MulteFire1.1 eMTC-U

I. INTRODUCTION

A. Overview of MulteFire 1.0

a. Existing unlicensed band technology

In 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 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 in configurations that use only unlicensed 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 upcoming 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 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 within a MulteFire network; 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 hiring network specialists for installations. 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.

B.Design goals/requirements for eMTC-U

In MulteFire 1.1, among other features [8] a new RAT (Radio Access Technology) based on 3GPP Rel-13 enhanced machine type communication (eMTC) is introduced with the aim to extend the capability of a MulteFire system and is designed to re-use the e2e (End-to-End) architecture and core networks from MulteFire 1.0. This allows customers to leverage existing investments in MulteFire technology while enabling LTE machine type communication (MTC) technology on unlicensed spectrum. The following design goals and requirements were considered for eMTC-U:

3GPP Alignment
The benefits by aligning as closely as possible eMTC-U with 3GPP are the potential to have single chip solution for both licensed and unlicensed operation and further reduction in user equipment (UE) cost. Another benefit is time to market due to the lower development cost and risk.

Global Design
The Industrial IoT landscape is increasing globally, which demands a single global solution. The 2.4 GHz band is chosen for eMTC-U as it is globally available, but it is subject to regional regulations dictated by the related regulatory bodies. eMTC-U uses a single physical layer design, which is compliant with both ETSI (European Telecommunications Standards Institute) and FCC (Federal Communications Commission) regulatory requirements, which are the two main set of rules that if satisfied guarantee a globally operable solution. This means simpler UEs design, higher volumes and lower device costs.

Coverage
Since eMTC-U uses unlicensed spectrum with reduced maximum transmission power as dictated

by the regulatory requirements and will be mainly deployed indoor, the maximum coupling loss (MCL) target is scaled down accordingly when compared to the 3GPP counterpart. While eMTC supports coverage extension (CE) mode A and mode B, where B is for deep coverage, only CE mode A operation is targeted for eMTC-U. This means a more modest number of repetitions is required (i.e., 32 repetition in eMTC-U vs 2048 repetitions for legacy 3GPP eMTC) per channel in an eMTC-U system. The target MCL for this type of system is 130 dB given a 20 dBm output power limitation imposed by regulations.

	Main			UL	RF		DL latency,	UL latency
Bluetooth LE	Smartphone compatible point-to-point multipoint	2.4GHz	1/2	100/200 kbps	1/2 MHz	100 dB	7.5 ms-4s	7.5 ms-4s
Bluetooth LE long range	Coded Bluetooh LE for 2x-4x range	2.4GHz	125 kbps	15 kbps	1 Mhz	107 dB	7.5 ms-4s	7.5 ms - 4s
802.15.4	Physical layer with mesh support for Thread and ZigBee.	2.4 hKz (900 Mhz)	250 kbps	80 kbps	2 MHz	110 dB	10ms - 60s	10 ms -60 s

Table 1: License Exempt Technologies

II. MF1.1 EMTC-U OVERVIEW

A. High-level design overview of MulteFire 1.1 eMTC-U

eMTC-U brings the proven 3GPP eMTC technology into the global 2.4 GHz band. This means that a UE can have global roaming by implementing a single solution for cell search, acquisition and data transfer. This lowers UE/eNB implementation and maintenance costs. The 2.4 GHz band hosts WiFi, Bluetooth, IEEE 802.15.4 and other incumbent technologies [Table 1]and hence eMTC-U employs listen before talk (LBT) and frequency hopping technology to avoid harmful interference towards them.

In eMTC-U, all over the world, a common set of anchor channels are defined, which are specific channels used by the UE to find the cell and determine the frequency hopping sequence. Once an anchor channel is found, the UE continues cell access via the data channels which are transmitted in a frequency hopping fashion. The eNB performs LBT before transmitting either the anchor or a data channel while on the other hand the UE, does not use any channel access mechanism to acquire the medium, but must comply with some duty cycle limitations imposed by the ETSI regulatory body to coexist well with other incumbent technologies. This single solution satisfies all the FCC and ETSI regulatory requirements making this a globally operable system. Furthermore, advanced features like link adaptation and radio link monitoring are supported to increase link performance, capacity and robustness.

B. Regulatory Requirements

The 2.4 GHz band is regulated by regional regulatory bodies, such as FCC and ETSI. This section will give a primer into these regulations as they are important to understand the overall design of eMTC-U.

1) ETSI

ETSI standards body specifies two modulation types that can be used in the 2.4 GHz band: frequency hopping spread spectrum (FHSS) and wide band (WB) modulation[9]. ETSI also defines two types of equipment: adaptive and non-adaptive equipment. An adaptive equipment performs sensing of the medium to identify whether this is utilized by other users, and in this case to avoid transmission and mitigate collisions. On the other hand, a non-adaptive equipment is restricted by a medium utilization factor to ensure fair co-existence with other incumbent technologies.

From an eMTC-U perspective, WB modulation compliance was only briefly considered, and was discarded due to the power spectral density regulation limitation of 10 dBm per MHz. This limits a 1.4 MHz channel to 10.3 dBm, thus making it challenging to meet the coverage requirement envisioned for this technology. On the other hand, the maximum allowed RF output power for a frequency hopping system is 20 dBm. A frequency hopping system is defined by the number of frequency channels used, the dwell time on each channel and the characteristics of the hopping sequence itself. It is understood that the transmitter and receiver follow the same frequency hop sequence. The dwell time is composed of an idle, a receiving and transmitting time spent on a channel before changing to another one.

The accumulated transmit time is the total time the equipment is transmitting, during an observation period on a hopping channel. The frequency occupation is the number of times that each hopping channel is occupied (visited) within a given period. A hopping channel is considered occupied when the equipment selects that channel given a hopping sequence. FHSS equipment may be transmitting, receiving or staying idle during the dwell time spent on that hopping channel.
The hopping sequence of a FHSS equipment is the unrepeated pattern of the hopping channels used by the equipment. However, there are no requirements on how the hopping sequence should be generated, i.e., no definition or requirements on pseudo-randomness.

Adaptive frequency hopping (LBT based)
The mechanism for co-existence in adaptive frequency hopping scheme is LBT. The equipment needs to sense the channel to assess whether this is clear or not before transmission can take place. The energy threshold is defined as being proportional to a 20 dBm e.i.r.p. transmitter: the energy detection threshold shall be ≤-70 dBm/MHz:

$$TL = -70\ dBm/MHz + 10 * \log10\ (100\ mW/Pout)$$

Clear Channel Access (CCA) observation time is defined as not less than 0.2% of the channel occupancy time (COT) or 18us. If the medium is clear the transmission occurs immediately. If the CCA is not cleared there are 2 options:

1. Stay on the current channel and perform eCCA (extended CCA) for a random duration between the CCA and 5% of the COT.

2. Skip to the following channel in the hopping pattern and start the CCA process on it.

The maximum COT is 60 ms, which translates to a maximum CCA time of 120 us and a maximum eCCA time of 3 ms. The maximum dwell time on a given channel is 400 ms.

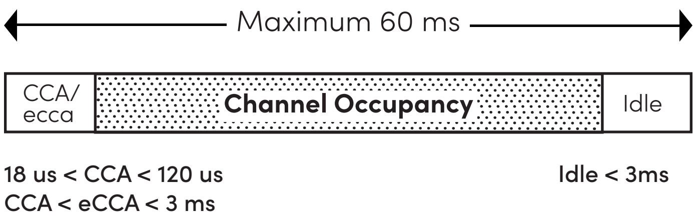

Figure 1: LBT based adaptive frequency hopping on a 60 ms COT.

For adaptive FHSS equipment, the minimum hopping frequency separation shall be 100 kHz.

Non-adaptive frequency hopping
The eMTC-U UE is designed to fulfil the non-adaptive frequency hopping requirements provided by the ETSI regulatory requirements.

The mechanism for co-existence in the non-adaptive frequency hopping scheme is to limit the medium utilization (MU) for transmitters operating above 10 dBm e.i.r.p. The maximum medium utilization factor is 10% for a transmitter operating at 20 dBm. The MU limits power and time according to the following formula:

$$\mu = (P/100mW) \times \delta$$

Where μ is the utilization factor in %, P is RF output power in mW and δ is the duty cycle in %. The maximum duty cycle must be declared by the manufacturer of the equipment. Note also that the equipment can dynamically vary the power and duty cycle with the provision that the equipment shall describe and declare how the system operates. For example, an equipment can declare that it operates at 100 mW/10% duty cycle and at peak demand hours operate at 50 mW/20% duty cycle. The duty cycle is observed over 2 full hopping sequences.

For non-adaptive frequency hopping equipment, the number of hopping channels must be at least 5 or 15 MHz divided by the occupied channel bandwidth (in MHz) of the equipment.

For non-adaptive FHSS equipment, the hopping frequency separation shall be equal to or greater than the occupied channel bandwidth with a minimum separation of 100 kHz.

For non-adaptive FHSS equipment with e.i.r.p. greater than 10 dBm, the occupied channel bandwidth for every occupied hopping channel shall not be greater than 5 MHz.

The Tx-sequence is defined as a period during which single or multiple transmissions may occur on the same channel. The Tx-gap is defined as the time when there are no transmissions on any of the hopping channels. Both the maximum Tx-sequence and the minimum Tx-gap time are 5 ms. The total accumulated transmission time on any channel is 15 ms, after which the equipment must switch channel. Figure 2 shows the maximum time and on/off periods an equipment can transmit on one frequency dwell.

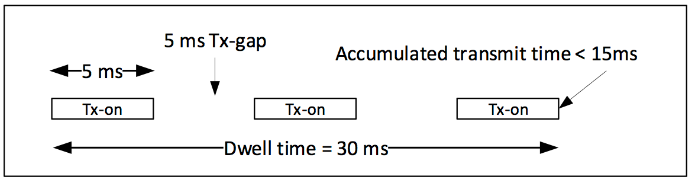

Figure 2: ETSI duty cycle, Tx-sequence, Tx-gap

2) FCC

FCC indicates that a radiator may qualify as one of the following 3 types of systems: FHSS, digital transmission system (DTS) and hybrid system.

When a radiator qualifies as FHSS, the RF transmit power is limited to 125 mW (~21 dBm) and shall have hopping channel carrier frequencies separated by a minimum of 25 kHz or the 20-dB bandwidth of the hopping channel, whichever is greater. Alternatively, in the 2.4 GHz band it may have hopping channel carrier frequencies that are separated by 25 kHz or two thirds of the 20-dB bandwidth of the hopping channel, whichever is greater, provided that the systems operate with an output power no greater than 125 mW peak. At least 15 hopping channels must be employed with a maximum dwell time of 400 ms on each of them within a period of 400 ms multiplied by the number of hopping channels. The system shall hop to channel frequencies that are selected at the system hopping rate from a pseudo randomly ordered list of hopping channels. The system receivers shall have input bandwidths that match the hopping channel bandwidths of their corresponding transmitters, and shall shift frequencies in synchronization with the transmitted signals. Incorporation of intelligence that enables the system to recognize other users of the band and to avoid occupied channels is permitted provided that the frequency hopping radiator does it individually and independently chooses or adapts its hopping sequence. The coordination in any other manner for the express purpose of avoiding the simultaneous occupancy of individual hopping channels by multiple transmitters is not permitted.

When a radiator qualifies as a DTS, the minimum 6 dB bandwidth shall be 500 kHz. The transmitter power spectral density (PSD) conducted from the transmitter to the antenna shall not be greater than 8 dBm in any 3 kHz band during any time interval of continuous transmission. Maximum transmission power is 1Watt root mean square (RMS).

FCC also specifies the regulatory requirements for a system that qualifies as a hybrid system, for which certain FHSS and certain DTS requirements apply. Recent clarifications related to the hybrid mode of operation are contained in the FCC Measurement Guidance [7]. The following is a summary of requirements imposed on a hybrid system:

- DTS requirements
  - o Max Tx power ≤ 1 Watt
  - o PSD ≤ 8 dBm/3 kHz
- FHSS requirements
  - o Dwell ≤ 0.4 seconds
  - o Channel Separation ≥ 20-dB channel bandwidth
  - o Pseudo-random hop sequence
  - o Equal use of each hop frequency
  - o Receiver matching bandwidth and synchronization

eMTC-U regulations compliance is shown in [III.E] and technical details which fulfil the regulations are described in the following section.

III. TECHNICAL FEATURES OF MF1.1 EMTC-U

A. Time/Frequency Structure

The system bandwidth of MF eMTC-U is 1.4 MHz for both the transmitter and the receiver from a capability point of view. A new frame structure is adopted for MF eMTC-U, namely FS3M, which is composed by a building block called mframe, and is structured as shown in Figure 3.

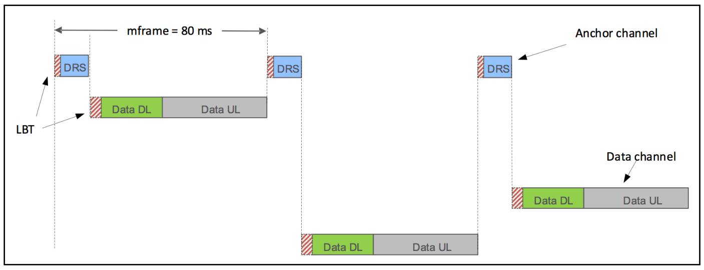

Figure 3: General Time Frequency Structure

The mframe has a fixed length of 80 ms and is composed of two time-periods: i) an anchor channel dwell of 5 ms duration and ii) a data channel dwell of 75 ms duration.

The data channel dwell may comprise of several uplink (UL) and downlink (DL) transmissions as illustrated in Figure 4. Each of the two dwells are preceded by LBT, and the data dwell always starts with a DL transmission. The LBT is based on continuous sensing during the CCA or eCCA period, as described more in details later in this section. The anchor channel dwell is always transmitted on the same frequency channel. Three anchor channel frequencies are defined in the standard and the eNB selects one of them to perform transmissions on it. As a UE performs initial acquisition, it may cycle through the defined anchor channels, attempting cell acquisition, until it detects the cell.

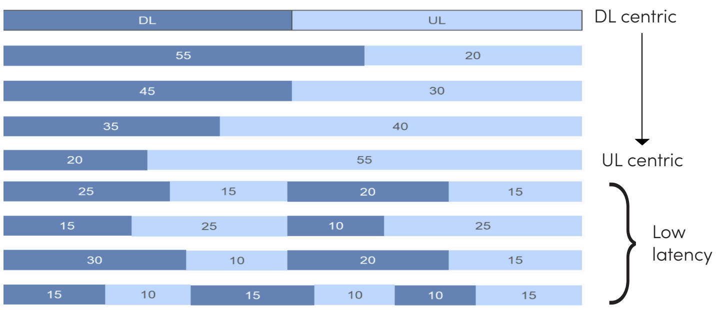

Figure 4: Allowed options for time multiplexed DL/UL transmissions during Data channel dwell.

B. Frequency Hopping Scheme

The 82.5 MHz bandwidth available within the 2.4 GHz band is split into 40 channels in groups of 4 (1.4MHz) x 10 channels for frequency hopping of the data channel. The channel spacing between hopping channels is 1.8 MHz which is wider than 1.4 MHz to comply with the FCC 20-dB channel separation requirement. The N hopping channels can be either N = 16 or 32 frequencies, which corresponds to 4 or 8 channel groups. The channel groups, which are used by the eNB, are signaled on the anchor channel. The anchor channel period dependent on the N hopping frequencies:

1. N=16 hopping frequencies => 80ms anchor channel period
2. N=32 hopping frequencies => 160ms anchor channel period

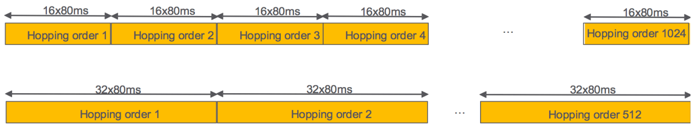

Figure 5: Hopping sequences for N= 16 and 32 hopping frequencies

The hopping sequence is the unrepeated pattern of the hopping frequencies and in the case of eMTC-U this is 8 hyperframes (81.92 seconds). The hopping sequence shall visit every channel in the sequence within one hopping cycle, where a hopping cycle is N*dwell, where N is 16 or 32 and dwell is 80 ms, denoted as hopping order in Figure 5. Hence the overall hopping sequence becomes a set of permutations of the channels in a hopping cycle. When N=32, idle periods are inserted between data channel hops when there are no DRS transmissions.

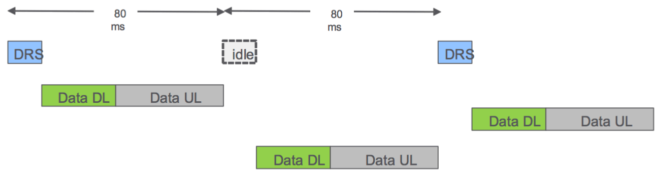

Figure 6: Illustration of idle periods when N hopping frequencies are 32

An anchor channel period of 80 ms has more overhead but can shorten initial access delay and improve battery life of UEs. On the other hand, if an application has many UEs in connected mode, a 160 ms period could be more suitable. Also, in dense deployment scenarios where initial cell access latency can be relaxed, N=32 provides less interference between intra-frequency eNB anchor channels while increasing the frequency diversity and mitigate interference on the data channel.

C. Anchor Channel

As already mentioned along this section, three anchor channels are defined in the 2.4 GHz band to avoid congestion, as one eNB utilizes only one anchor channel. Unicast data channels are not allowed on the anchor channel frequencies.
The anchor channel is used for:

- initial acquisition, through PSS/SSS/PBCH/SIB-A,

• re-establishing synchronization after a DRX period,
• acquiring the frequency hopping pattern of the cell,
• determining scheduling information (i.e., time, frequency, MCS) of the system information blocks which are not part of the anchor channel,
• indicating whether the system information has changed through a system information value tag,
• indicating whether the UE will be paged in the next upcoming paging occasion,
• indicating parameters related to the LBT used to initiate the data channel transmissions,
• indicating the pattern for UL/DL transmissions to be used for the data channel transmissions (as shown in Figure 4).

The anchor channel transmission (Figure 7) has a duration of up to 5 ms and consists of three parts: the first part is used for LBT, the second part is used for transmission of synchronization signals and MIB, and the third part is used to transmit SIB-A which containing essential system information. Prior to starting LBT, sometime is reserved in the 5 ms period for switching channels. The LBT is performed according to the regulatory rules imposed on an adaptive frequency hopping equipment, which is provided in ETSI EN 300 328.

If an initial CCA of 18us succeeds, then the transmission starts at time T_0+ 2 OS (OFDM symbols).. If the initial CCA fails, then the eNB performs an eCCA with a minimum duration randomized in the range of 18us < eCCA length < 193 us. The eCCA sensing is done immediately prior to T_0+ 1 ms + 2 OS, at which point an anchor channel transmission with shorter duration starts. Note that the time reserved for eCCA (1 ms) is much longer than the actual sensing, due to the fixed 1 ms frame-structure and to align with the OS boundary. The anchor channel transmission can thus take on two different durations depending on when the LBT clears, which affects the duration of the SIB-A transmission causing it to be transmitted with fewer physical channel bits, i.e. using a higher code rate. However, even if the transmission starting point is delayed due to eCCA, the subframe scrambling is not modified. Thus, the UE cannot determine which of the starting points were used by detecting different scrambling of the initial subframe.

Instead, the length of SIB-A transmission is explicitly indicated to the UE by signaling it in the MIB. The UE can then determine which of the starting points were used so that it can set a correct timing for the end of the transmission and start of the next frequency dwell.

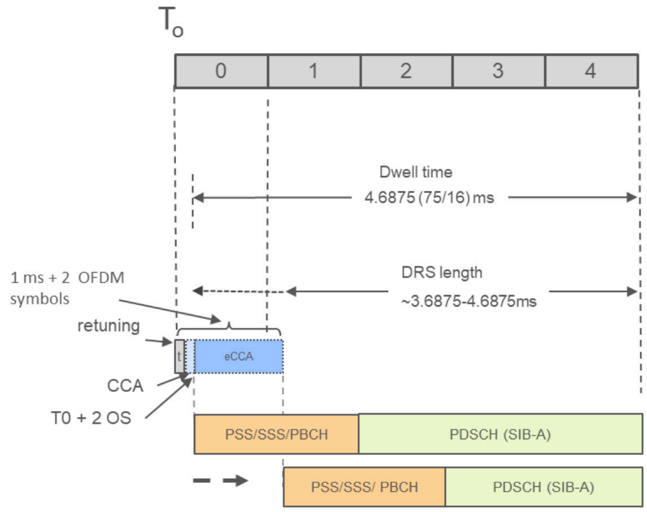

Figure 7: Anchor channel time domain structure.

1) PSS/SSS/ PBCH

The physical structure and position of the eMTC-U PSS/SSS/PBCH symbols within an anchor channel are shown in Figure 8. In eMTC-U additional PSS and SSS signals similarly as for MF1.0 and MF1.1 WCE, are transmitted for a total of 4 PSS OS, and 4 SSS OS per anchor channel.

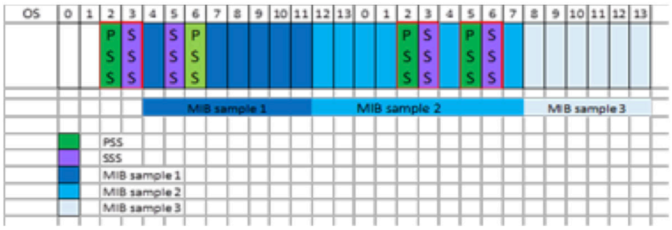

Figure 8: PSS/SSS/PBCH

To facilitate one-shot decoding and to achieve the required coverage levels, the PBCH utilizes 18 OFDM symbols. OSs of the anchor channel dwell, where the transport channel bits are encoded into 896 physical channel bits on 6 OFDM symbols which are then repeated three times.

2) MIB/SIB-A

Given the limited dwell duration on the anchor channel only the essential information required for efficient cell access, as shown in Table 2, is transmitted on it by forming a new SIB, namely

SIB-A, while all other system information blocks are transmitted on the data channels. The full content of the master information block (MIB) and SIB-A are summarized in Table 2.

	Anchor channel content	Length
MIB	schedulingInfoSIB1-BR	5
	System Frame Number	7
	Subframe Offset	1
	SIB-A TB size	1
	Spare	10
	Total	24
SIB-A	systemInfoValueTag	5
	Channel List	14
	HyperFrame	3
	Paging Indication	1
	UL/DL valid configuration	3
	PD-RS Window size	4 or 12
	Total	32 or 40

Table 2: MIB/SIB-A content

3) Cell Search

An eMTC-U cell is configured with one of the UL/DL configurations illustrated in Figure 4, selects an anchor channel frequency to use and a set of N data hopping channels. The anchor channel frequency can be selected based on the interference detected on each of the 3 possible frequencies.

For initial cell search, the UE selects one of the anchor channel frequencies and starts searching for the anchor channel, while for re-synchronization the UE may choose the last known frequency. The steps that are performed for cell search are like those followed in 3GPP design:

1. Detect PSS/SSS
2. Read BCH/SIB-A
3. Determine the FH sequence and the location of the next data channel dwell
4. Read SIB1-BR (i.e., cell barring info, and PLMN ID)
5. Access cell using RACH, while reading the remaining system information

D. Data Channel

The data channel transmission starts with a CCA procedure to ensure there are no other ongoing transmissions. The DL COT is counted as an absolute time from the start of transmission after CCA/eCCA success until the last defined DL subframe in the UL/DL mframe configuration. For the CCA, the first energy detection must span at least 0.2% of the DL COT and ranges from 40 us to 120 us are possible, depending on the UL/DL configuration. Subsequent eCCAs must at least be 5% of the DL COT and ranges between 1-3 ms.

The benefit of having such a flexible channel access mechanism is to offer higher probability to gain access in high interference environments.

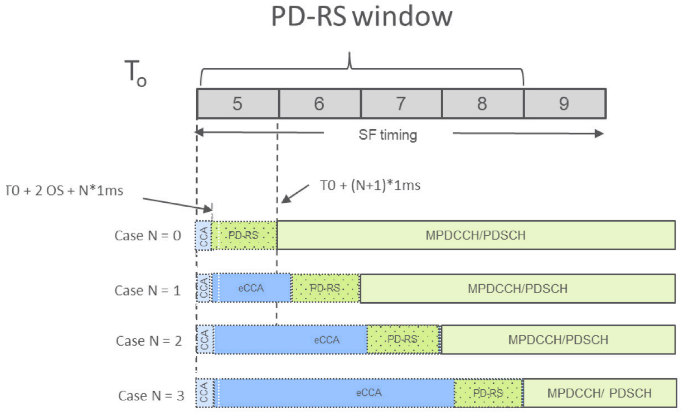

Figure 9: Data channel transmission timing

1) Downlink Data

The presence detection reference signal (PD-RS) is used to provide the UE with a reliable method for detecting the presence of the downlink data segment transmissions. If the presence signal is not detected, the UE may still transmit on the uplink time resources, for instance, PRACH or UL grants from the previous mframe. The performance target for the PD-RS is: 0.1%, false alarm, and 1% mis-detection. If CCA is successful, 12 symbols of PD-RS are transmitted giving an SINR of -5.6 dB which meets coverage requirements for eMTC-U.

PDCCH and PDSCH channel design are borrowed heavily from the Rel-13 eMTC design. CE Mode A repetition levels are used to reach the desired coverage levels. To reduce design complexity, a DL transaction composed of PDCCH and PDSCH are contained in one mframe.

2) System Information

SIB1-BR is scheduled at the beginning of the dwell on consecutive subframes and its periodicity is signaled in MIB. Like 3GPP legacy-eMTC, eMTC-U contains the fixed schedule for the remaining SIBs and is scheduled in a MPDCCH-less manner. DL subframes without system information are considered valid for DL unicast data. Subframes in the UE search space or unicast PDSCH subframes, which collide with system information, are skipped without reducing the number of subframes. The various SIB1-BR configurations are shown in Figure 10.

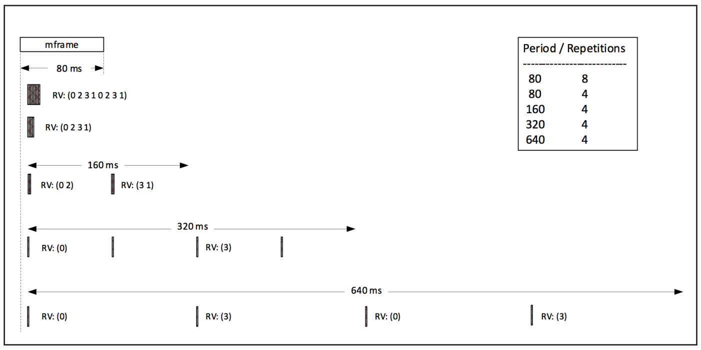

Figure 10: SIB1-BR transmission schedules

3) DL Scheduling

MPDCCH or SIBx on PDSCH follows the SIB1-BR transmissions in the DL data segment. The timing between MPDCCH and PDSCH follows that of legacy 3GPP eMTC (i.e. PDSCH is transmitted in subframe, n+2, where MPDCCH is transmitted in subframe n) where the UL SFs and SFs which contain system information are skipped. Due to the longer frame structures than in 3GPP, larger offsets up to 15 subframes can also be signaled. PDSCH scheduling in the next DL duration within the same dwell is allowed. While the MPDCCH/PDSCH can cross switching points within a dwell, it cannot span across frequency hops since an LBT would be required to continue transmissions in the subsequent dwell. Like eMTC CE Mode A, MPDCCH and PDSCH support repetitions of up to 16 and 32 subframes respectively. Certain mframe configurations contain 55 DL subframes to handle such transmissions.

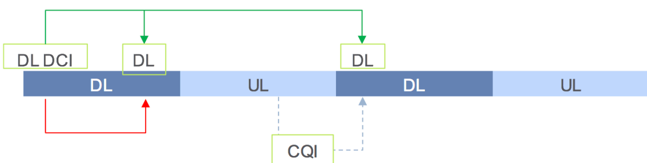

Figure 11: DL scheduling

The number of HARQ (Hybrid Automatic Repeat) processes follows 3GPP Rel-14 capability which supports of up to 10 HARQ processes. At initial access the UE can assume transmission with 2 HARQ processes.

4) Random Access

Due to the limited cell sizes in eMTC-U, only PRACH (Physical Random Access Channel) Format 0 is supported. A single RACH subframe transmission is sufficient to satisfy the basic MCL target of 130 dB when ETSI regulatory requirements must be followed. However, this is more challenging when instead the FCC regulatory requirements must be satisfied, since in this case the Tx power limit is 36 dBm, which the eNB can exploit leading to an imbalance between the UL and DL Tx powers. Hence, to compensate for the imbalance, 2 subframe transmission of the PRACH preamble is supported. An eNB configures either one or two PRACH subframe transmission in the cell.

The RAR (Random Access Response) window starts at the first subframe of the subsequent DL duration and can be up to 400 ms long, which is the same as legacy eMTC. With a window of 400 ms, the eNB can perform up to 5 LBTs and have 5 mframes to schedule the RAR response.

5) Uplink Data and Scheduling

Uplink transmissions do not require an LBT procedure. Like legacy 3GPP eMTC CE Mode A, 8 HARQ processes are supported. PUCCH transmissions can support up to 8 repetitions, while PUSCH transmission can be performed with up to 32 repetitions. Certain mframe configurations contain 55 UL subframes to handle such PUSCH transmissions. Data transmissions already incorporate the frequency diversity from the overall frame structure design, and for the sake of simplification, PUCCH frequency switching between slots is not specified.

UL supports non-adaptive transmissions with a maximum of 6 RBs and is adapted to satisfy the ETSI regulatory requirements according with the Tx-on time of 5 ms is followed by a 5 ms gap. The UL durations are divided into 2 sets of UL subframes as shown in Figure 12, which define two UL resource sets. The purpose of this is to ease the scheduling while meeting regulations. A UE which starts PUCCH or PUSCH transmissions in one resource set can only continue its repetitions in the same resource set, which is allocated in compliance with the 5 ms on/off Tx rules dictated by ETSI. To have a regional agnostic solution, the concept of resource sets is also utilized in regions that must comply with the FCC regulation, where such restrictions do not apply.

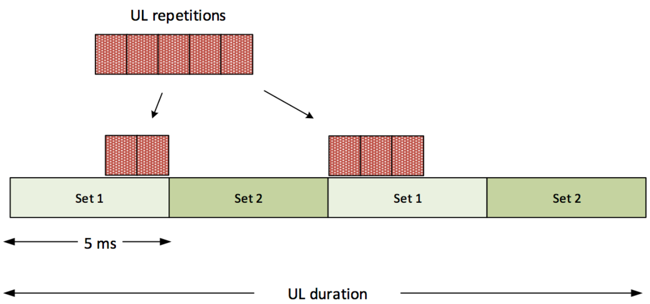

Figure 12: UL resource sets

Unlike DL transmissions, PUSCH transmissions can cross the dwell to the next frequency since UL transmissions are not dependent on LBT success. MPDCCH in one dwell can schedule the PUSCH in the next dwell. PUSCH starts k SFs from after the last SF of MPDCCH repetitions, where k is greater or equal to 4.

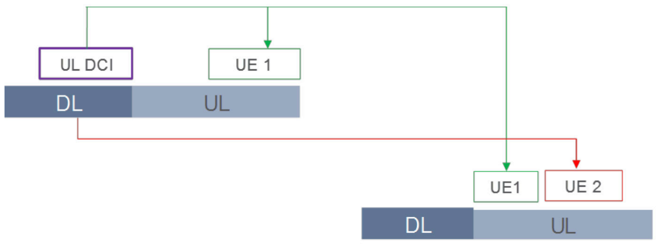

Figure 13: UL scheduling

6) Uplink Control Information

In eMTC-U, UCI functionality like legacy 3GPP eMTC is supported. That is:

1. Sounding Reference Signal (SRS)
2. HARQ ACK/NACK
3. Channel Quality Indicator (CQI)

These UCI functionalities are adapted to the time domain frame structure and frequency hopping capability of the system. PUCCH Formats 1/1a/2/2a/3 are supported. Both periodic and aperiodic SRS modes are supported. SRS period can be from 5 to 320 ms, and it is in subframes *n* where (*n* mod 5) = 4. SRS structure follows that of legacy 3GPP LTE for 1.4 MHz of 4 RBs where the SRS occasions override PUSCH transmissions. As aforementioned, 10 HARQ processes are supported, and considering the 80 ms mframe structure with long DL durations, there is a need to support ACK/NAK formats of up to 10 bits. PUCCH format 3 allows multiplexing HARQ ACK/NACK feedback for up to 10 DL HARQ processes. The UL efficiency is of importance since there are limitations such as the 5ms Tx-on time as well as a 10% duty cycle, which each UE must comply.

7) Link Adaptation

Link adaptation is an important aspect of eMTC-U as it gives it an advantage compared to other IoT technologies. The link adaptation framework from legacy 3GPP eMTC is re-used, and then further developed to support a system which operates in frequency hopping mode. Two general strategies are taken: i) obtain the link quality of a set of frequencies contained in the frequency channel list, and ii) obtain the link quality of the UE on the present channel.

The 16 or 32 data channels used can be portioned into narrowband groups of 4, 8, 16 or 32 channels and a periodic link quality report can be requested for each narrowband group. The benefit of this is that it allows the eNB to select frequencies which have the best link quality for its DL data transmissions (frequency selective scheduling), since UEs in certain parts of the cell may be experiencing interference in different parts of the 2.4 GHz band.

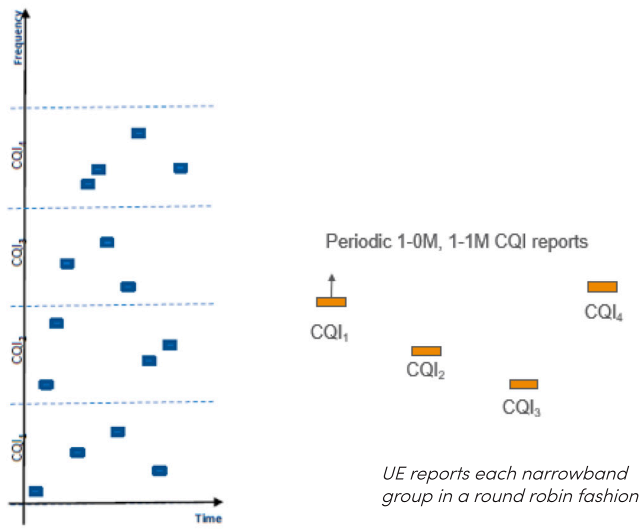

Figure 14: Periodic narrowband CQI measurements

Also supported is a single frequency CQI report on the current data dwell, which allows fast adaptation to the channel condition. This can be used effectively with mframe configurations with more than one switching point, as illustrated in Figure 15. The benefit for this type of link adaptation is to ensure optimal MCS selection, which improves spectral efficiency.

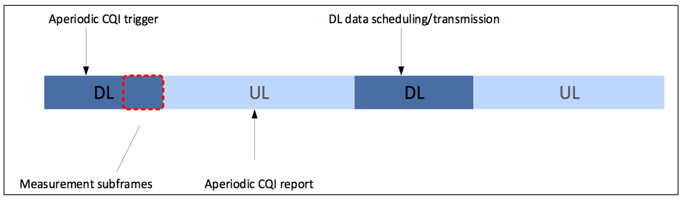

Figure 15: Aperiodic single frequency CQI report timing

8) Radio Link Monitoring

Radio link monitoring (RLM) is a function designed to check whether the radio link to the serving cell is good enough and if not, the UE can declare radio link failure (RLF) and attempt to re-establish the RRC connection. For eMTC-U, RLM has been adapted to the mframe structure and uses the subframes in the anchor channel as well as subframes in the frequency hopping data channels.

The anchor channel must always be transmitted by the eNB pending a successful LBT procedure. Thus, the UE can assume poor radio link quality when the actual measurement indicates poor Q value. RLM measurements on the anchor channel can be used for both Qout and Qin measurements.

Data channel are transmitted only when there is valid data to transmit, like system information or unicast data to scheduled UEs. This is to ensure good co-existence in the 2.4 GHz band. The UE must first detect the PD-RS before performing receptions, and RLM evaluations. Since the UE reliability to detect the PD-RS deteriorates in lower SINR regions, where Qout could be declared, the data channel is only used for evaluating Qin.

The Q_{in} assessment interval is every mframe (80ms). The Q_{out} assessment interval is every DRS period, which is 80 ms for N=16 and 160 ms for N=32.

E. Regulations Compliance

Now that the regional regulations and the system design have been described in previous sections, in this section summaries how eMTC-U fulfills the ETSI harmonized standard and FCC regulations.

Requirement	eMTC-U UE	eMTC-U eNB	ETSI Compliance
RF output power (dBm)	20 dBm	20 dBm	≤ 20 dBm
Hopping Frequency Separation (MHz)	1.4 MHz	1.4 MHz	≥ 100 kHz
Medium Utilization (MU) factor	10%	NA	≤ 10% @ 20dBm
Occupied Channel Bandwidth (MHz)	1.4 MHz	1.4 MHz	≤ 5 HMz
Adaptivity (Adaptive FHSS)	Non-Adaptive	LBT based DAA	
Tx COT	NA	< 60 ms	< 60 ms
Hopping Frequencies	N=16,32	N=17, 33	N> N_{min} =11[15 MHz/1.4 MHz]
ATT (ms) non-adaptive	15 ms	NA	< 15 ms per 165 ms Observation period: (15*N_{min})
ATT (ms) adaptive	NA	Anchor: 275 ms per 4.4 s	<400 ms per 4.4 seconds, Observation period: (400*N_{min})
Frequency Occupation (visits to a frequency)	4 visits per 5.12 s, N=16 10.24 s, N=32	Anchor: 275 ms per 4.4 s Data: 206 ms per 4.4 s	At least 1 visit every 4*dwell*N N=16, 17=>5.12s N=32, 33=>10.24s
		5.12 s. N=16 10.24 s, N=32	
Tx-sequence (ms)	5 ms	NA	≤5ms
Tx-gap (ms)	5ms	NA	≥5ms

Table 3: ETSI compliance

Table 4: FCC Compliance

IV. PERFORMANCE OF MF1.1 EMTC-U

A. Coverage

The coverage targets for MF eMTC-U is MCL 140 dB in FCC and 130 dB in ETSI. The link budget for MF eMTC-U is shown in Table 5 and Table 6, respectively.

MF eMTC-U FCC							
Physical channel name	**PUCCH**	**PRACH**	**PUSCH**	**PDSCH**	**PBCH**	**SCH**	**MPDCCH**
Data rate(kbps)							
Transmitter							
Max Tx power (dBm)	20	20	20	30	30	30	30
(1) Actual Tx power (dBm)	20,0	20,0	20,0	30,0	30,0	30,0	30,0
(2) Antenna Gain (dB)							
Receiver							
(2) Thermal noise density (dBm/Hz)	-174	-174	-174	-174	-174	-174	-174
(3) Receiver noise figure (dB)	5	5	5	9	9	9	9
(4) Interference margin (dB)	0,0	0,0	0,0	0,0	0,0	0,0	0,0
(5) Occupied channel bandwidth (Hz)	180000	1080000	1080000	1080000	1080000	1080000	1080000
(6) Effective noise power							
= (2) + (3) + (4) + 10 log((5)) (dBm)	-116,4	-108,7	-108,7	-104,7	-104,7	-104,7	-104,7
(7) Required SINR (dB)	-3,5	-11,4	-11,4	-5,3	-5,3	-5,3	-5,3
(8) Receiver sensitivity							
= (6) + (7) (dBm)	-119,9	-120,1	-120,1	-110,0	-110,0	-110,0	-110,0
(9) MCL							
= (1) + (2) - (8) (dB)	**139,95**	**140,07**	**140,07**	**139,97**	**139,97**	**139,97**	**139,97**

Table 5: Link budget for eMTC-U in FCC regions

MF eMTC-U ETSI							
Physical channel name	PUCCH	PRACH	PUSCH	PDSCH	PBCH	SCH	MPDCCH
Data rate(kbps)							
Transmitter							
Max Tx power (dBm)	20	20	20	20	20	20	20
(1) Actual Tx power (dBm)	20,0	20,0	20,0	20,0	20,0	20,0	20,0
(2) Antenna Gain (dB)							
Receiver							
(2) Thermal noise density (dBm/Hz)	-174	-174	-174	-174	-174	-174	-174
(3) Receiver noise figure (dB)	5	5	5	9	9	9	9
(4) Interference margin (dB)	0,0	0,0	0,0	0,0	0,0	0,0	0,0
(5) Occupied channel bandwidth (Hz)	180000	1080000	1080000	1080000	1080000	1080000	1080000
(6) Effective noise power							
= (2) + (3) + (4) + 10 log((5)) (dBm)	-116,4	-108,7	-108,7	-104,7	-104,7	-104,7	-104,7
(7) Required SINR (dB)	6,5	-1,5	-1,5	-5,3	-5,3	-5,3	-5,3
(8) Receiver sensitivity							
= (6) + (7) (dBm)	-109,9	-110,2	-110,2	-110,0	-110,0	-110,0	-110,0
(9) MCL							
= (1) + (2) - (8) (dB)	**129,95**	**130,17**	**130,17**	**129,97**	**129,97**	**129,97**	**129,97**

Table 6: Link budget for eMTC-U in ETSI regions

B. Link Performance

The performance of the anchor channel containing the SCH, PBCH and the PDSCH containing SIBA are critical for achieving the desired coverage level target.

Figures are requested by companies on the performance.

The performance of the channels on the data segment can typically be scaled dependent on the current coverage level and corresponding repetition level of the UE. MF eMTC-U follows eMTC CE Mode A in terms of repetition levels and the performance is listed in Table 7.

Data Channel	Allowed repeats	Repeats at Coverage Target (ETSI)	Repeats at Coverage Target (FCC)	Reference
MPDCCH	16	8(2)	8 (2)	mf2018.880, (Figure, 4, [3])
PDSCH	32	8(5.7 kbps)	8 (5.7 kbps)	mf2017.1044 (152 bits)
PUSCH	32	2 (47.3 kbps)	32 (6.3 kbps)	R1-153997 (504 bits)
PUCCH	8	1	2-4	Figure 8 [3], mf2017.1003, R1-152506
PRACH	2	1	2	R1-152282, R1-152233

Table 7: Link Performance summary

C. Data Rates

Like 3GPP eMTC, MF eMTC-U offers an instantaneous peak rate of 1 Mbps in both the uplink and downlink. In practical terms we need to consider the scheduling scheme and limitations in the frame structures to see what the sustainable data rate is possible.

For the downlink with 10 HARQ processes, TBS size of 1000 bits, and in good coverage where no repetitions are needed, MF eMTC-U can deliver a sustained max rate of 350 kbits per second [Figure 16].

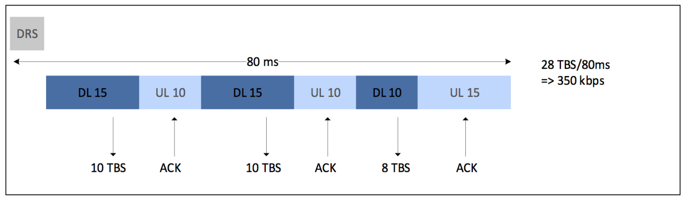

Figure 16: Max sustained DL data rate

Of course, data rates diminish at the cell edge and here we can choose a frame configuration which is optimized for deep coverage. At the MPL target in ETSI/FCC, which gives an SINR target of -5.3 dB for PDSCH requires 8 repetitions of 152 bits. Given the frame structure shown in Figure 16, 3 TBS of 152 bits each repeated 8 times can be delivered in 80ms which corresponds to 5.7 kbps.

Observation: DL data rates can range from 5.7 kbps to 350 kbps.

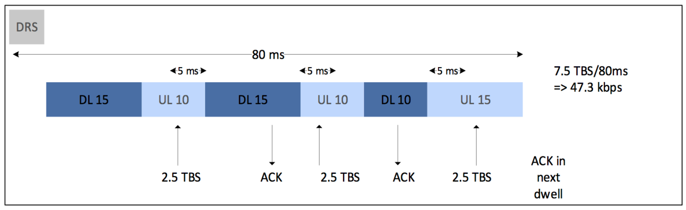

Figure 17: UL data rate for ETSI at cell edge

For the UL data rate with 8 HARQ processes, a maximum TBS size of 1000 bits can be used in good coverage where no repetitions are needed, and a sustained data rate of 200 kbps can be achieved in FCC and 187 kbps in ETSI, due to the accumulated transmission limitation on a single frequency of 15ms.

At the cell edge in FCC with an SINR target of -11.4 dB for PUSCH requires 32 repetitions of 504 bits. We can deliver 7.5 TBs with size 504 bits in 80 ms using 8 HARQ processes repeated 2 times. This give a corresponding UL data rate of 47.3 kbps.

Region	Direction	Coverage	Repetition x TBS Size	TBS/80 ms	Data Rate (kbps)	
FCC	Uplink	Good	1 x 1000	16	200	
		Cell Edge	32 x 504	1.7	10.8	
	Downlink	Good	1 x 1000	28	350	
		Cell Edge	8 x 152	3	5.7	
ETSI	Uplink	Good	1 x 1000	15	187	
		Cell Edge	2 x 504	7.5	47.3	
	Downlink	Good	1 x 1000	28	350	
		Cell Edge	8 x 152	3	5.7	

Table 8: Data Rates Summary

D. Latency

The use case for measuring latency is defined in [6] by 3GPP which entails the UE waking up, synchronizing to the cell and delivering a 20-byte packet of application data to the network. The results are summarized in Table 9. The 5G target for latency is 10 seconds [4] at 164dB MCL. It can be seen in Table 9 that eMTC-U has excellent latency characteristics while supporting the multiplexing of several users.

UE Activity	Latency in good coverage		Latency at the cell edge	
	FCC	ETSI	FCC	ETSI
Cell Synchronization	50	50	370	370
Random Access Procedure	115	115	295	215
UL data delivery	80	80	305	190
Total	245	245	970	775

Table 9: UE Latency

Action	Channel	Latency (ms)		
		Good	Cell Edge (FCC)	Cell Edge (ETSI)
Initial wait for the DRS (0-80ms)		40	40	40
Synch, decode PBCH, SIBA,no change in SIBA: PSS/SSS/PBCH/PDSCH	PSS/SSS /PBCH/SIBA	10	10 + (4 x80)	10 + (4 x80)
Preamble	PRACH F0	10	10	10
DL assignment	MPDCCH	15	20 (8 reps+2)	20 (8 reps+2)
RAR (includes UL grant)	PDSCH		20 (8 reps)	20 (8 reps)
RRC Connection resume request	PUSCH	10	60 (32 reps)	10 (2 reps)
DL assignment	MPDCCH	10	8+2	8+2
RRC Connection resume + RA cont. res.	PDSCH		8	8
HARQ ACK (for msg4)	PUCCH	15	10	15
UL grant	MPDCCH	10 (1 rep)	10 (8 reps)	10 (8 reps)
RRC Connection resume complete (+ RLC ACK msg4)	PUSCH	10	60 (32 reps)	10 (2 reps)
DL assignment	MPDCCH	15	20 (8 reps+2)	20 (8 reps+2)
RLC ACK for msg5	PDSCH		20 (8 reps)	20 (8 reps)
HARQ ACK	PUCCH	10	10	10
N x UL grant(s)	MPDCCH	10	15 (8 reps)	15 (8 reps)
N x UL data	PUSCH	15	120 (2x32reps)	10 (2 reps)
Wait time, reading NPDCCH	MPDCCH	10	40	40
N x DL assignment(s)	MPDCCH	5	20 (8+2)	20 (8+2)
N x DL data (+ RLC ACK for msg6)	PDSCH		20 (8)	20 (8)
N x HARQ ACK (for msg7)	PUCCH	10	15	10
Uplink grant	MPDCCH	15	10	15
RLC ACK for msg7	PUSCH	10	60 (32 reps)	10 (2 reps)
DL assignment	MPDCCH			
RRC Connection Release	PDSCH			
HARQ ACK	PUCCH			
Uplink grant	MPDCCH			
RLC ACK for msg8	PUSCH			

Table 10: Latency calculations (To be removed)

V. FUTURE EVOLUTION

Since the design of eMTC-U is based on 3GPP Rel-13 eMTC technology, adopting features from later releases of 3GPP as the market evolves is relatively straight forward. The eMTC-U design can also be easily adopted to the 26 MHz available in the FCC 902-928 band with 16 data hopping channels and 1 anchor channel.

VI. CONCLUSION

eMTC-U design is based on proven 3GPP eMTC technology, adapted to the 2.4 GHz global band using LBT and frequency hopping, providing a competitive blend of the key KPI's required in the IIoT market space. It is a new RAT when compared with MulteFire 1.0, but both have common e2e architecture and core networks. It extends the MBB use case supported by MulteFire 1.0 into the important IoT use case which require low cost devices, high device densities and improved coverage. Verticals such as Factory Automation and Asset Management are directly addressed with this technology without requiring network specialists for installations or the network deployment.

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GLOSSARY OF TERMS

3GPP – Third Generation Partnership Project

AGV – Automated Guided Vehicle

ATT - Accumulated Transmit Time

CBRS – Citizens Broadband Radio Service

CCA – Clear Channel Assessment

CE – Coverage Extension

COT – Channel Occupancy Time

CQI – Channel Quality Indicator

DAA – Detect and Avoid

DC – Duty Cycle

DRX – Discontinuous Reception

DTS - Digital Transmission System

e2e – End to End

eCCA – enhanced CCA

eLAA – enhanced License Assisted Access

eMTC – enhanced Machine Type Communications

eNB – eNodeB

ETSI - European Telecoms Standards Institute

FCC - Federal Communications Commission

FHSS - Frequency Hopping Spread Spectrum

HARQ – Hybrid automatic repeat request

IIoT Industrial IoT

IoT – Internet of Things

LAA – License Assisted Access

LBT – Listen Before Talk

MCL – Maximum Coupling Loss, equivalent to maximum conducted power

MCOT – Maximum Channel Occupancy Time

MCS – Modulation Coding Scheme

MIB – Master Information Block

MPDCCH – eMTC Physical Data Control Channel

MPL – Maximum Path Loss, equivalent to e.i.r.p.

MU – Medium Utilization

NHN – Neutral Host Network

PBCH – Physical Broadcast Channel

PD-RS - presence detection reference signal

PDSCH - Physical Data Shared Channel

PLMN – Public Land Mobile Network

PLMN Id - public land mobile network identity

PRACH – Physical Random Access Channel

PSD - Power Spectral Density

PSS – Primary Synchronization Channel

QoE – Quality of Experience

RACH - Random Access Channel

RAR – Random Access Response

RAT – Radio Access Technology

RLF – Radio Link Failure

RLM – Radio Link Monitoring

RMS - Root Mean Square

SF - Subframe

SFN – System Frame Number

SIB – System Information Block

SIB-A - System Information Block A

SRS Sounding Reference Signal

SSS - Secondary Synchronization Channel

UE – User Equipment

WB - WideBand