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OFDM – sub-channelization improvement and system performance – selected topics

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General

After the enhancement of the IEEE 802.16a with the sub-channelization optional mode for OFDM 256FFT, and taking into consideration observations made by the Ballot Resolution Committee, we propose an approach that will resolve the inconsistency between the OFDM and OFDMS (OFDM with up-link sub-channelization) and will enhance the OFDMS mode.

This proposal is not identical with our previous comments. We will discuss, when necessary, the implications on system efficiency, in order to respond to the Ballot Resolution Committee concerns.

The Ballot Resolution Committee resolution has addressed performance aspects of some parameters, as peak data rate and delay. The computed performance is presented here, together with a comparison between P-MP and Mesh systems, using OFDM, OFDMS and OFDMA.

OFDMS Overview

- Sub-channel definition
    - Carrier allocation
        - 4 clusters / sub-channel;
        - Frequency diversity
        - Pseudo random distribution

3	1	4	2	1	3	2	4	1	3	2	4	3	1	4	2

- Pilot allocation
    -2 pilots / channel (unfortunately, no consensus was achieved for introducing 192 data carriers and 16 pilot carrier)
- Coding
    - Convolutional only

Sub-channel grouping: 1,2,3,4, 1+2, 3+4.

Bandwidth request in sub-channelized mode

In the basic OFDM mode, there are 2 mechanisms for BW request:
- Full region, in which the are allocated in the UP-link map contention intervals for BE request; the BW request is done by BW request headers (6 bytes long)

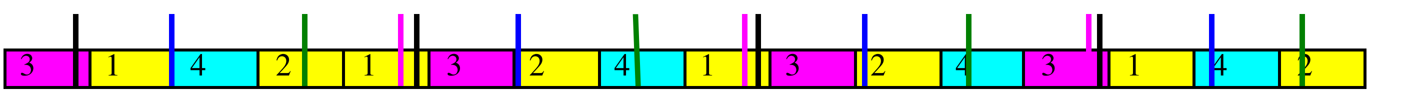
- Focused mode, in which the BW request is done by transmitting 2 symbols, on which only 4 sub-carriers are modulated with one of contention codes. The allocated sub-carriers per sub-channel are equally spaced, presenting a lower robustness to channel notches, relative to the case of a pseudo random distribution.

In the sub-channelized mode, there is only focused contention, based on the same carrier allocation as above. The existing carrier allocation is shown bellow:

Table 116bc—OFDM Contention channels

Contention Channel Index	carrier offset index 0	carrier offset index 1	carrier offset index 2	carrier offset index 3
0	-100	-50	+1	+51
1	-99	-49	+2	+52
2	-98	-48	+3	+53
...	...	...	...	...
k	k-100	k-50	k+1	k+51
...	...	...	...	...
48	-52	-2	+49	+99
49	-51	-1	+50	+100

The carriers used in focused contention, for every contention channel, occupy generally 2 sub-channels.
These 2 sub-channels are different from the couple of sub-channels that can be combined for data transmission, so actually no sub-channel can be used during the focused-contention.
For example, are shown contention channels having indexes 0,16,32,48. The sub-carriers allocated to the same "focused contention channel" have the same color.



Summary of the possible BW request mechanisms

	Full Region	Focused
All sub-channels	OFDM	OFDM + OFDMS
Sub-channel 1	OFDMS	OFDMS
Sub-channel 1,2	-	OFDMS

Performance Analysis

The performance indicator will be percentage of the used bandwidth for the contention interval. Will be considered a FDD system having 3.5MHz channel bandwidth.

The studied example will consider that every contention BW request interval should permit 1..N stations to request BW, with some 10%, 20% and 30% contention probability. The guard interval will be chosen to be 1/16 from the FFT duration. The MAC frame duration will be 5ms.

A. Full region, OFDM and OFDMS, 1 sub-channel

In full region, OFDM, the BW request burst will be composed of min. 2 symbols:
- Preamble – 1 symbol
- MAC BW request header: 6 bytes
- Padding bits.

We will define the slot time S_{time} as equal with 2 OFDM symbols. Every OFDM symbol, at QPSK, coding rate 0.5, will be able to carry 24 bytes/symbol. At same rate, 1 sub-channel will carry 6 bytes/symbol.
The success probability is given by:

$$p = (1 - \frac{1}{M})^{N-1}$$

If the success probability is relatively high, the delays associated with BW request failures are avoided.
In a system designed for low success probability, the back-off mechanism will introduce higher delays.
The following table and graph show the "used bandwidth" for BW request, for different cases of system design:
90% success probability
75% success probability
60% success probability.

Table 1a – >85% success probability

SS **number** Used BW (%)	**1**	2	3	4	5	6
Success probability (%)	100	91	89	88	87	87
OFDM - "Region-full"	3	32	49	65	81	97
OFDMS - "Region-full" – 1 sub-channel	3	8	12	16	20	24

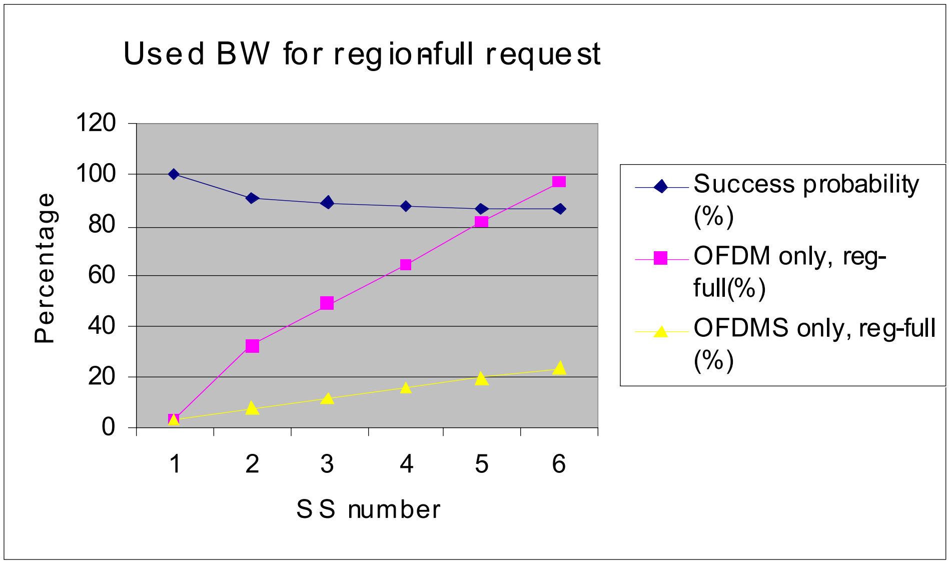


Table 1b – >80% success probability

SS number / Used BW (%)	1	2	3	4	5	6
Success probability (%)	100	86	83	81	81	80
OFDM - "Region-full"	3	22	32	43	54	65
OFDMS - "Region-full" – 1 sub-channel	3	5	8	11	14	16

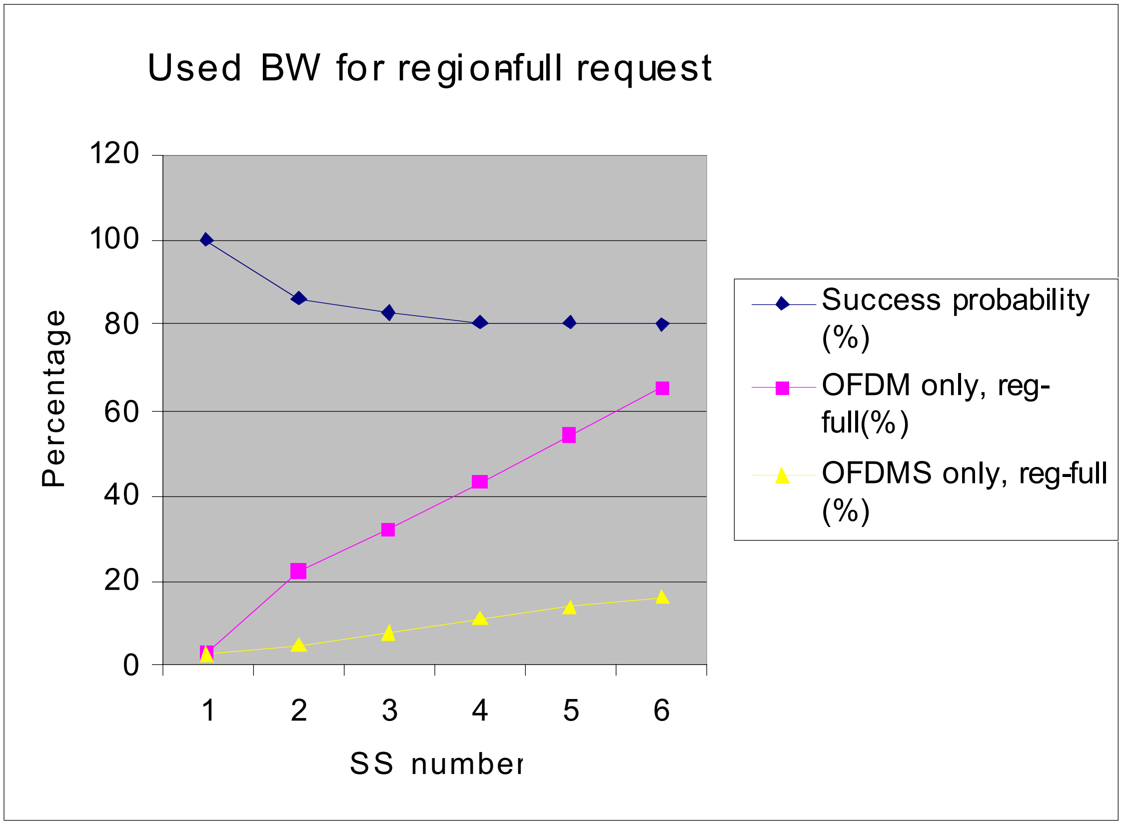


Table 1c – >60% success probability

SS number Used BW (%)	1	2	3	4	5	6
Success probability (%)	100	67	64	63	62	62
OFDM - "Region-full"	3	11	16	22	27	32
OFDMS - "Region-full" – 1 sub-channel	3	3	4	5	7	8

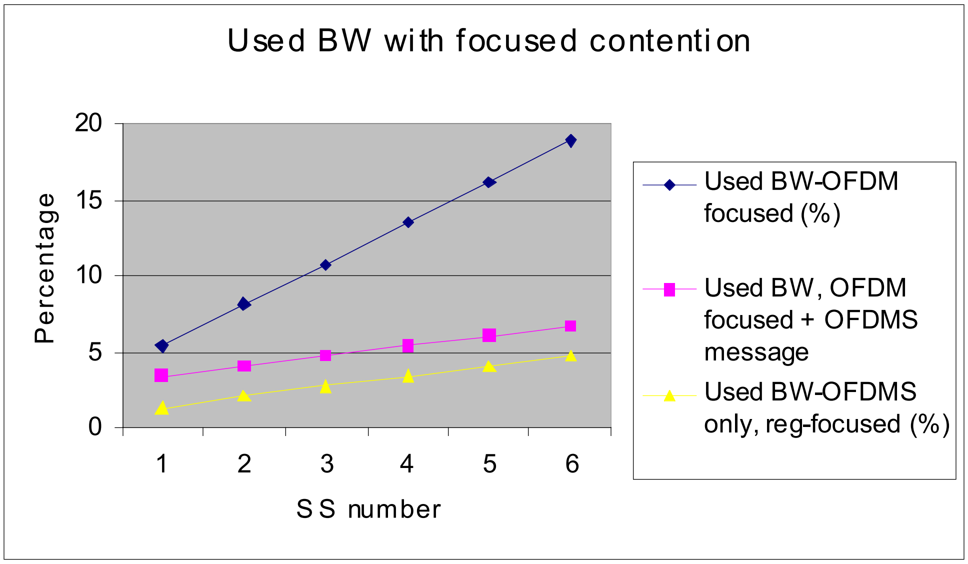
2. Focused region, OFDMS, 1 sub-channel

The "focused BW request" is actually a polling request. The BW request MAC header will be transmitted as uni-cast, during next up-link period. The penalty is a higher delay – typically 2 MAC frames.
The used bandwidth for the cases when the focused contention uses all the sub-channels (OFDM mode) or only one sub-channel is shown bellow. For OFDM mode was calculated the used BW in the case that the BW-REQ message is transmitted in OFDM mode or using only one sub-channel.

Table 2

SS number Used BW (%)	1	2	3	4	5	6
OFDM focused (%)	5.41	8.11	10.81	13.51	16.22	18.92

OFDM focused + OFDMS message	3.38	4.05	4.73	5.41	6.08	6.76
OFDMS only, region-focused	1.36	2.04	2.72	3.4	4.08	4.76



Advantages of focused BW request with sub-channelization:

1. The penalty of focused BW request, on one channel, is the lowest.
2. It eliminates the need for packet fragmentation, for the channels not-used in BW request.
3. Allows continuous up-link, independent of MAC frame time, in FDD.

In order to take advantage, especially in FDD systems, of avoiding packet fragmentation, the "focus contention channels" should be allocated within sub-channel boundaries. The proposed carrier allocation is shown in the next table.

Advantages of the new focused contention channels allocation:

1. Pseudo random sub-carrier distribution;

The remaining sub-channels can be used for data transmission.

Table 3

Contention Channel Index	Carrier offset index 0	Carrier offset index 1	Carrier offset index 2	Carrier offset index 3	Sub-channel
0	-87	-50	1	64	1
1	-86	-49	2	65	1
…	…	….	…	….	1

11	-76	-39	12	75	1
12	-75	-12	39	76	4
13	-74	-11	40	77	4
…	…	…	…	…	4
23	-64	-1	50	87	4
24	-100	-37	14	51	3
25	-99	-36	15	52	3
…	…	…	…	…	3
35	-89	-26	25	62	3
36	-62	-25	26	89	2
37	-61	-24	25	88	2
…	…	…	…	…	2
47	-51	-14	37	100	2

Network entry using one sub-channel

Network entry on only one sub-channel will allow increasing the cell size according to 6dB in link budget gain. We agree now that in this mode the entire channel will be used. No data will be transmitted on the non-used sub-channels.
In order to allow both OFDM and OFDMS stations to enter the network, will be necessary to allocate both OFDM and OFDMS network entry intervals.
Nevertheless, we consider that the penalty is not significant.
In the calculations, we have considered that 2/3 of the subscriber stations will use OFDM network entry and only 1/3 of the stations will use the OFDMS network entry. We have taken into account both the initial phase, for synchronization and coarse power control, as well as the periodic maintenance. Bellow are the results.
The difference was calculated considering that all the SS will work only in OFDM mode, versus 2/3 in OFDM mode and 1/3 in OFDMS mode.

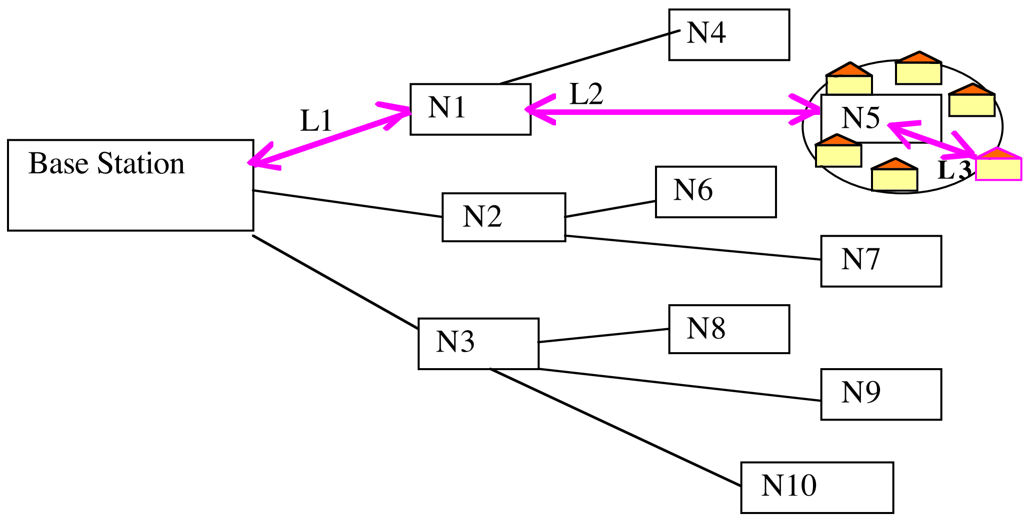
SS number per interval Used BW (%)	1	2	3	4	5	6
Success probability (%)	100	91	89	88	87	87
Network entry - OFDM	0.0547	0.1093	0.16402	0.219	0.273	0.328
Network entry - OFDMS	0.0359	0.0718	0.10771	0.144	0.18	0.215
Maintenance - OFDM	0.028	0.028	0.028	0.028	0.028	0.028
Maintenance - OFDMS	0.005	0.005	0.005	0.005	0.005	0.005
Total OFDM	0.1241	0.2057	0.2873	0.369	0.451	0.532
Difference – OFDM+OFDMS	0.0731	0.109	0.14495	0.181	0.217	0.253

For a typical case of 2 SS per initial ranging interval, the penalty will be only 0.11%

Peak-rate performance

The Ballot Resolution Committee had also concerns regarding the peak-rate performance. Comparative studies are done here, targeting to show the system peak-rate performance for OFM, OFDMS, OFDMA in P-MP network topology and OFDM in Mesh topology. The peak-rate OFDMS and OFDMA performance is calculated for one sub-channel, when using a 3.5MHz FDD paired channel.

The Mesh, being TDD, is considered to work in a 7MHz channel, with equal Rx and Tx times. The MAC frame is taken 5ms for P-MP and 10ms for Mesh (as required by HIPERMAN comparison criteria).
The Mesh topology was considered only for 10 active nodes, 3 nodes in Base Station vicinity – Level 1, with 3 active links, and 7 nodes at Level 2, with 7 active links. For simplification, the possible links between the nodes were omitted. Every node is supposed to feed a mini-cell. See figure bellow, showing a deployment example for a Mesh sector.



Up-link peak rate

BW-REQ is done in the mandatory modes for OFDM and OFDMA, and in region-full – 1 sub-channel, for the OFDMS.
For P-MP OFDM, we consider a system with 250 **residential subscribers** per sector, from which 20% active (50 subscribers).
Lets suppose that 80% of the active users are doing Internet browsing and 20% up-link file transfer.
If we take the Internet browsing example, with average 500 bytes DL packets, at an average rate of 8Mb/s a packet will be transmitted in 2ms and all the 40 subscribers will transmit in 80ms. This duration being much longer than the MAC frame time, the BW request in up-link for TCP ACKs, will be based mainly on BW request in contention, instead of piggy-back requests. Supposing 1/0.080*40 = 500UL packets to be transmitted, in average will be 2.5 BW requests per 5ms MAC frame, when assuming 100% success probability. Practically the 100% success probability conducts to extremely large intervals for contention, so will design the system for only 80% success probability in BW request.

The up-link traffic will come from 10 users doing FTP transfer. The total up-link data will be limited by the up-link available transfer time.
The P-MP systems will allow 3 SS in contention mode for BW request, the Mesh nodes will allow 2 SS per node, with a 80% target success probability. OFDMA in focused BW request mode will need 1% of bandwidth, but due to the small difference was not inserted a special column. The nodes will request BW in unicast mode.

For every frame, the used up-link BW for region-full request will be, taking into consideration 8Mb/s peak data rate:

	OFDM	**OFDMS Full region 1 chann.**	**OFDMS Focused 1 chann.**	**OFDMA Full region 2 channels**	**Mesh**
Used for BW request	32%	8%	3.4%	4%	27%
Used for UL data	68%	92%	96.6%	96%	63%

Channel number	1	4	4	32	3 + 2*7 = 17
Max. UL capacity	5.4Mb/s	7.3Mb/s	7.7Mb/s	7.6Mb/s	5Mb/s
Max. UL brut peak rate per node / sub-channel at 8Mb/s	5.4 Mb/s	1.8Mb/s	1.9Mb/s	240kb/s	294kb/s
Max. UL brut peak rate per node / sub-channel at 4Mb/s	2.7Mb/s	0.9Mb/s	0.95Mb/s	120kb/s	147kb/s

In the table above the protocol overhead was not considered.

Conclusion: in uplink, the P-MP OFDM mode has to highest peak-rate performance. The OFDMS comes on the second place, with _ of the OFDM performance. The OFDMA and Mesh systems have a low up-link peak-rate performance.

OFDMS Downlink peak rate

It is a big difference in the downlink peak data rate between P-MP and Mesh systems.
The P-MP systems (OFDM, OFDMS, OFDMA) can provide every subscriber with peak instantaneous data rate. In the mesh systems, even if is active only 1 subscriber, depending of the total link number from the BS, the subscriber will receive lower data rate. For example, lets take the subscriber connected to N5. The down-link traffic goes through 3 segments, so this subscriber will not be able to receive more than 1/3 of the peak rate (assuming that same modem rate will be used on every link), as compared with P-MP systems.

Capacity

The system capacity is defined as the aggregate traffic at system ports. Here also, there is a difference between the Mesh and P-MP systems, due to the fact that the Mesh will transmit the same data on a number of links.

OFDMS Delay Performance

We remain in the FDD arena for OFDMS and OFDMA systems.
The transmissions delays are considered to approximately be:

- P-MP OFDM, OFDMS and OFDMA: 1 MAC frame + packet transmission delay
- Mesh: same as before for the nodes in BS vicinity, 1..2 MAC frames + packet transmission delay for the second level nodes and SS associated to the first level nodes, 2..3 MAC frames + packet transmission delays for the SS connected to the second level nodes. Every Mesh node, acting as a small BS, has to re-classify the traffic, and this may introduce significant delays, with MAC frame granularity, not actually taken into account here.

The packet transmission delay is 2 times lower for Mesh systems, as compared with OFDM P-MP systems, due to using of a double BW (same assumption as in the precedent paragraph).

The transmission delay for up-link long packets (1518 bytes), for OFDM, OFDMS and OFDMA, for different sub-channel number, is shown bellow:

	Packet transmission delay (ms)					
	All OFDMA	**16 sub-chan**	**8 sub-chan**	**4 sub-chan/ All OFDMS**	**2 sub-chan**	**1 sub-chan**
OFDMA, QPSK, rate 1/2	4.128	8.256	16.512	33.024	66.048	132.096
OFDMA, 16QAM, rate 3/4	1.419	2.838	5.676	11.352	22.704	45.408
OFDMA, 64QAM, rate 3/4	0.258	0.516	1.032	2.064	4.128	8.256
OFDMS, QPSK, rate 1/2				4.42	8.704	17.408

OFDMS, 16QAM, rate 3/4				1.564	2.924	5.848
OFDMS, 64QAM, rate 3/4				0.34	0.51	1.02

Conclusions:

- **P-MP**

For the given example (16 QAM, rate _), the maximum packet transmission delays are:
<1.5ms when the full BW is used;
< 6ms for the 1 OFDMS sub-channel
< 46 ms for 1 OFDMA sub-channel
The BW request delays may add some 5ms (the duration of the MAC frame)

- **Mesh**

The packet transmission delay is 0.75ms * link number
for 1 link, < 0.75ms
for 3 links, < 2.25ms
The BW request and scheduling delays may add, in up-link, 1..4 MAC frame periods (10..40ms)
The resulting total delay will be higher than 10..40ms.

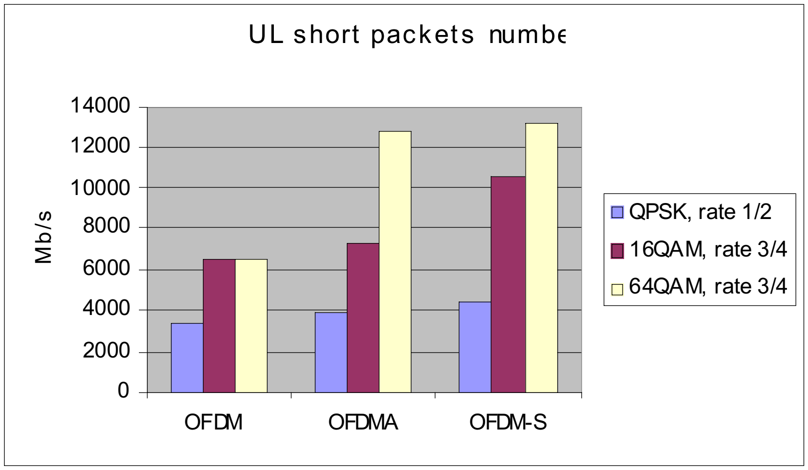
Conclusion: the maximum packet transmission delay is relatively low for P-MP OFDM and OFDMS systems, and high for OFDMA and Mesh systems.

OFDMS short packet performance

The short packet performance will be considered only for P-MP systems, using OFDM, OFDMA and OFDMS.
The performance is affected by the transmission granularity that results from the block size used in the coding schemes:
- 1 full symbol for OFDM, or 192 data carriers, carrying:
at 64 QAM, rate _, : 108 bytes
at 16 QAM, rate _: 72 bytes
at 4QAM, rate _: 24 bytes.
- 48*3 carriers for OFDMA, carrying:
at 64 QAM, rate _, : 82 bytes
at 16 QAM, rate _: 54 bytes
at 4QAM, rate _: 18 bytes.
- 48 carriers for OFDMS, carrying:
at 64 QAM, rate _ : 27 bytes
at 16 QAM, rate _: 18 bytes
at 4QAM, rate _: 6 bytes.

The resulting up-link short packet IPoE number is:

Up-link short packet number	**OFDM**	**OFDMA**	**OFDM-S**
QPSK, rate 1/2	3300	3938	4400
16QAM, rate 3/4	6600	7314	10560
64QAM, rate 3/4	6600	12800	13200



Conclusion: for a short packet traffic, at all the rates, OFDMS outperforms OFDM and OFDMA by 20% ..48%.

Conclusions

1. OFDMS (OFDM 256FFT with sub-channelization) is the best compromise between coverage, peak data rates, capacity, delay and short packet performance.

2. The OFDMS features are in this moment artificially limited in the 802.16a standard, without any technical justification.