Relaying in Long Term Evolution: Indoor Full Frequency Reuse

V. Venkatkumar[1], T. Wirth and T. Haustein
Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut,
Einsteinufer 37, D-10587 Berlin, Germany.
Email: venkat.kumar@hhi.fraunhofer.de

E. Schulz
Nokia Siemens Networks GmbH & Co.KG,
St. Martinstraße 53, 81617 Munich, Germany.

***Abstract*—Future cellular wireless networks could include multihop transmissions through relays. For LTE-Advanced networks multihop relaying is one of the candidate enabling techniques for coverage extension. In particular, relaying is envisioned for indoor coverage, such as in office and residential buildings. In this approach, a wireless relay is placed inside a building in order to reduce the building penetration path loss. A relay could perform analog signal amplification or decode and forward operation. Decode and forward operation is advantageous in the sense that a relay can employ full reuse of the bandwidth. The re-used bandwidth could also be used efficiently by independent link adaptation. This paper reports measurement results of state of art direct link and indoor decode and forward relaying in LTE downlink. Relaying has been implemented in a real-time test-bed with enabling transceiver techniques such as half-duplex interference suppression and IP packet forwarding. The relay test-bed reuses the full 20 MHz bandwidth with frequency dependent link adaptation. Field trial measurements are performed in a single cell single user indoor office scenario with one relay. Results show that indoor LTE relaying is capable of delivering high throughput above 60 Mbps, with a spectral efficiency of 3 bits/s/Hz. It also provides 16 Mbps to locations well inside the building which is seen to be more dramatic.**

I. Introduction

The finalisation of the 3GPP Long-Term Evolution (LTE) standard [8] is almost complete. New features such a MIMO-OFDM, frequency dependent scheduling are exepced to increase the link capacity in LTE systems significantly. The first multi-user field trial results of LTE downlink were conducted by Heinrich Hertz Institut (HHI) and Nokia Siemens Networks (NSN) at Berlin in October 2007 [5]. These field results were conducted after the single user indoor and outdoor measurements in [4]. Outdoor measurement runs validated throughput results exceeding 120 Mbps in a practical 2x2 MIMO system. Inspite of the tremendous improvement over existing WCDMA cellular systems, an open issue for the upcoming OFDM systems are the so-called coverage holes. These are typically areas in a cell where the link capacity is markedly lower.

LTE-Advanced [9], the evolutionary step of LTE has to meet the International Telecommunication Union (ITU) requirements [10] for fourth generation systems (4G). One of the latest requirements by ITU is a cell spectral efficiency of 3 bits/s/Hz/cell indoors [10]. In view of the requirement, LTE-Advanced [9] has been working on solutions to improve indoor coverage in office and residential buildings. Moreover, for future practices, a user-centric cellular system such as 4G would somehow have to ensure ubiquitious indoor coverage .

In interference coordination cells, coverage holes mainly occur because of low signal power. In a typical coverage spot with sufficient signal power, multiple-input multiple output (MIMO) technology [1] enables efficient utilisation of spatial multiplexing. However, in case of a coverage hole, low signal power not only limits link adaptation but also multiplexing mode selection [4], [6]. Low signal power is usually a result of non line of sight reception caused by material obstacles and building penetration loss. For example, indoors, modern window coatings orginally designed for thermal insulation cause severe additional pathloss between base station and user equipment. Previous measurements have shown that with a limited received peak power, frequency dependent link adaptation is not sufficient to alleviate the problem of coverage holes [4]. More improvement is needed. We wish to provide such an improvement via closed-loop broadband MIMO relaying.

In the considered relay deployment, an indoor relay is used in full decode and forward (DF) operation for downlink coverage inside a building. Because of insulation of the building to outdoors, the relay generated interference is isolated from the adjacent macro-cells. A DF relay can exploit this situation and reuse the entire bandwidth for forwarding. In LTE implementation, an operator could spatially reuse the allocated 20 MHz spectrum bandwidth with an indoor relay.

Relay based networks have been the subject of investigation over the last few years. Outdoor and indoor deployments concepts are proposed in [2]. In the European WINNER project [7], in-depth system level investigations have been performed. The study reports promising results with relay deployment in cellular networks. For instance, in the indoor case, relaying improves the 5 percentile by 3 dB and cell edge throughput is increased by 50 percent [7].

Our main contribution to these promising studies is to implement an spectrally efficient, 2x2 MIMO multi-hop test-bed [3] which is able to handle real-time media delivery. We conduct measurements with the developed test-bed. The measurements look at the basic but paramount question: will relaying enable pervasive wireless access to an indoor user ?

Secondly, we wish to identify practical deployment locations, and where and how a relay could be deployed. We

1. Venkatkumar is a PhD student with CTME, Victoria University, Melbourne, Australia.

conduct measurement runs in the selected indoor scenarios.

II. System Design

We first brief the system level aspects of decode and forward relaying and the implications of relay deployment to a macro base station scheduler. The system level briefing points out the design flexibility available from decode and forward approach. Results in the paper are however limited to a single user case.

A. Transmission Scheme

The time-frequency tiling for the OFDM downlink at base station is shown in **Fig. 1**. The radio-frame structure is divided into two types: relaying radio-frames and direct transmission radio-frames. Relaying radio-frame is further subdivided for base station to relay first hop and relay to UE second hop. A cellular network could comprise of users with either a good link connection to a base station, or to a nearby relay. Users with good connection to a base station are admitted to the direct transmission time slots (DTS) belonging to direct transmission radio-frames.

Users with only weak connection to the base station are required to identify a nearby relay node. Such users are admitted to the relay transmission slots. The relaying mechanism is two time-slot based within a radio-frame because of half duplex constraint. In first hop time slots (FHTS), the hop from base station to relay node is realised. In second hop transmission time slots (SHTS), the hop from relay node to user equipment is made. The relay works in a full decode-and-forward mode. The entire bandwidth is utilised in the relay transmission slots. Macro base station avoids interference situation with the relay by not transmitting during SHTS. Furthermore, it is possible that some frequency subcarriers in FHTS are not utilised for relays. Those vacant subcarriers in FHTS could used for direct transmission to base station affiliated users.

B. Rate Pulling

The bit-loading, link adaptation and multi-user scheduling in relay time-frequency slots are based on a so-called rate pulling mechanism. By this mechanism, the set of users under a relay cluster are required to place a service rate demand to the relay. The relay in turn passes on the demand to the base station, which is the only node connected to the internet gateway. In this way, relay time slots are utilised for fulfilling the user rate objective. The relay rate demand is required to be served by the base station to the relay node. The base station uses its transmission time slots i.e, FHTS, to cater for relay's demand. Because of this mechanism, the number of relay time slots is not necessarily fixed but a variable of the user rate demand.

III. Relaying Concept

The link level relay concept is depicted in **Fig. 2**. By itself, the base station is able to deliver data to a user equipment over a useful bandwidth B_1 using transmit power P_o. Useful bandwidth is characterised as one in which minimum modulation and coding (MCS) is loadable for a guaranteed packet error rate. On the other hand, the total available bandwidth for any of the three nodes in the relay network is B.

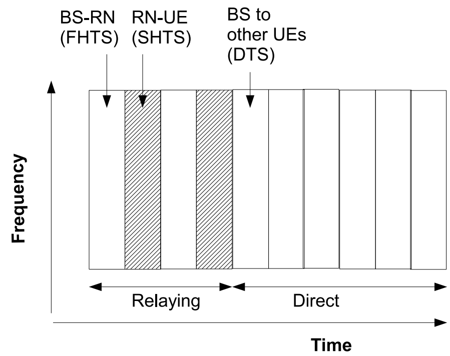

Fig. 1. FDD Multihop Radio-Frames: FHTS- First hop transmission slots, SHTS- second hop transmission slots, DTS- direct transmission slot. BS - base station, UE - User Equipment, RN - Relay Node.

The user equipment is indoors, therefore the direct link from base station is weak. As a result the useful bandwidth is small for direct link. A relay node is placed suitably to employ decode and forward operation in two time slots. In first time slot, the relay fully decodes the packets. In second time slot, relay delivers data to user equipment. The relay transmitter is placed indoors and relay transmit power $P << P_o$ and therefore the interference caused by relay node to other cells outside is minimal. The pathloss from relay to user equipment is less and therefore the useful bandwidth for relay is high. Relay node exploits the dual advantage and re-transmits over the full bandwidth B.

The presence of indoor relay simultaneously increases availability of bandwidth and signal power for user equipment. The increased signal power is used for polarisation multiplexing. In polarisation multiplexing, all three nodes, base station, relay node and user equipment employ cross polarisation. The base station delivers data to relay node over a bandwidth B_2. The BS used bandwidth B_2 could be less than relay used bandwidth B because of higher spectral efficiency of base station to relay link.

IV. Measurement Test bed

A. Baseline System

The planning of physical parameters of the experimental test-bed according to the new 3GPP-LTE air interface was

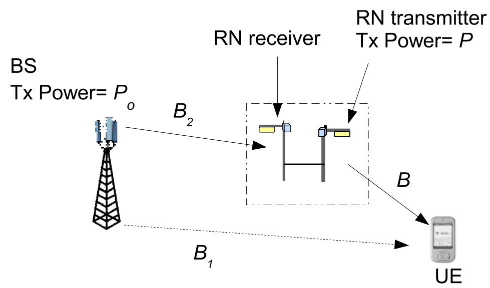

Fig. 2. Relay deployment concept : RN - Relay Node, BS - Base Station, UE - User Equipment. B_1 - direct link bandwidth, B_2 - feeder link bandwidth, B - full bandwidth for relay

completed during the early stage of the standardisation [3],[8]. The basic features of the test-bed include synchronisation, channel estimation, signal separation and link adaptation [3].

B. Feedback Implementation

The test-bed implements closed-loop OFDM-MIMO system in the following fashion. The user equipment (UE) reports the channel quality information (CQI) to the base station (BS) via a dedicated feedback link. The CQI information consists of adaptive modulation and precoding matrix index (PMI). PMI reports the best precoder from a set of precoding matrices and vectors. The UE also computes the best transmission mode, whether to transmit with a single stream (SS) or dual stream (DS), and reports it to the BS [6]. These calculations are done for every physical resource block (PRB). The CQI feedback is then taken as input for the BS scheduler at the MAC layer. The transmit power spectrum is flat. 7 long OFDM symbols with 1200 subcarriers per symbol makes a transmit time slot (TTS) of 0.5 ms duration .

The dedicated uplink control channel is protected with $\frac{1}{2}$ rate coding, a CRC, low order modulation BPSK/QPSK, DFT pre-coding and cyclic delay diversity (CDD) and MRC at the BS. The uplink bandwidth is scalable 20 MHz per UE. A lower uplink bandwidth can be selected for higher power spectral density, to compensate for the imbalance in power budget between uplink and downlink. The CQI feedback rate is set to 9 Kbps.

C. Multihop Link Adaptation

The multihop test-bed implements a complete layer 3 forwarding of IP packets. A multimedia streaming application is transmitted from the base station and gets routed via the multihop node. For this purpose, a user equipment is assigned an IP address. The multihop node uses the IP address for forwarding a packet. The advantage is that unwanted packets which are not meant for a UE could be discarded. The relaying operation is categorised as full decode and forward. The prototype conceptualises multihop technology as an interworking of two point-to-point baseline systems: one from base station to relay and second from relay to user equipment. The CQI feedback is therefore indepedently performed between base station to relay and relay to user equipment. In both hops, frequency dependent link adaptation and spatial mode selection are employed. Frequency dependent link adaptation along with full bandwidth reuse provides efficient utilisation of system resources.

The relay node employs two sets of antennas in downlink. One set of two antennas is used for MIMO reception. Another second set, also comprising two antennas, are used for MIMO transmission to user equipment. The duty cycle ratio between first and second hop is adjustable to $\frac{4}{6}, \frac{5}{5}, \frac{6}{4}$ over a total of 10 subframes (SF) as in **Fig. 3**. Relay uses 20 MHz bandwidth for data forwarding.

The timing diagram for relay transmission and reception is shown in **Fig. 3**. As illustrated relay reception and transmission are performed in different time slots within a radio-frame of 10ms. The half duplex constraint straightaway halves the throughput delivered to the user equipment. Each time slot implements a frequency duplexed uplink and downlink. Full decoding of IP packets from the first hop air interface is first done via a convolutional decoder. Upon successful decoding, the IP packets are re-numbered and transmitted via the second hop air interface. The hybrid ARQ process is implemented disjointly for the two air interfaces, the first hop and second hop. The data buffering capability at the relay station significantly reduces the end-to-end latency in case of re-transmissions.

V. Measurement Scenarios

A. Indoor Node placement

For the experiments a basic configuration of one base station and one UE in an interference free environment is set up. No other BS or UEs are active during the experiments. Upink control signals and feedback from the user equipment are routed through the multihop node. Please note that this is a single cell, single user setup, where there is no multi-user diversity on the one hand but also no inter-cell interference. This setup allows to study the relaying gains in an isolated hot-spot scenario.

The layout of the office is shown in **Fig. 4** with tracks A to G. Relay node placement is shown in **Fig. 5**. Relay receiver antennas are positioned in the corner of a typical office floor, track G. The relay receiver antennas are cross polarised (+/- 45). The relay receiver antennas are capable of reception from the base station through the window. The windows are not heavily coated for insulation, allowing for high received signal power near the window. The relay transmitter antennas are placed overlooking the corridor track A but positioned on track G. An ethernet cable connects the receiver and transmitter antennas. The office is equipped with standard office furniture and has doors at sides of the floor while one of the doors consists of a glass front.

Note that in case of heavy window coating, the relay receiver antennas will be placed such that it is projected outside the window. The relay transmit antennas will be placed inside the building.

The UE is moved on a small trolley through the office floor along predefined lines, i.e, tracks A to G with constant velocity. The start is from a door at the start of track A, going through on full trip away and the end is at the meeting point of tracks A and G.

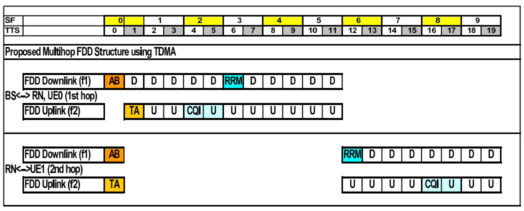

Fig. 3. FDD Relay Radio-Frame. D-downlink data, U- uplink data, RRM- radio resource management, AB/TA- preambles, CQI- channel quality indicator, TTS - transmit time slot, SF - subframe.

TABLE I
DOWNLINK SYSTEM PARAMETERS

Carrier frequency = 2.6 GHz	RN transmission BW = 20 MHz
BS transmit power = 43 dBm	RN transmit power = 23 dBm
Receiver detector = MMSE, MRC	Used subcarriers = 1200
Modulation = 2,4,6 QAM	Channel code = convolutional $\frac{1}{2}$
Sampling rate = 30.72 MHz	Transmission technology = OFDM
RN duplexing = TDMA	AGC = per RX antenna
BS downtilt = 10°	RN isolation = 20 dB
BS, RN TX antennas = 2 xpol	UE, RN RX antennas = 2 xpol

B. Single User Measurement

Three sets of measurements are performed using parameters defined in **Table I**. One without relay and two with relay. In the first measurement, the relay node is manually switched off and only BS is on. The number of relay time slots at BS is zero. UE is moved along tracks A to G.

Two sets of measurements with a relay are then performed. One measurement with transmit power levels of 23 dBm and other with 17 dBm. These pre-defined power levels are chosen because of their popular usage in indoor access points of WLAN networks. The relay node is switched on and operates in the aforementioned two time slot basis. UE is moved along the same set of tracks in the office floor. A multimedia streaming application is transmitted by the base station.

VI. INDOOR RESULTS

A. Without relay

Fig. 4 shows the measurement of user throughput without a relay and with only a base station link. The colour plot shows that in the side of floor facing towards base station, i.e, track G, high throughput exceeding 100 Mbps is possible. The floor windows are thinly coated enabling such high throughput. The same is observed in tracks F and part of A which are adjacent to track G. However, just 5 meters away from the window, on track A, a sharp decline in throughput to less than 20 Mbps is observed. At other end of track A in the same floor, appromimately 10 meters away, throughput is less than 2 Mbps. For most internet applications, throughput less than 2 Mbps is considered unsatisfactory [7]. Note that a user could also install his desktop at the end of track A which supports the need for wireless access.

The observation is similiar in tracks C and D as towards the end of track A. The two sections of tracks are connected via a glass door which validates such an observation. However, track E shows further deterioration in achieved throughput because of more penetration loss. Infact, some parts of the track show zero thoughput (as white spaces).

Therefore, from the colour map, we see that parts of track A, track C, track D and track E show throughput less than 2 Mbps. These spots are characterised as coverage holes. The ratio of coverage hole amounts to approximately 8% of the tracks. If outage is described as chances of being in a coverage hole, a LTE user suffers from outage probability of 8% in the measured tracks. In the count of track locations, 3 tracks (i.e, tracks C, D, E) out of total 8 tracks consist of coverage holes.

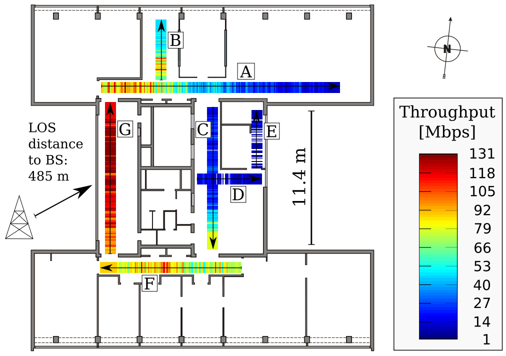

Fig. 4. **Colour map on the floor layout: direct BS connection. LOS - line of sight.**

That amounts to approximately 35% of the total measured area that cannot be guaranteed a satisfactory throughput. The problem in this case is that a user who is unaware of the coverage pattern in tracks C, D, E could consider the pattern as no connectivity. Clearly, a user cannot be expected to know the locations which are ideal to install a laptop in indoor corridors. Certain section of those tracks also show zero throughput with 5% chances. These observations are remarkable considering that only 10 meters away on the other side of the floor, throughput of 100 Mbps is received from the base station.

B. With relay

Now we deploy a relay working in two time slots. The need for two time slots halves the throughput. The relay receiver is placed in a convenient spot in track G to enable high feeder link throughput from base station. The relay transmitter is placed near the same spot but overlooking track A. In **Fig. 5**, the colour map shows the throughput halved in tracks G and F. The throughput still exceeds 50 Mbps, which is satisfactory for internet applications. However, now all the measured tracks show data throughput exceeding 16 Mbps, which removes all coverage holes in that floor. Tracks A, C, D, E are all now enabled for continuous wireless access.

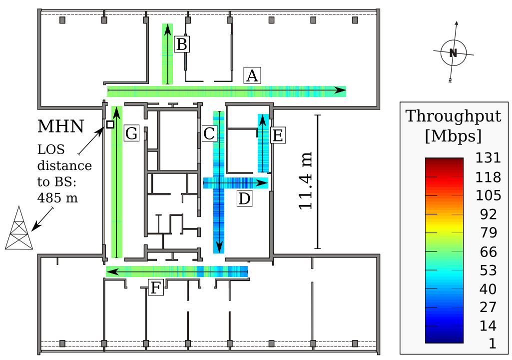

Fig. 5. **Colour map on the floor layout: Relay connection. MHN - Multihop node (also called relay node)**

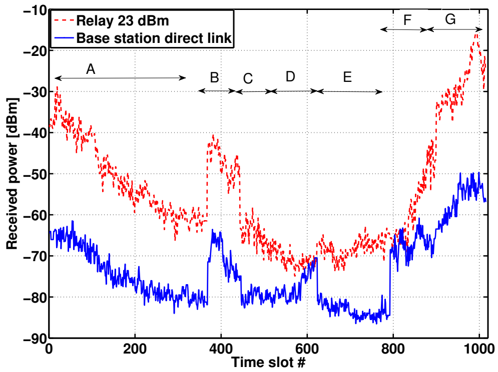

Fig. 6. **Received power over the measurement tracks**

C. Received power

Fig. 6 show the received power over the measurement tracks. The plotted received power is the average of powers with two receiver antennas. The received power validates the data throughput colour plot shown before. Segments of track A, C, D, E are below -75 dBm which results in lowered throughput. The throughput at -75 dBm received power is 30 Mbps. The difference between better part of track A and the worse is 15 dB of attenuation. Track E shows a more 6 dB attentuation because of more penetration loss. As a result, any deliverable throughput is not possible in parts of track E because minimum MCS is not loadable.

D. Throughput distribution

Fig. 7 shows the distribution of the throughput. Throughput with relay transmit power levels of 23 dBm and 17 dBm are shown. On median, relaying with 23 dBm (blue dotted curve) provides achievable throughput of 60 Mbps. Over the 20 MHz bandwidth, the resulting spectral efficiency is 3 bits/s/Hz. The median thoughput improvement is 50% over direct base station connection (black solid curve). The lower tail of the cdf starts at 16 Mbps with a relay. The direct connection throughput is 25% of the time less than the minimum relay throughput of 16 Mbps.

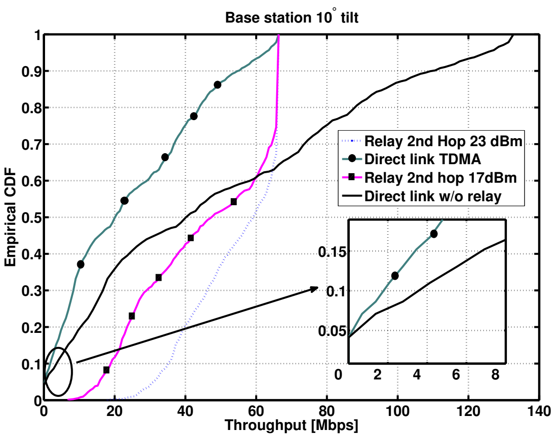

Fig. 7. **Distribution of measured data rate**

It is also possible that a base station could be operating in the time division multiple access (TDMA) mode. An example is base station accomodating transmission of some other relay elsewhere in the macro cell. In that case the direct connection throughput from base station is halved (grey circle curve). Relaying then triples the throughput as compared to direct connection.

However, in practice, a relay could be operating at a lower power level for co-existence purposes with other relay cells. For example, a relay might operate at 17 dBm i.e, with 6 dB power back off to reduce interference. We therefore provide the results with this power level. Relaying with 17 dBm (pink square curve) still provides 20% throughput gain on median and larger gains over lower 40% of the cdf.

VII. Conclusion

In this paper a relay deployment concept is considered by using decode and forward operation. Field trial results are conducted with a real-time LTE test-bed for both direct downlink and relay link. For direct downlink indoor measurements show the existence of coverage holes. As a solution, decode and forward relaying is demonstrated based on LTE working assumptions. The novelty of the approach is that an indoor relay employs full frequency reuse of the allocated bandwidth with LTE technology.

Measurements show that relaying in LTE framework does provide coverage gains and mitigates the occurence of coverage holes. Results show that in a single cell scenario, substantial throughput gain exceeding 50% is achievable with relaying as compared to without relaying. These test results advocate use of decode and forward relays for future LTE-advanced cellular systems.

References

[1] E. Telatar, ‘Capacity of multi-antenna Gaussian Channels,” *European Trans. Commns*, vol.10, pp 585-595.

[2] Pabst et. al, “Relay based deployment concepts for wireless and mobile broadband radio ,” *IEEE Comms Magazine*, pp 80-89, 2004.

[3] T. Haustein et. al, “Real Time Signal Processing for Multi-Antenna Systems: Algorithms, Optimization and Implementation on an Experimental Test-bed,” *EURASIP Special Issue on Implementation Aspects*, 2005.

[4] T. Haustein, V. Kumar, T. Wirth et. al, “Measurements of Multi-Antenna Gains using a 3GPP-LTE Air-interface in Typical Indoor and Outdoor Scenarios,” *EW 2008*, Prague, June 2008.

[5] V. Venkatkumar, T. Haustein, et. al, “Field trial results on multi-user MIMO Downlink OFDMA In Typical Outdoor Scenario Using Proportional Fair Scheduling ,” *WSA ITG*, Darmstadt, February 2008.

[6] R. W Heath and A. J Paulraj, “Switching between diversity and multiplexing in MIMO systems,” *IEEE Trans. Commns*, pp 962-968, 2005.

[7] IST-4-027756 WINNER II , “Final assessment of relaying concepts for all CGs scenarios under consideration of related WINNER L1 and L2 protocol functions ,” *D3.5.3 v1.0*, 30 September 2007.

[8] 3GPP Long Term Evolution Standardisation Working Documents 36. 212, 36. 213, 36. 214 found at www.3gpp.org/ftp/Specs.

[9] 3GPP TR 36.913 v 8.0.0, Technical Specification Group Radio Access Network Requirements for Further Advancements for E-UTRA, LTE-Advanced (Release 8) found at http://www.3gpp.org/ftp/Specs/archive/36_series/36.913/

[10] Report ITU-R M. 2134, Requirements related to technical performance for IMT-Advanced radio interface(s) found at http://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2134-2008-PDF-E.pdf