Support of Low Complexity LTE Terminals

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Abstract—**The support of low bandwidth LTE devices would allow LTE to be a cost effective means of supporting low rate applications such as machine to machine communications (M2M), facilitating the migration of mobile networks from GPRS to LTE. This paper describes why lowering device bandwidth leads to a significant reduction in baseband processing complexity, the issues that currently prevent the support of low bandwidth LTE devices, some potential solutions to these problems and analyses the coexistence and link budget implications of supporting these low bandwidth LTE devices.**

Keywords-LTE, M2M, bandwidth, aggregated carrier, virtual carrier, complexity.

I. INTRODUCTION

With approximately 80% of the worldwide population already connected through cellular networks in 2010 [1], the market for Human-to-Human (H2H) communication is expected to saturate in the near future. Mobile network operators around the globe are vigorously exploring ways to create new revenue streams and M2M communication has drawn attention as the next promising target. The market for M2M communication is expected to grow rapidly in the next ten years.

The requirements for M2M communication compared with conventional H2H communication are significantly different. One major difference is cost: lower expected call revenues mean that operators will not be able to subsidize devices; in order to provide low cost devices to the end user, the inherent device cost must itself be reduced.

In order to reduce the implementation cost of M2M devices, baseband processing needs to be re-evaluated, as it is a significant proportion of the overall cost of a device. One of the most significant factors in baseband cost relates to the supported bandwidth of the signal that the devices need to transmit and receive. If the supported bandwidth is reduced, the cost of the device can be significantly reduced.

Whereas many operators currently use multiple radio access technologies (RATs), future costs can be reduced by operating a single RAT. GPRS and LTE are two candidate RATs for M2M applications, with many current wide area M2M applications using GPRS. For many operators, LTE is the preferred single RAT for future M2M applications as it has better spectrum efficiency and coverage than GPRS. If M2M applications were supported using the same LTE modems as those used in smartphones, economies of scale would drive down the cost of devices running those applications. However it is unlikely that such LTE modems would ever be cost competitive with GPRS modems. Both a fundamental reduction in LTE modem complexity and economies of scale may however allow the cost of an LTE M2M device to be cost competitive with a GPRS device. For LTE, cost saving can be achieved by providing a backward compatible method to serve both the low cost M2M devices and legacy LTE UEs in the same network.

This paper explores ways to support low cost M2M devices in future LTE networks with approaches that permit coexistence with legacy Release 8-10 LTE UEs. The following section identifies that device bandwidth capability has the greatest impact on device baseband cost.

II. SIGNIFICANT ASPECTS OF DEVICE COST

Device cost is influenced by many factors, both commercial and technical. The specific device implementation influences cost. Many M2M devices are simple sensors, actuators or trackers. Such devices do not require a sophisticated user interface and the most significant component of their cost can be the communications modem. The cost of the modem can be subdivided into baseband (~50%), radio (~40%) and protocol CPU (~10%) costs. The indicated relative costs of these aspects will vary according to implementation; however the values detailed above are considered to be reasonable for a category 1 LTE UE (10Mbps peak downlink (DL) data rate, 5Mbps peak uplink (UL) rate, receiver diversity) operating in a 20MHz channel bandwidth. 3GPP RAN1 is currently studying how to reduce these aspects of LTE UE cost in a study item [3].

The radio cost can be reduced by reducing the number of supported radio access technologies, reducing the number of RF chains, implementing a half duplex mode device or reducing device transmit power. The protocol CPU cost may be reduced by either reducing the data rate supported by the device or simplifying the protocol processing that is required per higher layer message transmitted. These aspects of device cost are beyond the scope of this paper. In the following, this paper considers strategies for reducing the baseband cost, identifying that supported device bandwidth is the greatest cost contributor. It is assumed that gate count directly affects complexity and cost.

Approaches to reducing device baseband cost include reducing the bandwidth that the device has to support, reducing the peak DL and UL data rates supported by the device and removing some of the multi-antenna (MA) based capacity enhancing features. Table I lists a set of functions that are performed within the baseband processing of a device and indicates whether their complexity scales with bandwidth

(BW), device peak rate or implementation of multi-antenna techniques. This table also provides an estimate of the relative complexity of each of these functions for a reference device. The reference device is a category 1 / 20MHz bandwidth LTE UE. Note that this complexity is implementation dependent.

Table I indicates that the greatest area of complexity in the reference device occurs in the Turbo decoding / HARQ memory, channel estimation and downlink sample buffering functions. For a device implementing receive diversity, functions such as synchronization limit the possible complexity reductions.

Channel estimation algorithms have been reported [6] with a complexity of the order $O(L^2K + L^3)$ where L is the number of significant channel impulse response taps and K is the number of OFDM subcarriers. In the LTE OFDM downlink, the number of channel estimation operations is a function of the number of reference symbols: that number is linearly related to the channel bandwidth. Hence channel estimation complexity scales linearly with bandwidth.

The HARQ buffer memory size is related to the number of soft physical channel bits that the device is required to receive per subframe. The maximum number of physical channel bits processed per sub-frame is related to the number of transport bits processed per sub-frame: the device is specified to be able to operate at a defined minimum code rate when transmitting at the maximum data rate. Hence HARQ buffer memory size is linearly related to peak rate. The number of operations required to Turbo decode a transport block is linearly related to its size.

The downlink sample buffering function stores samples of the received signal upon which the signal processing functions operate. The required size of the buffering function is dictated by the bandwidth of the control channels: this bandwidth is a function of system bandwidth, not peak rate. The number of bits buffered is hence a linear function of the bandwidth.

The most significant aspects of complexity have been shown to scale linearly with either bandwidth or peak rate. Other functions whose complexity scales with either bandwidth or peak rate either have a less significant complexity in the reference device or scale with an order that is greater than linear. In terms of scaling down bandwidth or peak rate, these terms decay more quickly than the linear terms.

TABLE I. RELATIVE COMPLEXITY OF BASEBAND PROCESSING FUNCTIONS FOR THE REFERENCE CATEGORY 1 / 20MHZ LTE DEVICE

function	scales with	proportion
DL front end processing	BW, MA	2%
Time domain processing (FFT etc.)	BW, MA	3%
Synchronisation and frame tracking	MA	8%
UL modulation	peak rate	1%
UL bit level processing	peak rate	<1%
UL front end processing	BW	3%
DL control channel processing	fixed	5%
PDSCH bit level processing	peak rate	1%
Turbo decoding / HARQ memory	peak rate	21%
Channel estimation	BW, MA	36%
MMSE detection	BW, MA	4%
DL sample buffering	BW, MA	13%
MIMO processing	BW, MA	3%

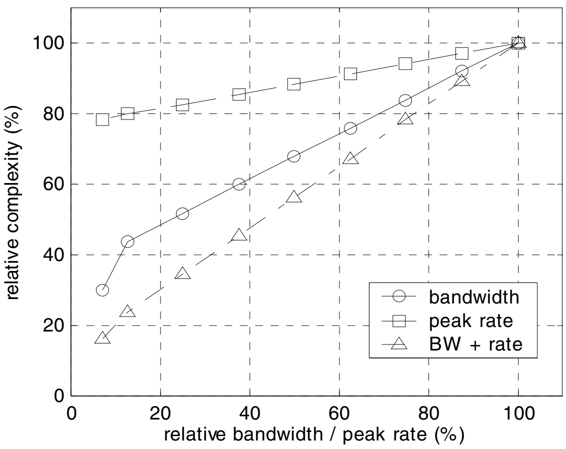

Figure 1. Scaling of complexity with bandwidth and data rate

In addition, at the 1.4MHz system bandwidth, the available amount of physical resource restricts the size of the Physical Downlink Control Channel (PDCCH) search space and the peak UL and DL rates that the device can support. The search space is the set of PDCCHs that the LTE device must blindly decode in order to find its allocation messages. The search space at the 1.4MHz system bandwidth is 50% smaller than for the other system bandwidths; the peak DL rate is 4.4Mbps and the peak UL rate is 2.3Mbps.

Figure 1 shows how the complexity of a two branch receiver diversity LTE device scales with bandwidth or device peak rate assuming this linear relationship and accounting for the exceptions at the 1.4MHz system bandwidth. The reference device has a baseline relative bandwidth of 100% and relative complexity of 100%. When the bandwidth is decreased to 1.4MHz (7% of the baseline device's bandwidth), but the LTE device supports the maximum peak rate at that bandwidth, the baseband complexity reduces to 30% of that of the original device. In contrast a reduction in peak rate to 7% of the baseline (yielding a 700kbps device), while leaving the bandwidth unchanged, only reduces the baseband complexity to 79% of the baseline. An analysis of reducing baseband complexity through use of a single antenna device allows the design of a device with 64% of the baseband of the reference device. Simultaneous reduction of bandwidth and peak rate can produce a device that has only 17% of the baseband complexity of the reference device.

The potential complexity savings identified in Figure 1 and the expected size of the M2M market provide a motivation for architecting device implementations that will achieve those complexity savings. The greatest baseband complexity savings can be achieved by reducing device bandwidth. The following sections of this paper discuss methods of supporting a low bandwidth device in an LTE network in a backwards compatible manner, analyzing the implications on link budget and coexistence.

III. REQUIREMENTS

In LTE, the minimum UE receiver bandwidth is the maximum bandwidth of the band in which the UE operates. The LTE control channels have been designed according to this assumption. Hence in any band supporting 20MHz channel allocations, an LTE UE would need to implement a 20MHz receiver bandwidth. A low bandwidth LTE device would need to be backwards compatible with networks supporting the full channel bandwidth. The backwards compatibility requirement is that an upgraded LTE base station (eNode B) can support both Release 8+ UEs and low bandwidth devices within the same carrier. Ideally the eNode B should be upgradeable via a software upgrade, but this possibility is implementation dependent.

Many M2M applications only require low rate communications, are cost sensitive and power constrained. GPRS is commonly used for such applications, but LTE would also be suitable if the bandwidth of the device could be reduced to make the LTE device cost competitive with GPRS [3].

When the Physical Downlink Shared Channel (PDSCH) processing requirements are reduced in order to create a lower cost device, the complexity of the Release 10 control channel decoding functions may be greater than those for the PDSCH. This may require a re-evaluation of the PDCCH structure: such a re-evaluation may also lead to a structure that is better aligned with M2M traffic types characterized by small infrequent data transmissions [7]. A Release 10 UE may not be able to decode these PDCCHs, but must be able to coexist with them.

Operators have deployed LTE networks in set channel bandwidths, according to their spectral holdings and supported technologies (GSM, 3G, LTE etc.). Low bandwidth LTE devices should be supported within these existing channel bandwidths. Existing users of these LTE networks will have become accustomed to a certain performance level. The support of low bandwidth devices should not reduce this level of performance. In particular the support of low bandwidth devices should not reduce the throughput that can be achieved by legacy UEs.

IV. DESIGN APPROACHES

A. *Separate low bandwidth carrier*

A network operator could split its spectrum into a carrier for the support of legacy UEs and a separate low bandwidth carrier for low bandwidth devices. While this is a simple approach, it has the disadvantage of reducing the bandwidth (and hence throughput) that is available for legacy UEs. Some eNode B implementations may not support multiple carriers within the same channel bandwidth.

When there are multiple carriers within the same channel bandwidth, UEs must choose which of the carriers to camp onto. A low bandwidth device would only choose a carrier whose bandwidth was less than or equal to its capability. However a legacy UE could camp on to either the low bandwidth carrier or the remnant carrier. In this case load balancing algorithms would be required to move legacy UEs between the low bandwidth carrier and the remnant carrier.

In addition, load balancing algorithms may be required in order to make full use of the low bandwidth carrier when there are few low bandwidth devices. In this case the low bandwidth carrier could be used for both low bandwidth devices and for legacy UEs that are not transmitting and receiving significant amounts of data. Such legacy UEs that are transferred to the low bandwidth carrier would suffer a higher latency when they need to transmit and receive larger amounts of data as they would need to be handed over to the larger bandwidth remnant carrier, with associated signaling delays.

B. *Carrier Aggregation*

3GPP Release 10 specifications support carrier aggregation. Carrier aggregation allows a UE to be allocated data across multiple carriers in the same sub-frame, effectively increasing the bandwidth of the channel available to the UE. While the original motivation for carrier aggregation was to increase the peak rates available to UEs, it can also be used to provide low bandwidth carriers for low bandwidth devices while still allowing legacy UEs to achieve high peak data rates. In this way a high bandwidth carrier can be fragmented into a set of lower bandwidth carriers: the lower bandwidth carriers can then either support low bandwidth devices or be aggregated in order to support higher bandwidth Release 10 UEs.

For the support of low bandwidth devices, a wideband carrier could be split into a number of lower bandwidth carriers. In 3GPP Release 10, LTE supports carrier bandwidths of 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz and 20MHz. Figure 2 shows an example where a 20MHz carrier is fragmented into a 15MHz carrier, a 3MHz carrier and a 1.4MHz carrier (other fragmentations are also possible but the possible bandwidth of any one component carrier is limited by Master Information Block (MIB) signalling). Low bandwidth devices would be served by the lower bandwidth fragmented carrier. Release 10 UEs would be served by carrier aggregation of the fragmented carriers. Pre-Release 10 UEs would be served by one of the higher bandwidth fragmented carriers, but would not be able to achieve the peak throughputs that could have been achieved with the original carrier.

In the case that an LTE carrier is fragmented into a 1.4MHz or 3MHz carrier and higher bandwidth carriers, there is a potential loss of subcarrier resource due to the 1.4MHz or 3MHz carriers not tessellating perfectly to the bandwidth of the original LTE carrier. This imperfect tessellation is illustrated in Figure 2. Table II shows that when a 1.4MHz low bandwidth carrier is formed by the fragmentation of a higher bandwidth LTE carrier, the tessellation loss varies between 4% and 16%

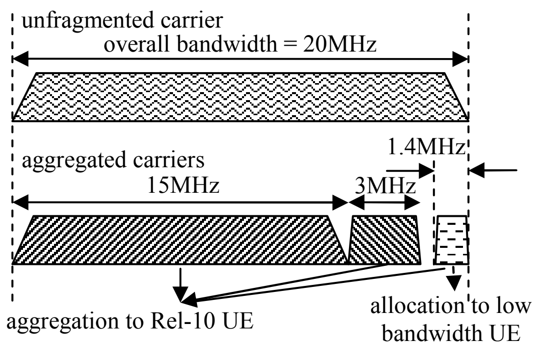

Figure 2. Support of low bandwidth devices via carrier aggregation

for original un-fragmented bandwidths of between 20MHz and 5MHz.

The set of carriers that are aggregated by Release 10 UEs needs to be Release 10 compatible. Given that the traffic requirements for devices that are likely to use the low bandwidth carrier, such as M2M devices, may develop differently to the requirements for the high data rate UEs supported on the higher bandwidth carriers, this requirement places restrictions on the future development of any low bandwidth carrier that could form one of the aggregated set.

C. *Virtual Carrier*

Any LTE UE needs to be able to decode the PDCCH, Physical Control Format Indicator Channel (PCFICH) and the Physical Hybrid ARQ Indicator Channel (PHICH) across the entire channel bandwidth of the carrier. Hence a low bandwidth device would not be able to decode these channels from a higher bandwidth carrier. It is hence necessary to restrict the bandwidth of these channels to the lower bandwidth. However any legacy UE will expect to receive these channels across the full system bandwidth. In order to resolve this conflict, it is necessary to have separate control channel regions for the legacy UEs and the low bandwidth devices. Separation is most easily achieved in the time domain: the initial OFDM symbols of a sub-frame are used for the control channels of the legacy UEs whereas the control channels for the low bandwidth devices occupy a restricted set of sub-carriers in other OFDM symbols. Figure 3 illustrates an example positioning of control channel resources in a downlink frame.

The OFDM symbols and subcarriers assigned to low bandwidth devices that are used for control channels and PDSCH are self-contained. A low bandwidth device is only required to monitor and decode these resources and there is no requirement for a low bandwidth device to monitor or decode resources outside the bandwidth of the virtual carrier. The LTE carrier can thus be considered to be a “host carrier” supporting a low bandwidth “virtual carrier”. High bandwidth UEs decode their control channels across the entire carrier bandwidth and are scheduled PDSCH resource in subcarriers outside the bandwidth of the virtual carrier. In this manner the virtual carrier is transparent to the legacy UEs that are scheduled in the host carrier.

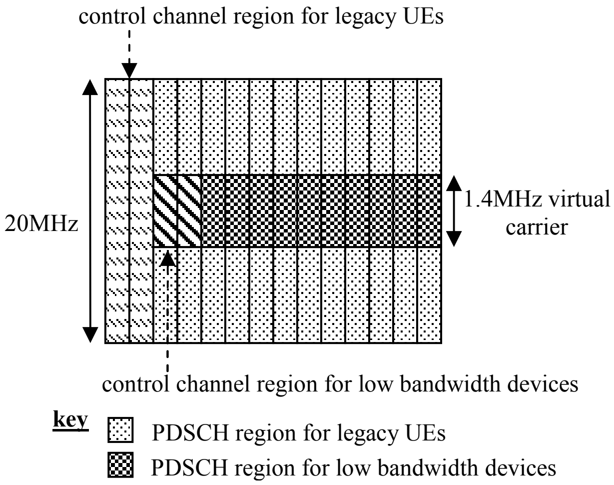

Figure 3. Control and data channel location for low bandwidth devices

TABLE II. TESSELATION LOSS FROM CARRIER AGGREGATION

LTE carrier bandwidth	fragmented carriers	tessellation loss
20MHz	15MHz + 3MHz + 1.4MHz	4%
15MHz	10MHz + 3MHz + 1.4MHz	5.3%
10MHz	5MHz + 3MHz + 1.4MHz	8%
5MHz	3MHz + 1.4MHz	16%

A legacy UE expects to decode reference signals in defined OFDM symbols and subcarriers within the LTE sub-frame. Some of these reference signals will fall within the resources occupied by the virtual carrier. The virtual carrier is hence required to support Release 10 reference signals. These reference signals can be used for the purposes of channel estimation and measurements by both low bandwidth devices camped onto the virtual carrier and legacy UEs supported by the host carrier, provided the virtual carrier is transmitted from the same antenna ports synchronously with the host carrier. The virtual carrier could support additional reference signals within the virtual carrier bandwidth provided those reference signals occupy different resource elements to those required by legacy UEs camped onto the host carrier. In the UL, reference signals are transmitted by the UE and there is no requirement for a low bandwidth device’s reference signals to be compatible with those of a Release 10 UE.

When the virtual carrier is active, legacy UEs are only scheduled in host carrier resources. In this case they are unaware of the existence of the virtual carrier since they are never scheduled PSDCH in virtual carrier resources. Legacy UEs can also detect legacy reference signals in the virtual carrier. When there are no low bandwidth devices active in a sub-frame, the eNode B can dynamically schedule legacy UEs in the virtual carrier resource (physical resource blocks can be scheduled dynamically as either a virtual carrier or as regular PDSCH resources).

The eNode B transmits the Physical Broadcast Channel (PBCH) and synchronization signals to allow a UE to camp onto the carrier. Once camped on, the UE can maintain synchronization by decoding the DL reference signals rather than the synchronization signals. The PBCH only changes infrequently (apart from the system frame number: the UE can maintain frame number alignment by counting frames). Hence the virtual carrier does not need to exist in the same subcarrier range as the synchronization signals and PBCH.

The existence of the virtual carrier can be signaled either through a specific synchronization signal within the virtual carrier or via signaling in the master information block (MIB) transmitted on the PBCH. Use of a specific synchronization signal may facilitate dynamic scheduling between low bandwidth devices and legacy UEs, allowing the virtual carrier to be switched on and off. The PBCH is transmitted with a bandwidth of 1.08MHz (6 LTE resource blocks) and is hence decodable by a low bandwidth device. When the MIB signals some parameters of the virtual carrier, a low bandwidth device can decode these parameters and then camp on to the virtual carrier. System information is scheduled by the eNode B: it may schedule this system information in a low bandwidth such that both low bandwidth devices and legacy UEs can decode it. Since system information is allocated dynamically using PDCCH signaling, both a low bandwidth PDCCH within the virtual carrier and a high bandwidth PDCCH would be required to allocate common system information.

The uplink transmissions from low bandwidth devices can be bandwidth constrained by not scheduling some uplink physical resource in the host carrier and instead utilizing that physical resource for low bandwidth device transmissions. Hence the eNode B can schedule some of the uplink resource space as an uplink virtual carrier.

In LTE the Physical Uplink Control Channel (PUCCH) is transmitted in a time and frequency multiplexed fashion using subcarriers at both extremities of the carrier. A low bandwidth device would be unable to transmit at both extremities of the bandwidth of the host carrier (due to transmit bandwidth restrictions) and would hence be unable to transmit PUCCH. Figure 4 illustrates an uplink virtual carrier transmitting low bandwidth PUCCHs at the lower extremity of the uplink host carrier. Positioning the uplink virtual carrier at either the upper or lower extremity of the uplink host carrier provides the greatest amount of contiguous physical resource in the host carrier in which high bandwidth Single Carrier Frequency Division Multiple Access (SC-FDMA) transmissions can be scheduled.

The Physical Random Access Channel (PRACH) allows UEs to initially attach to the cell and to request UL resources. Low bandwidth devices can be assigned PRACH resources that are distinct from those assigned to legacy UEs: either by assigning a separate set of PRACH preambles or by assigning PRACH preambles in different subframes to those assigned to legacy UEs. The ability to distinguish legacy UE PRACHs from low bandwidth device PRACHs allows the eNode B to send the random access response on the appropriate carrier in the downlink: either the host carrier or the virtual carrier. In the case that the downlink virtual carrier had previously been deactivated due to inactivity, the eNode B may instantiate a virtual carrier in response to a PRACH from the set of PRACH preambles assigned to low bandwidth devices.

When M2M devices are massively deployed, simultaneous network access requests have the potential to cause network congestion. Of itself the virtual carrier does not change the total amount of PRACH resource available in the cell. Research into the control of PRACH congestion is ongoing. Methods of avoiding PRACH congestion may be equally applicable to the virtual carrier and to wider bandwidth carriers.

The eNode B is able to schedule resource for the virtual carrier down to the granularity of a single resource block (180kHz). Since the virtual carrier's subcarriers and symbols are synchronous with those of the host carrier's, there is no wasted physical resource when a virtual carrier is inserted into a host carrier: the virtual and host carriers tessellate perfectly.

The virtual carrier is transparent to legacy UEs when the virtual carrier supports the host carrier reference signals. Provided the virtual carrier is synchronous and orthogonal to the host carrier, the virtual carrier does not necessarily need to operate in the same mode as the host carrier. Hence the transmission formats and control signaling used in the virtual carrier can be optimized for the traffic models that are most appropriate for low bandwidth devices and future applications.

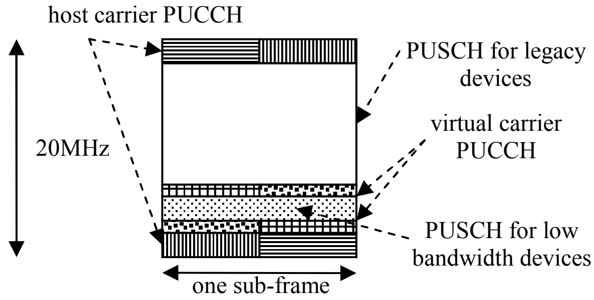

Figure 4. Uplink virtual carrier support of low bandwidth devices

V. COEXISTENCE

LTE has been designed to allow adjacent carriers to coexist with one another. Hence there are no coexistence issues associated with supporting low bandwidth devices either using separate carriers or using aggregated carriers.

The virtual carrier consists of a set of OFDM modulated subcarriers that are synchronous with and orthogonal to the OFDM modulated subcarriers of the host carrier. The subcarriers of both the virtual carrier and the host carrier are transmitted by a sector of an eNode B as part of a set of OFDM modulated subcarriers. Hence the level of inter-subcarrier interference between host and virtual carrier subcarriers should be no different to that between those of the host. To a legacy UE operating in the host carrier, the virtual carrier appears as a set of OFDM subcarriers that are scheduled to another UE, hence the virtual carrier does not appear to the legacy UE to be any different to PDSCH resource assigned to a different UE.

A low bandwidth device that applies linear bandpass filtering to accept the virtual carrier's subcarriers and reject the host carrier's subcarriers will not suffer interference from the host carrier's subcarriers: the host carrier's subcarriers will remain orthogonal to the virtual carrier's subcarriers.

Since the virtual carrier's subcarriers are part of a set of OFDM modulated subcarriers that are orthogonal to and synchronous with those of the host, the waveform from a sector supporting a virtual carrier appears identical, from an interference perspective, to the waveform from any other LTE sector. Hence there should be no additional inter-sector interference associated with the support of a virtual carrier.

VI. MINIMUM SUPPORTED BANDWIDTH

Section II showed that reducing the device bandwidth to 1.4MHz achieves most of the potential relative complexity savings from reducing device bandwidth: below this the complexity of functions that do not scale with bandwidth start to dominate. In addition, if the LTE device bandwidth were reduced below 1.4MHz, the device would be unable to decode the PBCH and synchronization channels, requiring those channels to be replicated at a lower bandwidth. There is hence little motivation to reduce the LTE device bandwidth below 1.4MHz.

VII. LINK BUDGET IMPLICATIONS

Provided the power spectral density of the carrier is maintained across the host carrier and the virtual carrier, the transmit power per subcarrier for a low bandwidth device served by a virtual carrier is the same as for a device served by a set of subcarriers scheduled from across the entire system bandwidth.

LTE is resilient to frequency selective fading through the support of distributed and localized scheduling. The gain available from these techniques depends on the coherence bandwidth of the channel. The largest r.m.s. delay spread considered in [5] is 991ns leading to a 50% coherence bandwidth of 200kHz [4]. Although the coherence bandwidth is greater for channels with smaller delay spread, there are many cell sizes where the coherence bandwidth is less than 1.4MHz: for these cells there is little frequency diversity loss compared to systems operating in greater channel bandwidths.

At the cell edge, where devices are transmitting at their maximum transmit power, uplink transmissions are localized into the minimum number of resource blocks in order to increase the power spectral density of the signal received at the eNode B. Hence both virtual carrier and host carrier transmissions will be transmitted with the same number of resource blocks. It is possible to frequency selectively schedule UL transmissions when feedback from the device is available, for example through the use of sounding reference signals. As discussed above, for many channels sufficient frequency diversity is available in a 1.4MHz channel.

VIII. CONCLUSION

M2M communications are expected to create significant revenue for mobile network operators in the near future. In order to fully exploit the opportunities of M2M communication, the cost of the M2M devices needs to be minimized.

This paper has analysed those aspects of device cost that have the greatest impact on complexity, finding that reducing the device's bandwidth provides the greatest potential for cost reduction. It is shown that it is possible for such low bandwidth devices to co-exist with Release 8-10 LTE UEs.

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