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Re:	
Abstract	This document compares the main PHY contributions from the point of view of achievable capacity.
Purpose	Provide information for comparison of the various PHYs.
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Analysis and calculations of re-use factors and ranges for OFDMA in comparison to TDMA systems

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1. Introduction

In this document we compare the effects of OFDMA features proposed as candidates for the PHY layer of 802.16a. The comparison is made vs. a hypothetical system and we demonstrate the effects of adaptive modulation, adaptive bandwidth allocation, forward power control and improved adjacent channel rejection in a single cell and multi-cell environments.

2. System parameters

The baseline system is a generic system, which would serve as a benchmark for comparison of the different systems. The following parameters are taken for that system:

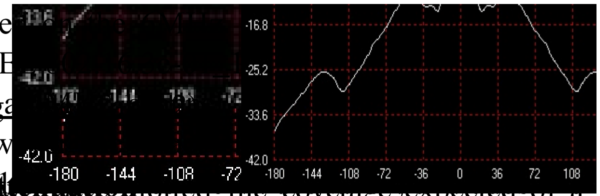
Transmission Power: 20 dBm (both Base station and CPE)
Base station antenna:

- Beamwidth: 60 degrees (6 sectors configuration)
- Gain: 15 dB
- Polarization: Vertical

CPE antenna:

- Beamwidth: 30 degrees
- Gain: 18 dB
- Polarization: Vertical.

Simulated radiation patterns were used for both antennas, both in azimuth and in elevation. The patterns are presented below.



minimal Received Signal Strength (RSS) needed for good reception.

Using the channel models, according to IEEE ... we have plotted the coverage expected of a single cell in Figure 1.

	Basic	Improved	Best

Table 1: Minimal C/(I+N) and minimal RSS

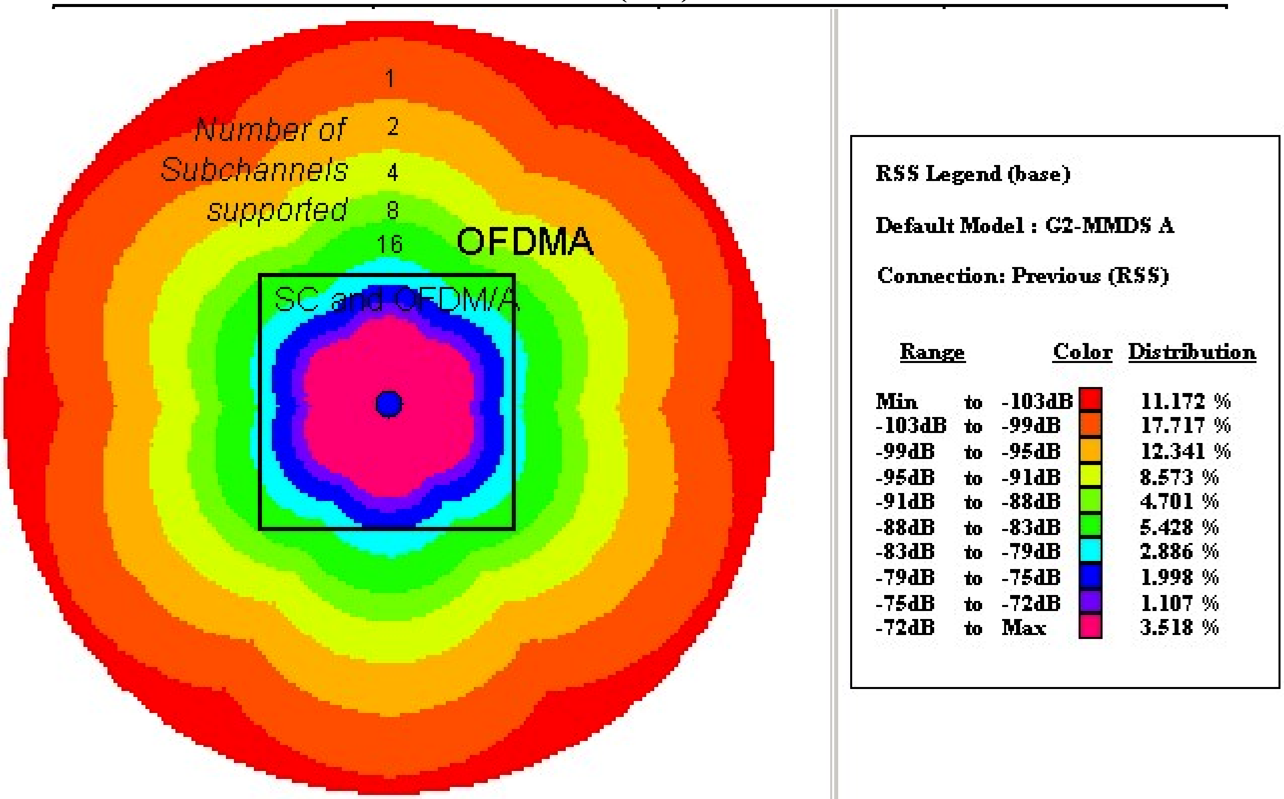


Figure 1: Received Signal Strength

The figure shows a single cell (in the middle), with 6 sectors, the Received Signal Strength (RSS) is shown by the colored contours, according to the enclosed legend, ranging between the lowest range (up to —103dBm, the red zone) to the highest one (above —72 dBm, in magenta)

Basically, with the parameters described above, the system provides a full coverage of a 10km radius cell, as depicted by the 10km x 10km square in the middle of figure 1. Note that if the system is TDMA, the coverage is limited to the blue line, representing the -79dBm limit of the lowest possible rate. With OFDMA on the other hand, the range can be extended to over 20km, provided the number of usable channels is limited. If only a single channel is used, 15dB can be added to the link budget, as stated in IEEE 802163c-01_11, and the coverage can be extended to the orange contour in Figure 1 representing a —103dBm line.

A more important feature than the received signal strength is the C/(I+N), which represents the signal to noise ratio that the system is coping with. This map is shown in Figure 2a, for the basic system, Fig. 2b for the Improved system (as in Table 2) and in figure 2c for the best system.

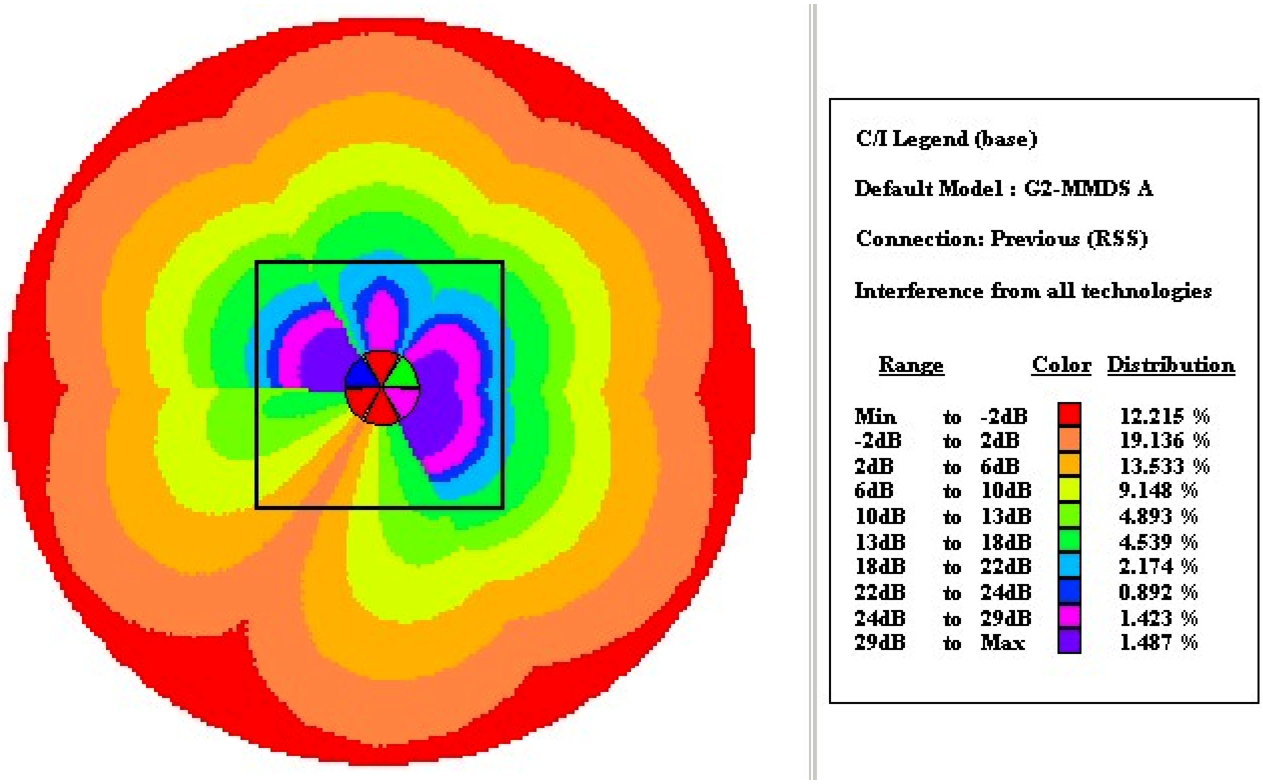


Figure 2a: Carrier to noise plus interference ratio, basic system

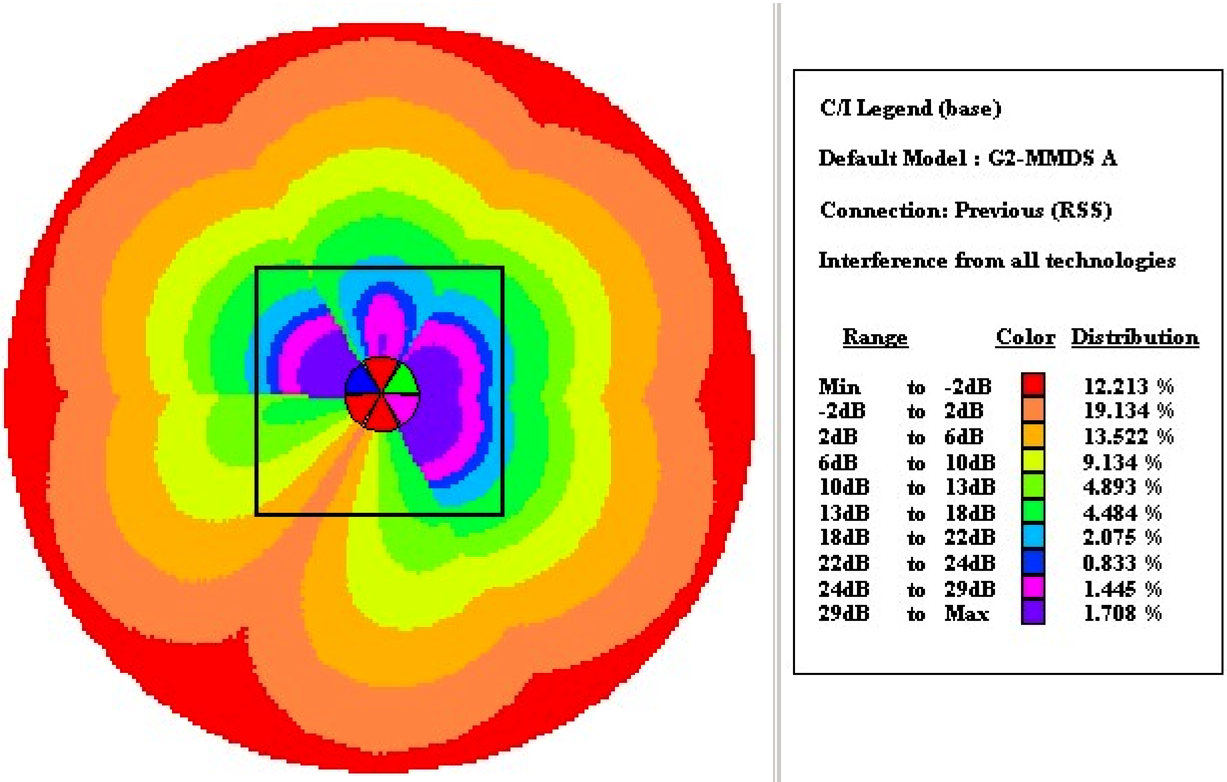


Figure 2b: Carrier to noise plus interference ratio, improved system

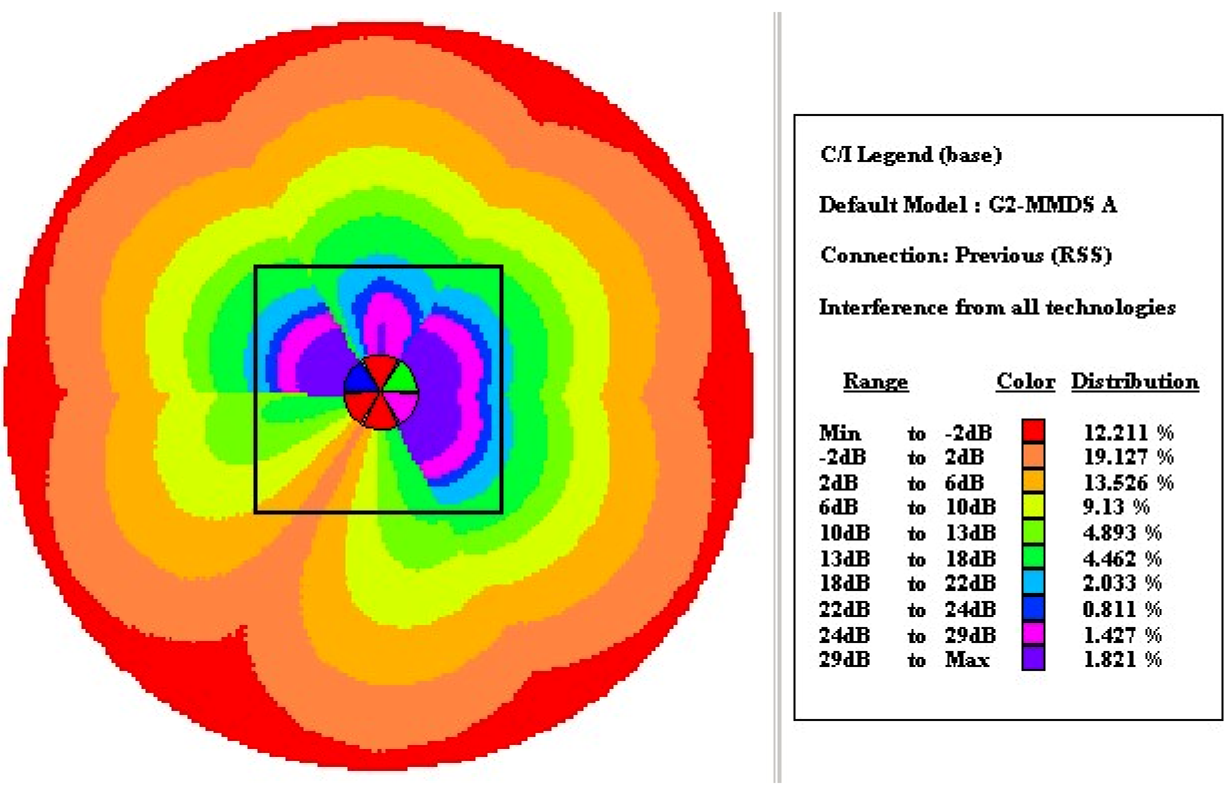


Figure 2c: Carrier to noise plus interference ratio, best system

In addition to the C/I values, this map also shows the channel allocated to each sector by the small pie chart in the middle indicating by red- the first channel, green, the second channel, blue, the third one and magenta —the fourth. Thus, the map describes four possible deployment scenarios:

The same channel operates in neighboring sectors. (The south and southwest sectors). All those sectors operate in the same channel and the only isolation mechanism in this case is the antenna pattern.

Two sectors operating in adjacent channels, as the case of the northeast sector. This configuration allows low and medium bit rates for most of the sector, and high bit rate for the improved and best systems, with better adjacent channel attenuation. Note that in this case the northern sector suffers from co-channel interference from the south western sector.

The two sectors operating in 2^{nd} adjacent channels (the northwest sector). In this case the C/(I+N) allows for high bit rate in part of the coverage area.

Two sectors operating in further channels (the southeast sector in figure 2). The coverage pattern is similar to that of the previous case.

It should be noted that this analysis is a worst-case analysis for the OFDMA, as it assumes for each sector that the other sectors are full. Ideally, two adjacent sectors can have 16 non-overlapping sub-channels in each, thus enable co-channel adjacent sector operation. This is equivalent to FDMA channel separation, only with a wider more flexible bandwidth. Furthermore, OFDMA can handle 12 overlapping carriers (out of 48/53 carriers assigned for each sub-channel), which increases the number of non- interfering sub-channels to 21 per sector. As the allocation is done randomly, it is safe to assume that in each sector 5 sub-channels can operate without causing interference to its neighbors.

OFDMA can also benefit from the flexibility to transfer and trade-off load and range between sectors. This flexibility improves the total capacity as it provides an effective wider channel thus improving the statistical multiplexing gain. We, however, have not included this effect in the present analysis.

4. Multi-cell operation

For the multi-cell coverage, we will assume hexagonal coverage, as depicted in figure 3, with 2km and 6km radius cells.

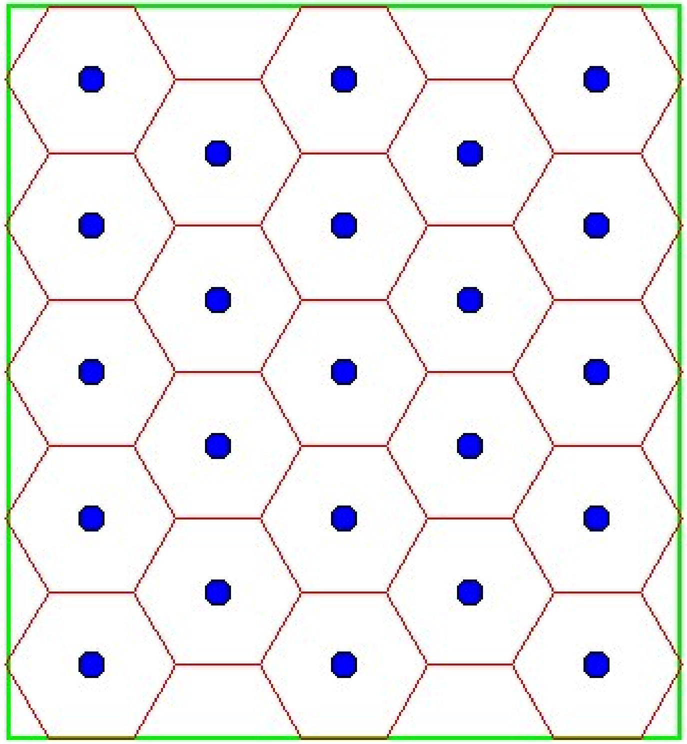


Figure 3: Hexagonal coverage of an area

It can be shown that the maximal interference is received along the line connecting the base stations, as depicted in Figure 4, because along that line there is a main beam to main beam illumination between the terminal station and base station antennas. Assuming co-channel situation, equal transmission power and antenna gains, and assuming a channel model in accordance with IEEE 802163c-01_29r1, of the form $PL = Ad^{\gamma}$, the C/I received by a terminal station located at range x from its own base station is:

$$\frac{C}{I} = \left(\frac{2R + x}{x}\right)^{\gamma}$$

which gets its minimum as x gets its maximum, at $x = R$. Thus the minimal C/I ratio due to co-channel interference is 3^{γ}.

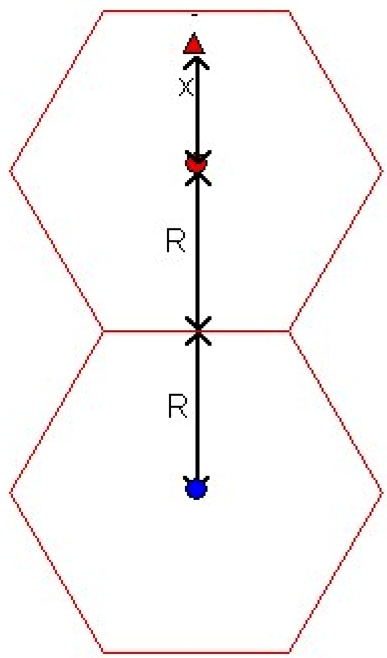
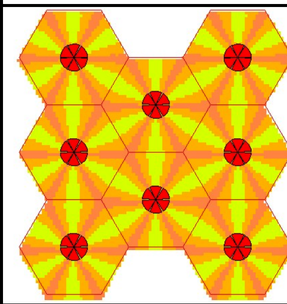
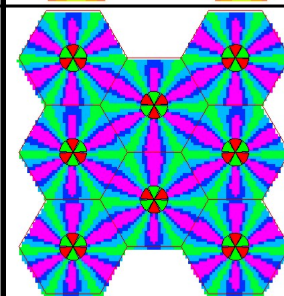
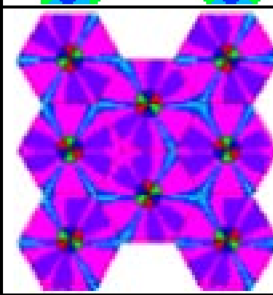
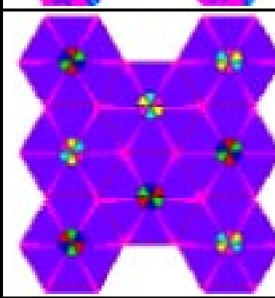


Figure 4: inter- cell interference

The values of γ, assuming 20m base station antenna, is 5.08, 4.725, 4.5, which yields a C/I value of 24 dB, 22.5dB and 21 dB for terrain types A, B and C respectively. Thus inter-cell interference has the potential to limit the C/I, such that it makes it impossible to use high bit rates, if a frequency is re-used in neighboring cells. Table 3 describes the C/I distribution in the hexagonal configuration as a function of the number of frequency channels used, together with a typical pattern of the C/I ratio. The corresponding values for the colors can be seen in the legend of figure 2. The various channels are indicated by a color code in the pie chart in the center of each cell. The table does not include the effect of forward APC, which improves the C/I.

Table 3: C/I distribution as a function of the number of frequency channels and adjacent channel interference rejection capability

	C/I Distribution	

freq. hannels	C/I (dB)	Basic		Improved		Best		Typical Pattern
		2km	6km	2km	6km	2km	6km	
	-2 — 2 2 — 6 6-10	23% 45% 32 %	23% 44% 33%	-	-	-	-	
	24-29 22-24 18-22 13-18	19.5% 19.2% 33% 28%	17% 20% 34% 29%	29% 18% 30% 24%	27% 19% 30% 24.5%	33.7% 16.54% 30% 20%	31% 17% 30% 22%	
	>29 dB 24-29 22-24 18-22	30.6 % 50.7% 11.6% 7%	16.2% 50.65% 20.45% 13%	30.7 % 51% 12% 6%	37.7 % 46.6% 13.6% 2%	85 % 15% 0% 0%	53% 38% 8.5% 0.5%	
	>29 dB 24-29 22-24 18-22	33 % 49.4% 11.6% 5.6%	21 % 55% 15.5% 8.9%	72.3 % 26.3% 1.3% 0%	48.53 % 43.9% 6.8% 0.68%	88 % 12% 0 0	66.7 % 30.6% 2.6 %	

The table shows a very small difference between the 2km and 6km cell sizes. Improving the adjacent channels rejection

5. Capacity Calculation

The average capacity supported by TDMA systems using adaptive modulation, can be calculated according to the area ratios indicated in table 3, assuming a uniform distribution of customers within the area.

For OFDMA, the calculation is more elaborate, because, thanks to the forward power control, power can be allocated to different users, and further extend the capacity, if the instantaneous distribution of customers is favorable. We concentrate that we choose to allocate power to increase the system capacity, and not for increasing the cell range.

For the single frequency case, the channel can be efficiently partitioned by OFDMA to several sub-channels with interference pattern similar to that of the best case described above. We can assume that in each sector we have 5 OFDMA sub-channels, with effectively no mutual interference. The data rate in this case would ideally be 5*(15/32) = 2.35 Mb/s, which is equivalent to 0.39 bps/Hz, or 2.35 bps/Hz/cell.

In the case of two frequencies, one can also partition the band and enjoy the advantage of forward power control. In the best case for 2km cells, assuming a uniform distribution of CPEs and hence sub-channels in the area, we can in average reduce 4.5dB of power in 33.7% of the sub-channels, and another 1dB in average for another 16.54% of the sub-channels and still use the medium sub-channel rate of 10/32 Mbps. The power could boost that of the other sub-channels. 30% of the rest need in average boost of 2 dB, while another 20% would need a boost of 6.5 dB in average to reach the higher data rate value. A rough calculation shows that the resulting data rate would be 9.2 Mbps/sector, instead of 7.52 Mbps/sector achieved by TDMA.

It should be noted that it is the downlink that limits the capacity. For the uplink, it is possible to allocate all the terminal station power to the reduced bandwidth, while using a higher modulation order, and hence higher capacity with better spectral efficiency.

Table 4 summarizes the average capacity and spectrum efficiency according to the cases described above in terms of the overall capacity per sector, the spectral efficiency in bps/Hz and the system efficiency in terms of bps/Hz/cell.

Table 4: Capacity per sector and efficiency of TDMA systems

# Freq. Channels		Sys. Type	Basic		Improved		Best	
			2km	6km	2km	6km	2km	6km
1	Mbps/sector	TDMA	0	0	0	0	0	0
		OFDMA	**2.35**	**2.35**	**2.35**	**2.35**	**2.35**	**2.35**
	Bps/Hz	TDMA	0	0	0	0	0	0
		OFDMA	**0.39**	**0.39**	**0.39**	**0.39**	**0.39**	**0.39**
	Bps/Hz/cell	TDMA	0	0	0	0	0	0
		OFDMA	**2.35**	**2.35**	**2.35**	**2.35**	**2.35**	**2.35**
2	Mbps/sector	TDMA	6.92	6.83	7.4	7.3	7.52	7.43
		OFDMA	**8.6**	**8.7**	**8.96**	**8.92**	**9.2**	**9.25**
	Bps/Hz	TDMA	1.15	1.14	1.23	1.22	1.25	1.24
		OFDMA	**1.43**	**1.45**	**1.49**	**1.49**	**1.53**	**1.54**
	Bps/Hz/cell	TDMA	3.46	3.42	3.70	3.65	3.76	3.72
		OFDMA	**4.30**	**4.35**	**4.48**	**4.46**	**4.60**	**4.63**
3	Mbps/sector	TDMA	11.17	10.18	11.2	11.8	14.25	12.6
		OFDMA	**13.2**	**11.9**	**13.3**	**13.44**	**15**	**14.2**
	Bps/Hz	TDMA	1.86	1.70	1.87	1.97	2.88	2.10
		OFDMA	**2.20**	**1.98**	**2.22**	**2.24**	**2.50**	**2.37**
	Bps/Hz/cell	TDMA	3.72	3.39	3.73	3.93	4.75	4.20
		OFDMA	**4.40**	**3.97**	**4.43**	**4.48**	**5.00**	**4.73**
6	Mbps/sector	TDMA	11.33	10.59	13.6	12.4	14.4	13.3
		OFDMA	**13.1**	**12.4**	**15**	**15**	**15**	**15**
	Bps/Hz	TDMA	1.89	1.77	2.27	2.07	2.40	2.22
		OFDMA	**2.18**	**2.07**	**2.50**	**2.50**	**2.50**	**2.50**
	Bps/Hz/cell	TDMA	1.89	1.77	2.27	2.07	2.40	2.22

		OFDMA	**2.18**	**2.07**	**2.50**	**2.50**	**2.50**	**2.50**

The table shows a consistent advantage of OFDMA of between 5% to 25% in efficiency.

6. Conclusions

This document is a preliminary analysis of the spectral efficiency and spectrum utilization efficiency of an OFDMA system, in comparison to a baseline TDMA system. The main conclusions of this analysis are:

- OFDMA provides a graceful degradation for long range and NLOS conditions. Namely it can trade off capacity with range thus achieving twice the range of TDMA systems. It does that by making use of the statistical nature of subscribers activity patterns and enables service to distant customers or higher rate transmissions by using higher constellation modulations with a narrower bandwidth.
- Adjacent channel interference rejection capability is important. It provides a non-negligible improvement in capacity and spectrum efficiency for the cases where the spectrum is scarce.
- OFDMA is capable of operation even in a single frequency deployment, namely it can operate in very low C/(I+N) ratios.
- OFDMA provides a significant improvement in capacity. It is superior to TDMA in all the cases tested.

As mentioned above, this is only a preliminary analysis. We expect the advantages of OFDMA to be even more significant with higher cell ranges, in which there is a higher dynamic range of the C/(I+N) values will enable even a more flexible power allocation. We also expect that statistical multiplexing of the wider channels of OFDMA will show an additional advantage.

We would also like to include in future work:

- Comparison in realistic scenarios, using terrain information and non-uniform distribution.
- A simulation to estimate the favorable vs. non-favorable scenarios for OFDMA
- Analyses to estimate the statistical multiplexing gain in various scenarios.
- Additional data for other proposed system for a more realistic comparison