Coverage and Capacity Analysis for Machine Type Communications in LTE

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Abstract — **Machine type communications (MTC) is defined as data communication among devices without the need for human interaction. Examples of MTC services include security, tracking, payment, smart grid, and remote monitoring. With the widespread introduction of LTE and decommissioning of legacy systems, migration of MTC devices to LTE is under investigation by many cellular operators. This paper examines LTE uplink coverage and capacity for machine type communications. It is seen that LTE provides similar coverage to other cellular systems but significantly higher capacity for MTC services. Capacity, however, may be significantly reduced for devices with lower maximum transmit power or QPSK-only modulation. MTC on LTE is also shown to be robust to interference and may be a good candidate for deployment in unlicensed band.**

I. Introduction

Machine type communications (MTC) is defined as data communication among devices without the need for human interaction [2]. This may be data communication between devices and a server, or device to device. Another common name for machine type communications is machine-to-machine (M2M) communications. Examples of MTC services include security, tracking, payment, smart grid, and remote maintenance/monitoring. While MTC applications are diverse, salient features of this communication system include low cost, low mobility, delay tolerant (in most cases), large number of devices, small and infrequent data transmission (in most cases), high reliability, time-controlled operation and group-based communications [1][2][5][6].

MTC services are supported at the physical layer using cellular systems such as GSM, cdma1x, and UMTS. With the widespread introduction of LTE and decommissioning of legacy systems, migration of MTC devices to LTE is under investigation by many cellular operators. To efficiently support MTC on LTE, higher-layer system issues unique to MTC have been studied in [1][4]. They include group-based optimization, time controlled operation, congestion control, overload control, network access, and IP addressing. This paper examines the physical layer coverage and capacity for machine type communications. Since most MTC applications are uplink-centric (i.e. data is transmitted up from the devices to the network), only uplink coverage and capacity will be analyzed. It is seen that LTE provides similar coverage to other cellular systems while providing significantly higher capacity.

The paper is organized as follows. In Section II, an overview of machine type communications is provided. In Section III, MTC in LTE is discussed. Section IV investigates LTE coverage compared to other cellular systems while Section V presents uplink system-level performance for two representative deployment scenarios. Finally, conclusions are drawn in Section VI. LTE terminologies for mobile device and base station are User Equipment (UE) and evolved NodeB (eNB), respectively. Therefore, these terms will be used in the rest of the paper.

II. Machine Type Communications

Machine type communications does not require human interaction and can be viewed as data communication between devices and a server, or device to device. MTC has great commercial potential as large number of devices becomes connected and wireless access is ubiquitous [7]. Some typical examples of MTC services and applications are shown in Table I.

TABLE I
MTC SERVICE EXAMPLES [2][6]

Service	Application
Security and Public Safety	Surveillance systems, home security, building access control
Tracking	Fleet Management, traffic sensor, roadway signs, traffic lights
Payment	Credit machines, vending machines, gaming machines
Health	Monitoring vital signs, remote diagnostics
Remote Maintenance	Sensors, vending machine control, vehicle diagnostics
Smart Grid	Power, gas, water, heating
Consumer Devices	Appliances, eBook

Important characteristics of MTC services include low cost, low mobility, delay tolerant (in most cases), large number of devices, small and infrequent data transmission (in most cases), high reliability, time-controlled operation and group-based communications [1][2][5][6]. Time-controlled operation refers to data communication only within a predefined period. Group-based communication refers to the ability to simultaneously address a group of MTC devices.

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Some examples of MTC application average transaction time, message size, and equivalent data rate are given in Table II.

TABLE II
MTC APPLICATION EXAMPLES [6]

Application	Average Transaction Time (Seconds)	Average Message Size (Bytes)	Data Rate (bits/sec)
Surveillance	1	8000	64,000
Home Security System	600	20	0.27
Health Sensor	60	128	17.07
Smart Meter	9090	2017	1.78
Traffic Sensor	60	1	0.134

III. MTC IN LTE

LTE system provides support for high peak data rates, low latency, improved system capacity and coverage, reduced operating costs, multi-antenna support, flexible bandwidth (1.4, 3, 5, 10, and 20 MHz) operations and seamless integration with existing systems. This makes LTE well-suited for MTC services.

A. Deployment Scenario

For MTC deployment, several options are possible –

- Sharing of MTC and other data traffic on the same carrier. For example, a 20MHz LTE system may be deployed with some resources reserved for MTC traffic. This allows efficient resource sharing and reduces costs for the operators. One potential issue with this approach is that low-cost MTC devices may only support reduced bandwidth options (e.g. only 1.4, 3, and 5 MHz). In this case, changes must be made to enable this operation.
- A dedicated carrier may be deployed exclusively for MTC traffic. Furthermore, as legacy systems are decommissioned, the available spectrum and sites may be used for MTC services. For example, several legacy GSM carriers may be combined for use to support MTC on LTE. As long as the coverage of the two systems is comparable, there will be no coverage hole. Otherwise, coverage enhancement techniques may be needed to match LTE coverage to that of the legacy system.
- Carrier aggregation may be used to support MTC services. Since MTC is uplink-centric, asymmetric bandwidth can be used. For example, a paired FDD 5MHz carrier may be used as primary carrier for control and regular data traffic, and an unpaired 1.4MHz uplink carrier can be used exclusively for MTC traffic.

One potential MTC deployment scenario is to use TDD system in unpaired spectrum. However, in LTE, the largest uplink-centric allocation is 40:60 DL/UL split. This is unlikely to match the actual DL/UL traffic ratio of MTC services. In addition, since scheduling grants are carried on the downlink control channel, uplink capacity may be limited by lack of downlink control channel resources.

Due to its low rate, low power, and delay tolerant characteristics, MTC services may also be good candidates for deployment on unlicensed band. Although performance cannot be guaranteed in unlicensed deployment due to interference issues, MTC services have infrequent and small transmissions that can take advantage of HARQ to overcome the interference.

One issue that has been studied extensively for MTC deployment is network congestion. Due to the large number of MTC devices, network congestion could be an issue if many of them try to access the network simultaneously. The random access channel could be heavily congested, leading to long delay and possible network access failure. To solve this problem, several solutions were proposed including time-controlled access, staggered access, an overload indicator to prevent MTC devices from access attempts, and restrictions on random access resource utilization [1].

B. Low-Cost Devices

In LTE, cost reduction for LTE MTC devices are being studied. Some of the features being recommended include power amplifier cost saving, reduced maximum channel bandwidth below 20MHz, half-duplex FDD operation, reduced peak data rates, and one receive antenna [10]-[14]. Peak rate reduction includes QPSK-only modulation, reduced transport block size, and reduced number of HARQ processes. Table III highlights the approximate cost saving in the UE modem (compared to Category-1 UE) from the various techniques.

TABLE III
UE MODEM COST SAVING [10]-[14]

Technique	Approximate Saving (%)
Single receive antenna	14-18%
Reduced maximum UE power	1-3%
Half-Duplex FDD	9-12%
Reduced maximum UE bandwidth	6-10%
Peak rate reduction	5-7%

IV. COVERAGE ANALYSIS

Table IV provides uplink link budget comparison of LTE to several cellular systems (UMTS, cdma1x, and GSM) that are currently used for machine type communications. Only the uplink is shown because it is usually the limiting link from a coverage perspective. To provide a valid comparison, the systems are assumed to operate in a similar frequency band. The link budget shows the maximum allowable path loss for each technology. From the table, it is seen that LTE provides comparable link budget to existing cellular systems.

LTE coverage comparison in Table IV is, however, based on maximum UE transmission power of 23 dBm. For low-power MTC devices, to close the link budget, subframe bundling and HARQ can be used. Subframe bundling allows a packet to be transmitted over four consecutive subframes and therefore can provide up to 6 dB of gain. In addition, HARQ allows retransmission of packets that were not decoded successfully at the eNB. For example, if a maximum of 5 retransmissions is allowed, up to 7 dB of combining gain can be achieved. Note that the link budget shown in Table IV does not assume subframe bundling or HARQ.

TABLE IV
UPLINK LINK BUDGET COMPARISON OF CELLULAR SYSTEMS.

Uplink	LTE (Rel-8)	UMTS (HSUPA)	cdma1x (1xEV-DO)	GSM
UE EIRP				
Power (dBm)	23	23	23	33
Tx Antenna Gain (dBi)	-2.0	-2.0	-2.0	-2.0
EIRP (dBm)	21.0	21.0	21.0	31.0
eNB Sensitivity				
Antenna Gain	17.0	17.0	17.0	17.0
Trans Line Loss	1.0	1.0	1.0	1.0
eNB Noise Figure	5.0	5.0	5.0	5.0
Thermal Noise	-174.0	-174.0	-174.0	-174.0
Required SNR (dB)	-7.0	-17.3	-12.4	7.0
eNB Sensitivity	-136.5	-136.3	-136.4	-125.0
Margins				
Soft Handoff Gain	0.0	2.0	2.0	0.0
Lognormal Margin	5.6	5.6	5.6	5.6
Interference Margin	1.0	3.0	3.0	1.0
Penetration Loss	18.0	18.0	18.0	18.0
Body Loss	2.0	2.0	2.0	2.0
Total System Margin	26.6	26.6	26.6	26.6
Maximum allowable Path Loss	130.9	130.7	130.8	129.4

V. CAPACITY ANALYSIS

In this section, uplink system-level performance results are provided for two distinct system deployment scenarios defined in [3] – urban and suburban macro-cell deployment. For urban macro-cell scenario, the inter-site distance (i.e. the distance between one eNB site to another) is 500 meter, while for suburban macro-cell it is 1732 meter. The macro-cell system simulation scenario is of a traditional 57-cell system setup with wrap-around. Thermal noise level of -174 dBm/Hz is assumed. Table VI provides other relevant system simulation parameters.

The pathloss profiles of the two scenarios are shown in Fig. 1. Pathloss denotes the transmission loss between the user and the eNB. From the profile, it is seen that performance of the urban system will be limited by interference, while the suburban system will be limited by the noise.

In LTE, the total transmit power of the data channel is govern by the eNB according to –

$$P_{\mathrm{PUSCH}} = \min\{P_{\mathrm{CMAX}}, 10\log_{10}(M) + P_{\mathrm{O\_PUSCH}} + \alpha \times PL + \Delta_{\mathrm{TF}} + f(i)\}$$

where P_{cmax} is the maximum transmit power, M is the assigned number of resource blocks, $P_{o,PUSCH}$ is the reference power setting, α is the fractional pathloss compensation factor, PL is the pathloss, Δ_{TF} is an adjustment factor based on the assigned MCS, and $f(i)$ is the closed-loop power adjustment which can be given in the scheduling grant. User selection and resource allocation algorithms are described in [8].

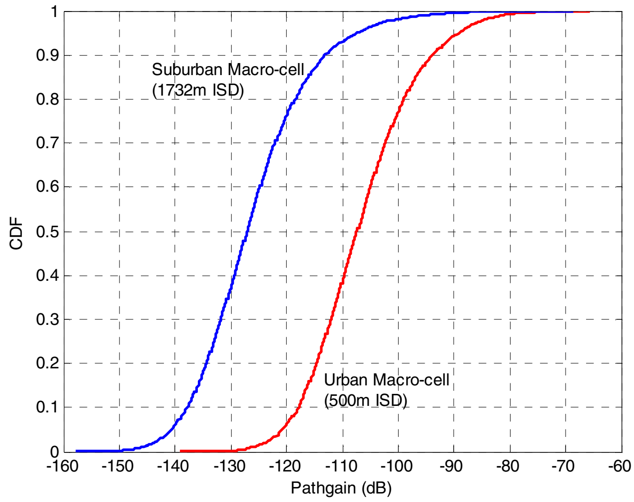

Fig. 1. Pathloss CDF for the deployment scenarios.

Table V illustrates the uplink cell spectral efficiency using full buffer traffic for various systems. From the table, it is seen that LTE offers significantly larger system capacity compared to other cellular systems.

TABLE V
UPLINK CELL SPECTRAL EFFICIENCY (B/S/HZ) [9]

LTE (Rel-8)	UMTS (HSUPA)	cdma1x (1xEV-DO)	GSM (EDGE)
0.82	0.33	0.28	0.14

For MTC analysis, devices are randomly dropped within each cell. The set up assumes an FDD system with 1.4MHz bandwidth and two uncorrelated receive antennas at the eNB. The UE has only one transmit antenna. Performance is evaluated for standard MTC devices which satisfy LTE UE Category-1 requirements. In this case, capacity is defined as the number of devices that can be supported based on the required data rate within the cell. UE Category-1 devices have a maximum transmit power of 23 dBm and support both QPSK and 16-QAM modulation levels. In addition, performance with reduced maximum power (between 14 – 20 dBm) and QPSK-only modulation is also evaluated.

A. *High Data Rate Services*

For LTE capacity analysis of high data rate devices, two data rates were studied – 64 kbps and 16 kbps video streaming. Capacity results for the suburban scenario are shown in Fig. 2. For the large cell size considered, normalized capacity of approximately 36 and 10 devices per MHz can be achieved for 16 and 64 kbps video streaming. This is using standard MTC devices. With devices capable of only QPSK transmission and maximum transmit power of 17 dBm, capacity degrades to 13 and 4 devices per MHz for 16 and 64 kbps video streaming, respectively.

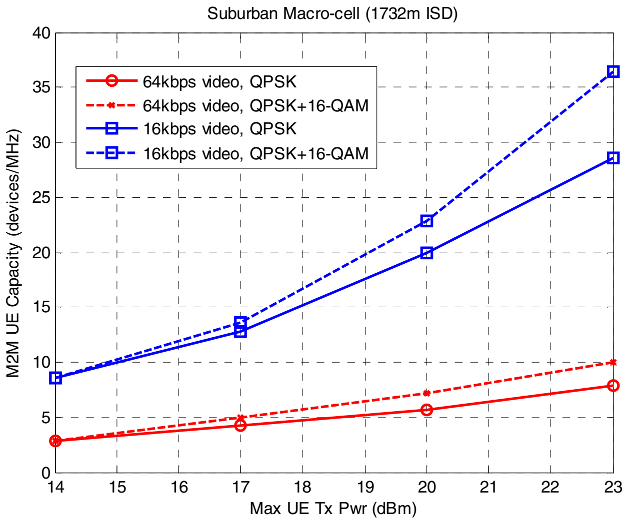

Fig. 2. Uplink capacity for high data-rate services – suburban scenario.

Capacity results for urban scenario are shown in Fig. 3. In this case, with standard MTC devices, normalized capacity of approximately 56 and 14 devices per MHz can be achieved for 16 and 64 kbps video streaming. This is significantly larger than suburban scenario due to the higher received SINR on average. For devices with QPSK only and maximum power of 17dBm, the capacity reduces to 43 and 11 devices per MHz for 16 and 64 kbps video streaming, respectively.

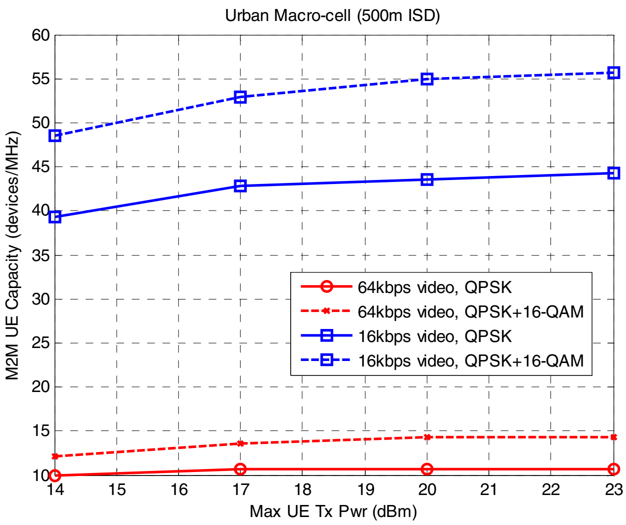

Fig. 3. Uplink capacity for high data-rate services – urban scenario.

Based on the results shown in Fig. 2 - Fig. 3, it is seen that uplink LTE can provide very large capacity and is well suited for high data-rate machine type communications. Low-power and QPSK-only MTC devices, however, will result in a reduction in capacity, especially in large cells where the system is noise-limited.

B. Low Data Rate Services

Fig. 4 illustrates the uplink capacity for low data-rate MTC services. The traffic model is that of a home monitoring service where the device transmits 128 bytes of information every 1 minute (equivalent to a data rate of 17 bits/s). An example application for this type of devices is health-care monitoring as shown in Table II. From the figure, it is seen that a substantial number of devices can be accommodated. When normalized by the system bandwidth, approximately 30,000 devices per MHz can be supported in suburban macro-cell and 48,000 devices per MHz can be supported in an urban macro-cell. Note that, in this case, capacity may be limited by the downlink control channel instead of the data channel.

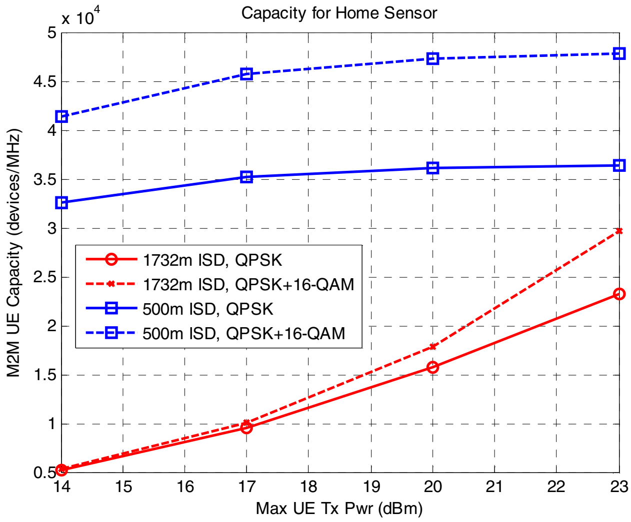

Fig. 4. Uplink capacity for low data-rate devices.

Fig. 4 also illustrates the capacity reduction when low-power MTC devices are deployed. In this case, when the maximum power is limited to 17 dBm, capacity loss of 67% and 6% are observed for suburban and urban scenarios, respectively. In addition, if low-power MTC devices can only used QPSK modulation, additional losses of 2% and 21% are observed.

C. MTC Deployment in Unlicensed Band

As discussed in Section III, certain MTC services are a good candidate for deployment in unlicensed band due to its delay tolerance and low data rates. Fig. 5 illustrates the uplink capacity loss when MTC is deployed in an unlicensed band. In this case, the aggressor system is assumed to be another uplink LTE system occupying the same bandwidth. Access node density is the same as for MTC (i.e. same cellular layout as described in Table VI) and traffic activity of the aggressor is 100%. The maximum transmit power of the aggressor system is 23 dBm. No coordination is performed between the two systems.

The results show that capacity loss on the MTC system operating in an unlicensed band is reasonable. When the maximum transmission power of the two systems is the same, capacity loss is approximately 10%. When maximum transmission power of the MTC devices is 9 dB below that of the aggressor system, capacity loss is on the order of 20%.

Based on these results, it is seen that MTC LTE deployment on unlicensed band is feasible.

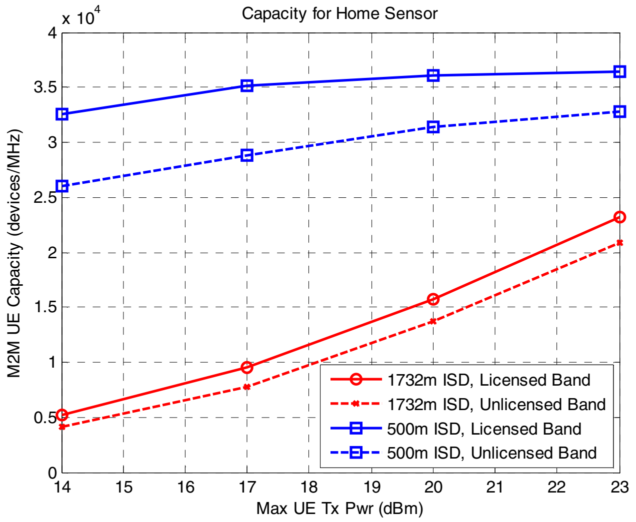

Fig. 5. Uplink capacity loss for MTC deployment in unlicensed band.

D. *Observations*

Several observations may be made regarding machine type communications in LTE.

LTE provides very large capacity and can support large number of devices. Coverage is similar to other cellular systems, but at significantly higher capacity.

Capacity can be significantly reduced with lower maximum power in large cells (noise-limited scenario) or with QPSK-only transmission in small cells (interference-limited scenario). Furthermore, coverage is also reduced with lower maximum power. Since the cost saving from these two techniques is small (see Table III), they should not be mandatory for MTC devices.

Machine type communications on LTE is very robust to interference and can be deployed in unlicensed band with only a small reduction in capacity. For low data-rate devices, capacity may be limited by the control (i.e. by the number of users that can be scheduled) and not the data channel. The results show that LTE is extremely well-suited to carry machine type communications.

VI. Conclusion

In this paper, LTE coverage and system-level performance results for machine type communications are provided. Our results show that LTE is well-suited for machine type communications, offering both extensive coverage and large capacity.

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Table VI
Simulation Parameters

<table>
<tr><th>Parameter</th><th>Urban Macro-cell</th><th>Suburban Macro-cell</th></tr>
<tr><td>Inter-site distance</td><td>500m</td><td>1732 m</td></tr>
<tr><td>Cellular Layout</td><td colspan="2">Hexagonal grid, 19 cell sites,
3 sectors per site</td></tr>
<tr><td>System Bandwidth</td><td colspan="2">1.4 MHz</td></tr>
<tr><td>Penetration Loss</td><td colspan="2">20 dB</td></tr>
<tr><td>Carrier Frequency</td><td colspan="2">2 GHz</td></tr>
<tr><td>Distance-dependent path loss</td><td colspan="2">L=I + 37.6log10(.R), R in kilometers
I=128.1 – 2GHz</td></tr>
<tr><td rowspan="2">Power Control Setting</td><td colspan="2">Fraction power control with Ks=0</td></tr>
<tr><td>α = 0.8, Po=-80</td><td>α = 1.0, Po=-80</td></tr>
<tr><td>Link Adaptation</td><td colspan="2">On, MCS-based link adaptation</td></tr>
<tr><td>Channel model</td><td colspan="2">Typical Urban (TU)</td></tr>
<tr><td>Channel Estimation</td><td colspan="2">Non-ideal</td></tr>
<tr><td>Scheduling</td><td colspan="2">Proportional fairness (α=1.0, β=0.7), frequency non-selective</td></tr>
<tr><td>Receiver</td><td colspan="2">MMSE</td></tr>
</table>