project

AGV – Automated Guided Vehicle

ANR – Automatic Neighbor Relation

AUM – Autonomous UE Mobility

B-IFDMA – Block Interleaved FDMA

BLER – Block Error Rate

CBRS- Citizens Broadband Radio Service

CoMP – Coordinated Multi-Point

CP – Cyclic Prefix

CQI - Channel Quality Indicator

C-RNTI – Common Radio Network Temporary Identifier

DAS - Distributed Antenna System

DL – Downlink

DCI – Downlink Control Information

DMRS – Demodulation Reference Signal

DMTC - DRS Measurement Time Configuration

DRS – Discovery Reference Signal

GUL – Grantless Uplink

GUL DCI – Grantless uplink Downlink Control Information

GUL UCI – Grantless Uplink Uplink Control Information

eIMTA - Enhanced Interference Mitigation & Traffic Adaptation

eNB – eNodeB

eLAA - Enhanced Licensed Assisted Access

ePDCCH – Enhanced Physical Downlink Control Channel

ES – Energy Saving

feLAA - Further Enhanced Licensed Assisted Access

HARQ – Hybrid Automatic Repeat Request

HO - Handover

ICIC - Inter-Cell Interference Coordination

ID - Identifier

IoT – Internet of Things

MCS – Modulation and Coding Scheme

PUCCH – Physical Uplink Control Channel

PUSCH – Physical Uplink Shared Channel

LAA – Licensed Assisted Access

LBT – Listen-Before-Talk

LTE – Long Term Evolution

M2M – Mobile-to-Mobile

MCL – Maximum Coupling Loss

MCOT – Maximum Channel Occupancy Time

MF - MulteFire

MIB – Master Information Block

MLB - Mobility Load Balancing

MNO – Mobile Network Operator

MRO - Mobility Robustness Optimization

NHN – Neutral Host Network

NW – Radio Network

OFDM – Orthogonal Frequency Division Multiplexing

PBCH – Physical Broadcasting Channel

PCI – Physical Cell Identity

PLMN – Public Land Mobile Network

PMI – Precoding Matrix Indicator

PRACH – Physical Random Access Channel

PSS/SSS – Primary and secondary Synchronization Signal

QoE – Quality of Experience

RACH - Random-Access Channel

RLF – Radio Link Failure

RNTI – Common Radio Network Temporary Identifier

RRC – Radio Resource Control

RSRP - Reference Signal Received Power

SI – Study Item

SIB – System Information Block

SIM – Subscriber Identity Module

SINR – Signal-to-Interference and Noise Ratio

SON – Self-Organized Network

SPS - Semi-Persistent Scheduling

SR - Scheduling Request

TxOP – Transmission Opportunity

UCI – Uplink Control Information

UE – User Equipment

UL – Uplink

UPT – User Perceived Throughput

VoLTE - Voice over LTE

WCE – Wide-Coverage Enhancement

WI – Work Item

MulteFire Alliance | 5177 Brandin Court, Fremont, CA 94538
Phone: +1 510.492.4026 | Fax: +1 510.492.400
info@multefire.org | www.multefire.org