Orthogonal Frequency Division Multiple Access : Is it the Multiple Access System of the Future?

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Abstract

There is significant interest worldwide in the development of technologies for broadband cellular wireless (BCW) systems. One of the key technologies which is becoming the de-facto technology for use in BCW systems is the orthogonal frequency division multiple access (OFDMA) scheme. In this tutorial article, we discuss the reasons for the popularity of OFDMA and outline some of the important concepts which are used in OFDMA as applied to BCW systems. We shall use the IEEE 802.16 based WiMAX standards for highlighting some of the significant ideas in the practical use of OFDMA systems.

1. Introduction

Broadband Cellular Wireless (BCW) systems are expected to be rolled out in the near future to satisfy demands from various segments. As demand for mobile services continuous to grow worldwide system vendors and cellular operators have noticed the enormous popularity of 2nd generation mobile cellular systems and are keen to extend this trend to BCW systems. Several challenges exist in the development and deployment of BCW systems and research work addressing these challenges is ongoing in several labs around the world. The orthogonal frequency division multiple access (OFDMA) based systems are being adopted for use in different flavors of BCW systems [1]. The IEEE 802.16d and 802.16e standards which are popularly known by the industry forum name WiMAX are being considered for BCW systems and are the first standards to use the OFDMA technique [2]. We shall refer to these standards as WiMAX which is a forum driving the adoption of the technology and fostering interoperability among products [3]. Other proprietary BCW systems like the one pioneered by Flarion [1] which is likely to influence emerging standards like IEEE 802.20 [4] and other evolutions to 3G cellular systems [5] have also used OFDMA. Hence, there seems to be a trend emerging with respect to the use of OFDMA in BCW systems and this forms a motivation for this tutorial article. Our objective is to outline the key features of OFDMA and highlight the advantages of using OFDMA in solving important technical challenges in BCW systems. We shall use the WiMAX system as an example to showcase the practical use of the various OFDMA related concepts.

One of the challenges in wireless systems is the severe frequency selective fading (FSF) caused due to the multipath channel between the transmitter and the receiver. The signal bandwidth in BCW systems typically exceeds the coherence bandwidth of the multipath channel [6]. Consequently, FSF results and this leads to intersymbol interference (ISI) which is usually dealt with by physical (PHY) layer solutions like orthogonal frequency division multiplexing (OFDM) which can address the problem in an elegant manner [7]. Also, the use of multiple antennas to enhance spectral efficiency and reliability is almost a certainty given the findings from the latest research results in this area [6]. Hence, a transmission technique which is amenable to the use of multiple antenna schemes will be crucial in the next generation wireless systems. In BCW systems, it is expected that support for multiple users with disparate traffic requirements will be a necessity, i.e., users with low bandwidth requirements will have to be served alongside an user with users who have high bandwidth requirements. This implies that a medium access control (MAC) method which can satisfy these disparate requirements efficiently will be necessary in BCW systems. Spectral Efficiency is a major concern and tight frequency reuse is likely to be enforced by spectrum regulatory agencies (like the FCC in the U. S) in many countries. Consequently, a BCW system should take multicellular deployment with tight frequency reuse into perspective so as to achieve high spectral efficiencies.

Thus, one can summarize the challenges in BCW systems as follows:

- Frequency selective fading leading to ISI
- Incorporation of multiple antenna techniques to enhance spectral efficiency and reliability
- Handling multiple users with different service/traffic requirements efficiently
- Multicellular deployment with tight frequency reuse to achieve high spectral efficiency

In this paper we shall present the OFDMA technique for BCW systems and comment on the effects of these challenges**.** We shall first present a short review of the OFDM transmission technique [7] as it forms an important part of OFDMA. The combination of different multiple access schemes which can be used with OFDM will be discussed along with comparisons. We will then focus on OFDMA and discuss it in the context of challenges in BCW systems. We shall consider the WiMAX system as an example of the use of OFDMA and highlight some of the important concepts.

2. OFDM Review

The OFDM transmission technique has established itself as an elegant and popular method for overcoming the FSF in broadband wireless systems [5]. The IEEE 802.11 a/g standards for wireless local area networks (WLANs) [8] which are popularly known as WiFi have used OFDM to achieve speeds of the order of 50 Mbps in an indoor multipath environment. The discrete multitone (DMT) system used in the ADSL modems also uses OFDM to achieve high bit-rates in the telephone channel [9]. The WiMAX [2] standards have proposed various OFDM based methods for use in fixed and mobile environments. Various other systems that use OFDM include powerline communications, digital audio and video broadcasting systems, and ultrawideband based systems for short range wireless.

Some of the key concepts in OFDM include the use of orthogonal subcarriers for sending several data symbols in parallel resulting in better spectral efficiencies and simple equalization methods at the receiver. The samples of the transmitted OFDM signal can be obtained by performing an IFFT operation on the group of data symbols to be sent on orthogonal subcarriers. Similarly, the recovery of data symbols from the orthogonal subcarriers is accomplished using a FFT operation on a block of received samples. Thus, the IFFT and FFT blocks at the transmitter and at the receiver, respectively, are important components in an OFDM system. A lot of work has gone into the optimization of the FFT implementations and the design community has leveraged this trend to advantage leading to popularity of OFDM based systems.

The time-frequency view of an OFDM signal is shown in fig. 1, where the important parameters like subcarrier spacing and OFDM symbol period are shown.

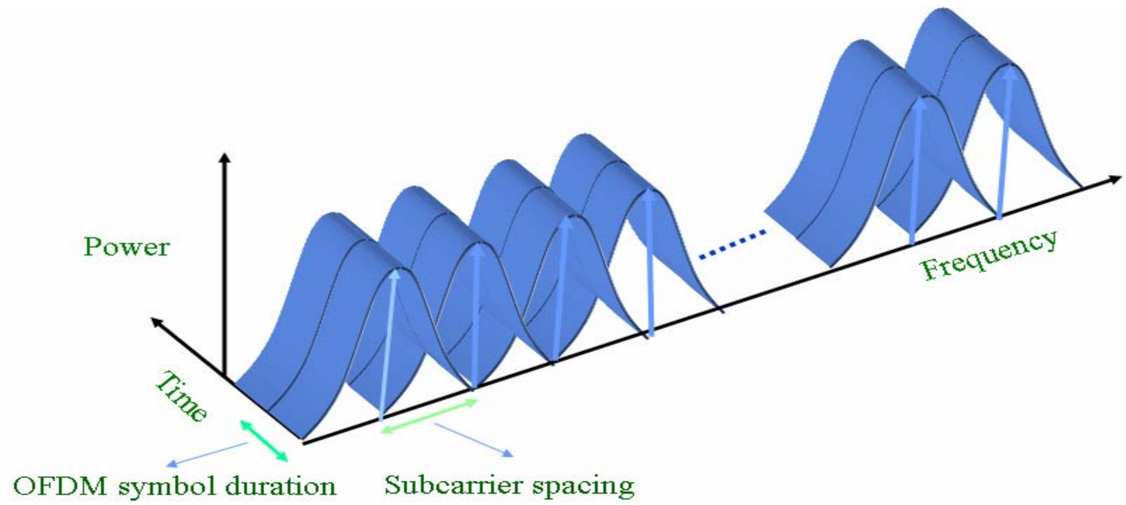

Fig.1 Time-Frequency view of OFDM signal

One can see from the figure that eventhough the subcarrier signals are overlapping in the time and frequency domains, there is no mutual interference when the sampling is done at certain specific points in the frequency domain called as subcarrier positions. This is one of the important properties of an OFDM signal and this leads to higher spectral efficiencies as compared to a frequency division multiplexed (FDM) system. The granularities in the time and frequency domain are the OFDM symbol period (T_{os}) and the sub-carrier spacing (Δf), respectively. In addition, a cyclic prefix (CP) is added to the OFDM symbol to protect against interference between OFDM symbols and against the loss of orthogonality due to the multipath channel. The choices of values for these parameters are based on channel conditions, efficiency requirements, hardware, and algorithmic capabilities. For example, in a typical WLAN application where mobility is not an issue, the channel delay spread and the frequency offset are important factors in the design of the OFDM parameters. However, in mobile WiMAX systems, the Doppler spread has to also be considered along with the above mentioned parameters in the design. For WiFi, the subcarrier spacing is about 300 KHz while in mobile WiMAX the value is around 11 KHz while the CP duration is around 800 nanoseconds for WiFi and is typically about 10 microseconds for WiMAX

Adaptive modulation and coding (AMC) on the different subcarriers is another feature in OFDM systems which has been successfully used in the DMT standard [9] and has been proposed for use in WiMAX and in high speed extensions of WiFi referred to as 802.11n [10]. The frequency domain variations of the multipath channel are used effectively with AMC so as to obtain advantages like higher data rates and lesser transmitted power when compared with an uniformly loaded system. In OFDM systems with AMC, the knowledge of the multipath channel's characteristics at the transmitter is obtained through feedback mechanisms which are also being considered in WiFi and WiMAX.

The ability to use multiple antennas to enhance data rates and reliability is expected to be an important feature of most high-speed wireless systems. However, the use of this feature is much easier in OFDM as compared to their use in single carrier communication systems. The reason is due to the inherent multicarrier nature which transforms a broadband transmission in a mutipath fading channel to several parallel narrowband transmissions . Thus, techniques and concepts which have been extensively developed for narrowband or flat fading wireless channels can be reused in a broadband context. For instance many innovations in MIMOand space-time coding [6] which are likely to be the key feature in wireless systems can be easily extended when OFDM is used. Related signal processing tasks like channel estimation are much easier in OFDM systems as compared with their implementation in other transmission techniques.

2.1 **OFDM based Multiple Access**

Various multiple access schemes can be combined with OFDM transmission and they include orthogonal frequency division multiplexing-time division multiple access (OFDM-TDMA), OFDMA, and multicarrier code division multiple access (MC-CDMA). In OFDM-TDMA, time-slots in multiples of OFDM symbols are used to separate the transmissions of multiple users as shown in fig. 2.This means that all the used subcarriers are allocated to one of the users for a finite number of OFDM symbol periods. In WiMAX, one of the allowed transmission mode uses OFDM-TDMA wherein the basestation allocates the time-slots to the users for the downlink (DL) and uplink (UL) transmissions. Note that even in the distributed access scheme in WiFi, assuming that there are no collisions, a similar principle is followed. The only difference from OFDM-TDMA is that the users capture the channel and use it for certain duration, i.e., the time dimension is used to separate the user signals [8].

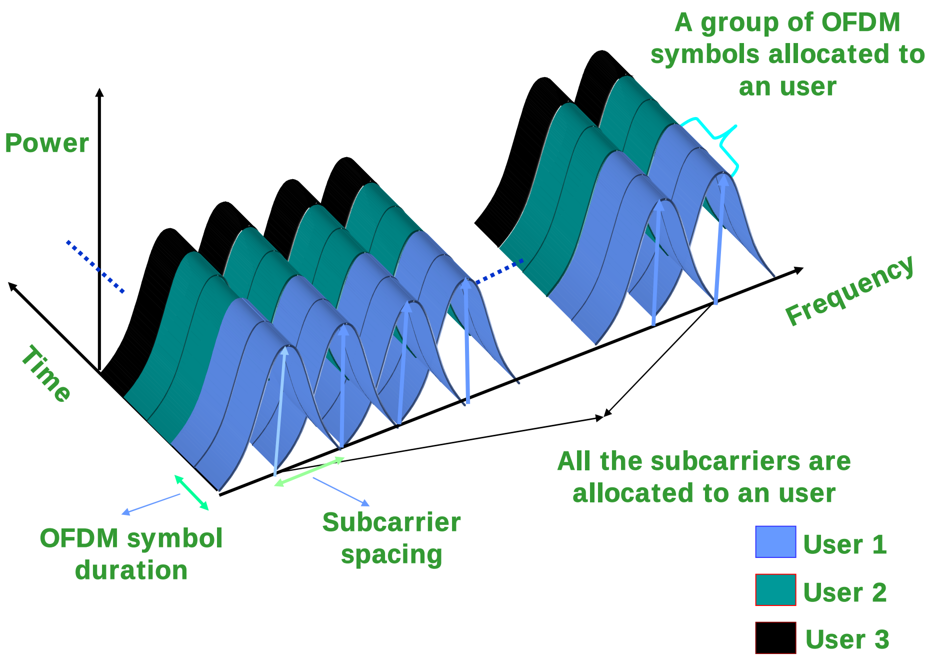

fig.2 Time – Frequency view of an OFDM-TDMA Signal

In OFDMA systems, both time and/or frequency resources are used to separate the multiple user signals. Groups of OFDM symbols and/or groups of subcarriers are the units used to separate the transmissions to/from multiple users. In fig.3, the time-frequency view of a typical OFDMA signal is shown for a case where there are 3 users. It can be seen from fig. 3 that users' signals are separated either in the time-domain by using different OFDM symbols and/or in the subcarrier domain. Thus, both the time and frequency resources are used to support multiuser transmissions. We shall discuss this technique in more detail in the subsequent sections and also compare it with OFDM-TDMA.

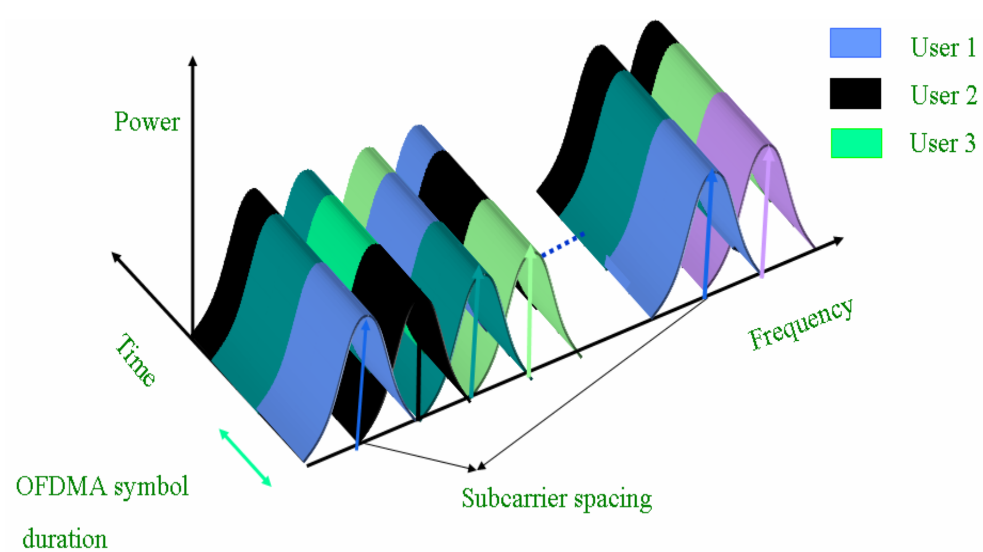

fig.3 Time – Frequency view of an OFDMA Signal

In MC-CDMA systems, a data symbol is sent on multiple subcarriers by using a spreading code, which is different for the multiple access users [7]. Multiple user signals overlap in the time and frequency domain but they can be separated at the receiver by using the knowledge of the spreading codes. Thus, MC-CDMA can be considered as a combination of OFDM and CDMA schemes resulting in benefits due to both these approaches. Various other variants of MC-CDMA systems have also been discussed in the literature [11].

The various features of OFDM transmission discussed so far can be summarized as in fig. 4. We shall now discuss details of OFDMA and its application to WiMAX.

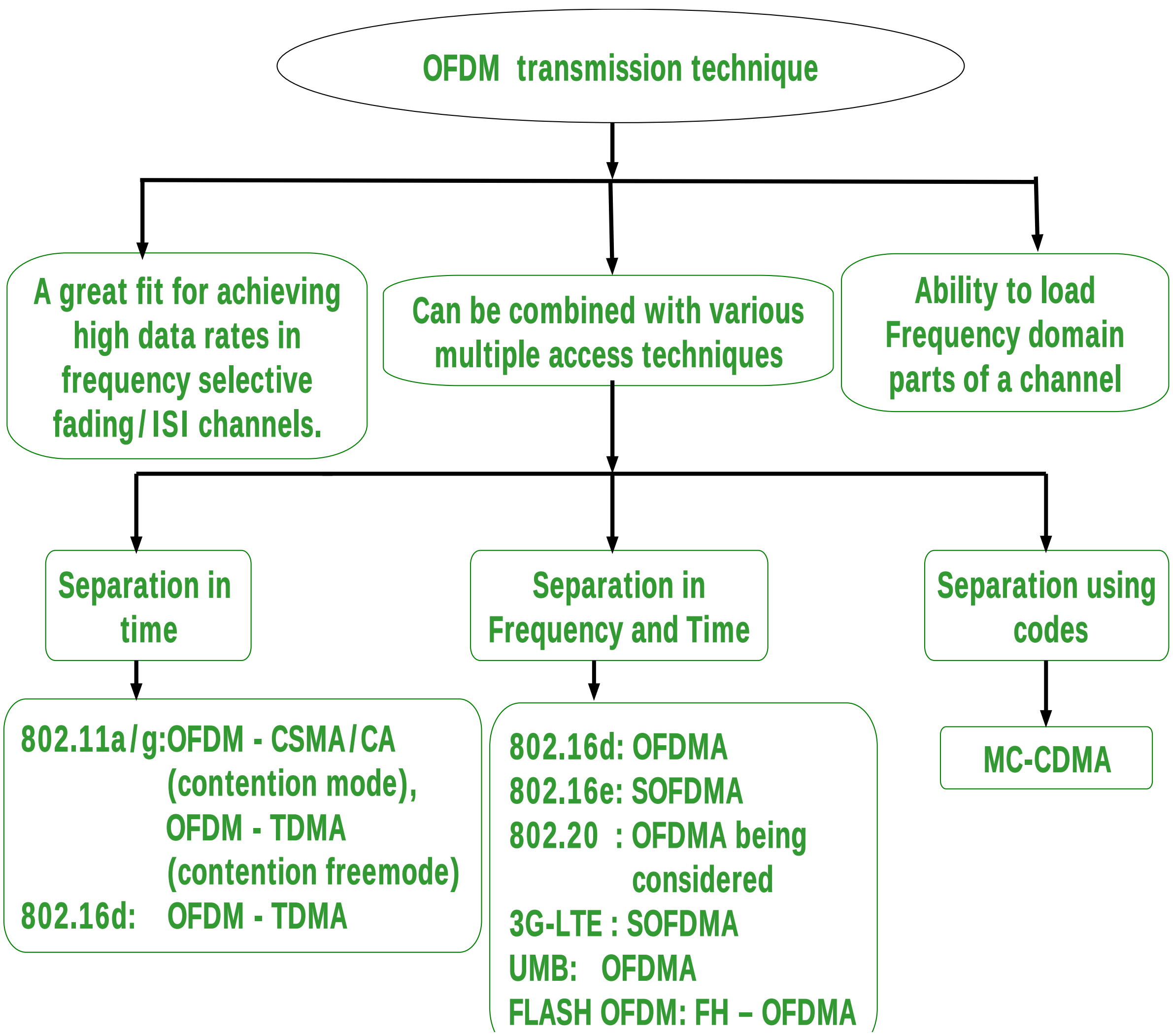

fig.4 Various Features of OFDM Transmission

3. Orthogonal Frequency Division Multiple Access

In OFDMA systems, the multiple user signals are separated in the time and/or frequency domains. Typically, a burst in an OFDMA system will consists of several OFDM symbols. The subcarriers and the OFDM symbol period are the finest allocation units in the frequency and time domain, respectively. Hence, multiple users are allocated different *slots* in the time and frequency domain, i.e., different groups of subcarriers and/ or OFDM symbols are used for transmitting the signals to/from multiple users. For instance, we illustrate an example in fig. 5 wherein the subcarriers in an OFDM symbol are represented by arrows and the lines shown at different times represent the different OFDM symbols. We have considered 3 users and we have shown how resources can be allocated by using the different subcarriers and OFDM symbols.

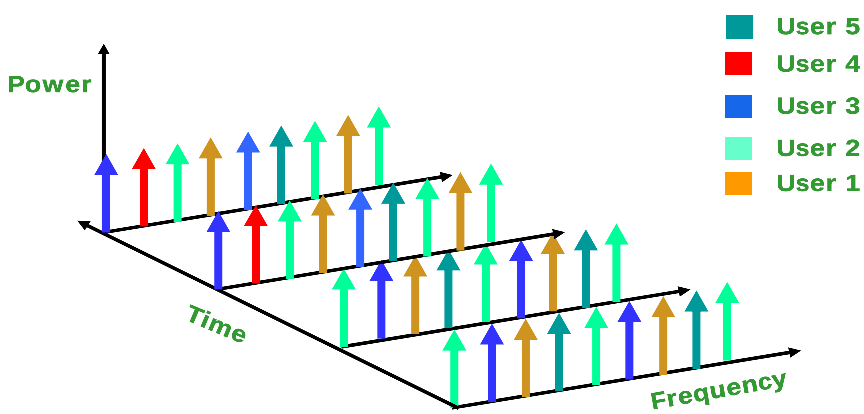

fig.5 Example allocation of resources to users in an OFDMA system

3.1 Subchannels in OFDMA

In practice, the allocation in the frequency domain is not addressed at the level of subcarriers. Typically, subchannels which are the smallest granular units in the allocation are created by grouping subcarriers in an OFDM symbol in various ways. The formation of these subchannels from subcarriers is an important concept in OFDMA systems. The formation can be classified into 2 types; one is the mapping of a contiguous group of subcarriers into a subchannel called as the adjacent subcarrier method (ASM) and the other is the diversity/permutation based grouping called as diversity subcarrier method (DSM) wherein the subchannel typically contains non contiguous subcarriers. An example of the allocation using the two methods is illustrated in figs.6a and 6b, respectively.

In the ASM method, a subchannel typically contains a group of contiguous subcarriers and it is expected that the channel frequency responses on the subcarriers in a subchannel will be strongly correlated. This is based on the fact that subcarriers which fall within the coherence bandwidth have similar responses. The ASM method is suitable for the use of AMC as a strongly correlated block of subcarriers can be considered together as an unit to enable simple channel feedback which is necessary to implement the bit-loading. Note that if the subcarrier responses were uncorrelated, then the channel responses on each subcarrier would have to fed back to the transmitter resulting in a higher overhead. Thus, the channel feedback which consumes valuable bandwidth and power can be simplified when AMC is used along with ASM. Moreover, simplifications to the adaptive loading algorithm used in AMC can be achieved when the adjacent subcarriers have similar responses [12]. We shall explore the use of AMC in WiMAX and compare it with the DSM in detail in later sections.

A FSF channel has inherent frequency diversity (FD) due to the variations of the channel response in the frequency domain, i.e., the subcarriers from different positions in the frequency domain are likely to experience different channel fading conditions. This FD has been leveraged in WiFi systems by using suitable error control coding and interleaving. In the DSM, subcarriers from seemingly random positions in the frequency domain are grouped into a subchannel. Thus, a subchannel has potential frequency diversity which can be leveraged when the data to be sent on this subchannel is suitably coded and interleaved. Such bit interleaved coded modulation (BICM) methods have been used in WiFi and are also being used in WiMAX systems. Frequency hopping methods can also be combined with the DSM method such that the subcarriers in a particular subchannel are not constant in time.

The time granularity for ASM and DSM is in multiples of OFDM symbols; for example, the same subchannel in two OFDM symbols could be the basic allocation unit. Users are typically allotted one or more subchannels for one or more OFDM symbols depending on the allocation and the requirements. Note that subchannelization allows us to handle resources as groups of subcarriers and OFDM symbols. We shall see some practical examples and understand the advantages by considering the WiMAX system.

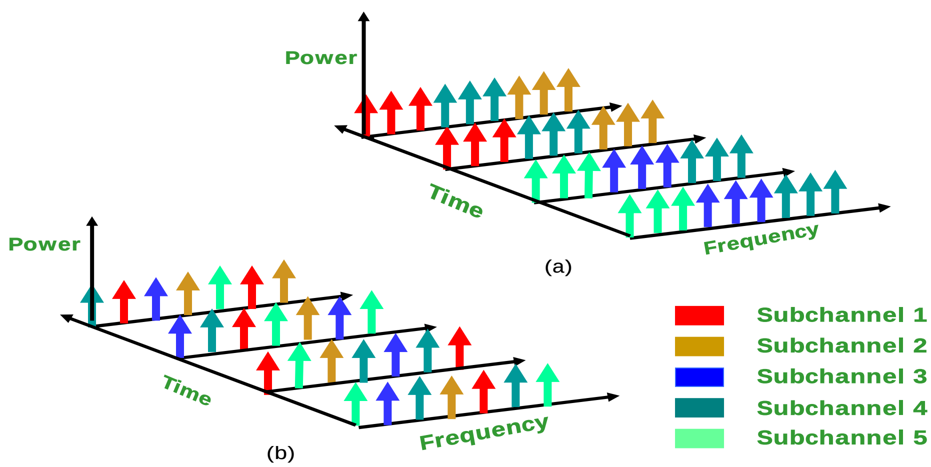

fig. 6. Subchannelization example (a) ASM method (b) DSM method

4. Subchannelization in WiMAX

In WiMAX both the ASM and DSM based subchannelization have been defined with the latter being mandatory. We shall first discuss the mandatory DSM method and explore an example of a subchannel formation in the WIMAX systems. In WiMAX, the number of subcarriers is not fixed and we shall consider a system with a maximum of 2048 subcarriers which typically is used with a 20 MHz deployment. For spectral rolloff reasons, only 1680 subcarriers are used and the edge subcarriers are unused as shown in fig. 7. In addition, certain subcarriers are earmarked for sending known symbols and are called as pilot subcarriers. These subcarriers can be used for tracking the various effects caused by channel and hardware. We shall consider the downlink (DL) as an example case to highlight the various points in the mandatory DSM which is called as the partial usage of subcarriers (PUSC) method.

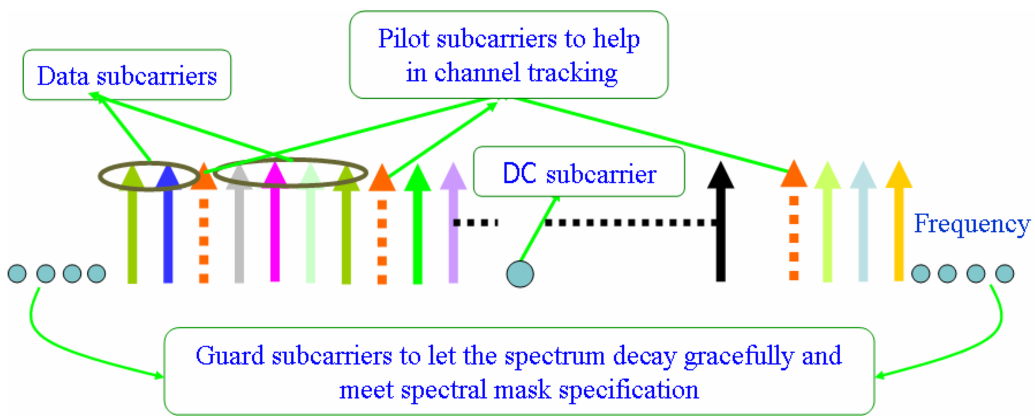

fig. 7 Typical subcarrier view of an OFDM symbol in WiMAX

The DL PUSC allocation method specified in WiMAX groups 24 randomly positioned subcarriers (defined in the standard) into a subchannel which enables leveraging of the frequency diversity. The same subchannel is allocated in 2 consecutive symbols thus making 48 subcarriers as the basic resource unit in this method. Hence, the user data is partitioned into 48 symbols for fitting this slot mentioned in WiMAX. The details of the subchannelization are specified in detail so that all users clearly know the specific subcarriers that are grouped in a specific subchannel. Note that the granularity of about 24 subcarriers in an OFDM symbol allows us to flexibly allocate resources for different services. A voice call might need only a single subchannel in every OFDM symbol while a video application might need a large number of subchannels. This subchannelization allows us to address the requirements of different types of services while leveraging frequency diversity. There are other DSMs specified in WiMAX including the full usage of subcarriers (FUSC) method which will be discussed when we consider multicellular operation in WiMAX

4.1 Use of frequency Diversity

To show how frequency diversity is used in the PUSC method, let us consider the positions of the subcarriers constituting a subchannel. We illustrate the steps in the PUSC subchannel formation in fig. 8 when the total number of subcarriers is 2048 as outlined in the 802.16 standards [13]. The 1680 used subcarriers are split into 120 clusters of 14 contiguous subcarriers each and these are called as physical clusters. The 120 physical clusters are rearranged as shown in the second step and logical clusters are formed and numbered as shown. Note that adjacent logical clusters contain subcarriers from non-adjacent physical clusters. A subchannel which consists of 24 subcarriers in this case is formed by picking a subcarrier from adjacent logical clusters which means that the subcarriers constituting the subchannel come from different positions in the frequency domain over the entire spectrum used as outlined in fig. 8 leading to frequency diversity in a subchannel.

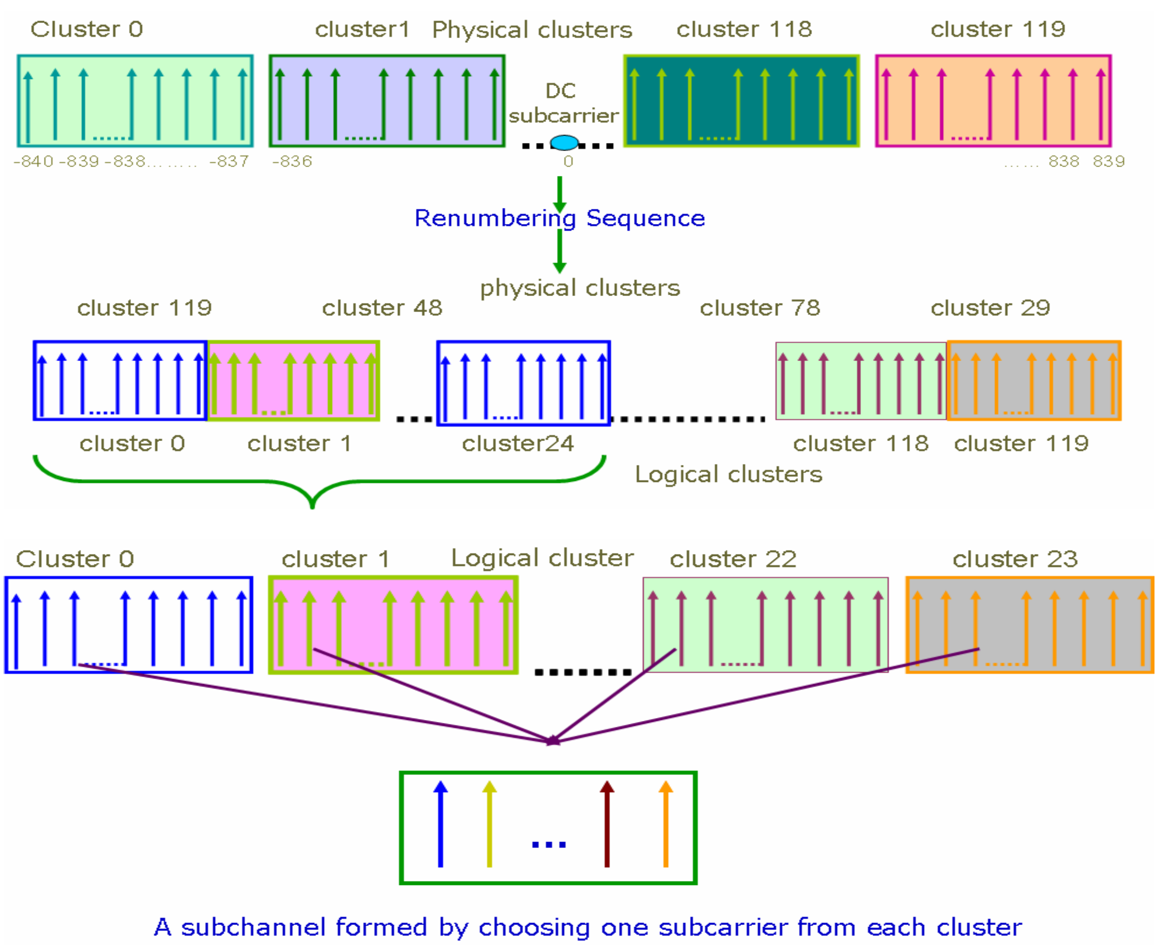

fig. 8 Subchannel formation in WIMAX DL PUSC

An example of the subcarrier positions allocated to subchannels is given in Table 1 for a WiMAX system with 2048 subcarriers indexed from -1024 to +1023. The absolute frequency position of the 24 subcarriers for the 12 subchannels which is typically used by a sector of a BS is shown. By looking at any one of the rows, it can be clearly seen that frequency diversity is used in the PUSC subchannel formation as the subcarrier positions in a subchannel are chosen in a distributed manner. In WIMAX, the PUSC method is outlined in detail and the users are informed of their allocation using the subchannel index and the OFDM symbol index in a frame. The basestation (BS) and the mobiles clearly understand the subchannel definitions and hence signaling takes place only at the subchannel level and not at the subcarrier level.

Subchannel number	Subcarrier number											
	0	1	2	3	4	5	6	7	8	9	10	11
0	834	-157	748	529	811	-239	-834	-474	668	-193	-643	435
1	692	725	223	-519	-330	185	500	-81	44	-392	-553	838
2	755	532	805	-250	-831	-473	660	-196	-637	446	552	697
3	217	-530	-327	186	492	-84	50	-381	-555	837	-156	756
4	808	-249	-839	-476	666	-185	-639	445	559	700	721	213
5	-335	183	498	-73	48	-382	-548	840	-162	745	528	802
6	-833	-465	664	-186	-632	448	553	689	724	214	-531	-336
7	496	-74	55	-379	-554	829	-159	746	520	799	-245	-829
8	671	-183	-638	437	556	690	716	211	-525	-325	188	501
9	49	-390	-551	830	-167	743	526	810	-247	-830	-464	672
10	-635	438	548	687	722	222	-527	-326	195	504	-78	45
11	-559	827	-161	754	524	809	-240	-827	-470	661	-187	-641

Subchannel number	Subcarrier number (contd....)											
	12	13	14	15	16	17	18	19	20	21	22	23
0	554	698	720	221	-520	-323	189	493	-75	46	-391	-560
1	-163	753	531	812	-246	-838	-467	662	-195	-644	442	558
2	727	224	-526	-334	192	494	-83	43	-385	-549	832	-158
3	525	801	-243	-837	-475	659	-189	-633	440	557	699	728
4	-523	-333	184	491	-77	54	-387	-550	839	-155	749	521
5	-251	-840	-469	670	-191	-634	447	560	693	717	220	-529
6	190	502	-79	53	-380	-547	833	-166	752	522	800	-252
7	-471	669	-184	-631	441	549	696	718	212	-532	-329	194
8	-72	56	-386	-558	836	-165	744	519	806	-241	-835	-466
9	-190	-642	444	550	688	715	218	-521	-331	193	503	-71
10	-383	-557	828	-168	750	530	804	-242	-828	-463	665	-194
11	436	547	694	726	216	-522	-324	196	497	-82	52	-389

Table 1: Subcarrier positions for different subchannels in a WiMAX cell

4.2 **ASM in WiMAX**

The ASM is optional in WiMAX and different ways of forming a subchannel are specified. A simple modification to the PUSC method that was discussed above can be used in ASM. Instead of rearranging the physical clusters into logical clusters, 2 consecutive physical clusters can be grouped to form a subchannel. Channel knowledge is essential at the transmitter and a feedback mechanism is specified in WiMAX. For instance, special slots are allocated in the uplink part of the frame for the users to feedback the channel information. The channel information typically contains the SINR values as measured by the mobile in certain frequency bands which is used by the BS to perform AMC on the different associated subchannels. Channel feedback can also used in the DSM, but it is used to infer the average channel strength in the entire band of operation, i.e., it roughly indicates the distance of the mobile from the BS. Suitable modulation and coding can be chosen for all the subcarriers used for that particular user by using this information so as to achieve higher throughputs. Such a method is also used in other systems which are being proposed as enhancements to the 3G standards. The uniqueness of OFDMA systems is that the modulation and coding can be chosen at a subchannel level rather than for the entire frequency region over which the signal is sent resulting in gains which is not available in CDMA based 3G standards. The challenge lies in leveraging the potential advantage by intelligent scheduling of traffic to users based on channel information, mobility, and QoS requirements as discussed in [14].

A BS can use different subchannelization methods in a frame by informing the associated mobiles about the subchannelization procedure followed in a particular duration. For example, a typical frame starts by using subchannels formed using DBM, however, in the latter part of the frame, ASM and other optional subchannelization methods can be used after proper signaling information is broadcast to the associated users as shown in fig. 10.

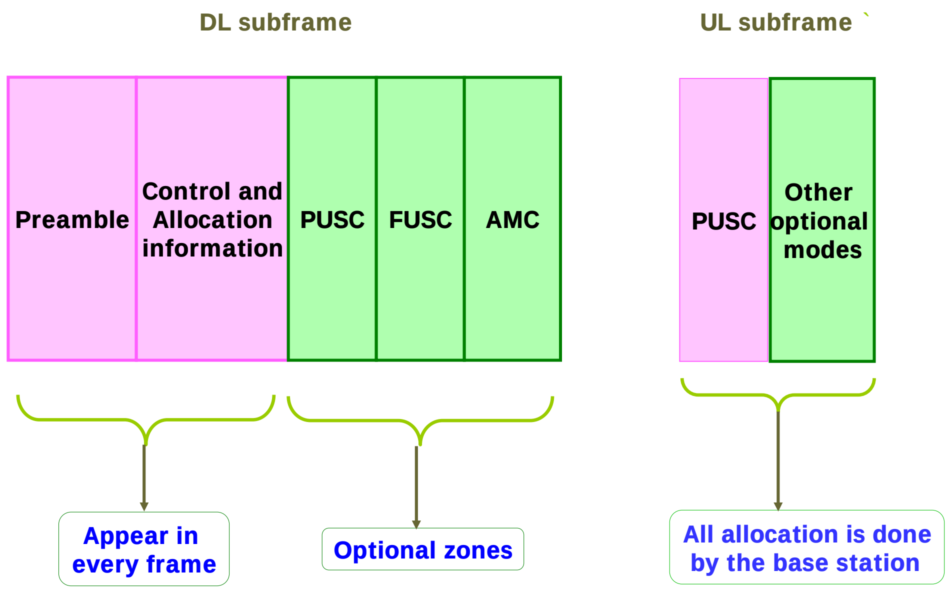

fig.10 OFDMA frame with multiple zones

5. Multicellular operation in WiMAX

Typical deployment of wide-area wireless systems uses a cellular approach so that the spectrum can be used efficiently. Most cellular systems are employing reuse factors close to 1 (originally pioneered by IS-95 CDMA systems) so as to satisfy the concerns of spectrum regulators. Hence, tight frequency reuse will be a major selling point for a technology which is a candidate for BCW systems. To satisfy this requirement, WiMAX has specified subchannelization methods which take this challenge into account. In multicellular OFDMA systems, where tight frequency reuse is used, there is no inherent protection from the ensuing cochannel interference (CCI). Hence, to address this problem, the mapping of subcarriers to subchannels is done differently in the different cells in the neighborhood while using the mandatory DSM.

Let us consider an unit frequency reuse scenario as an example as this is potential deployment scenario in WiMAX which is enabled by the FUSC method.

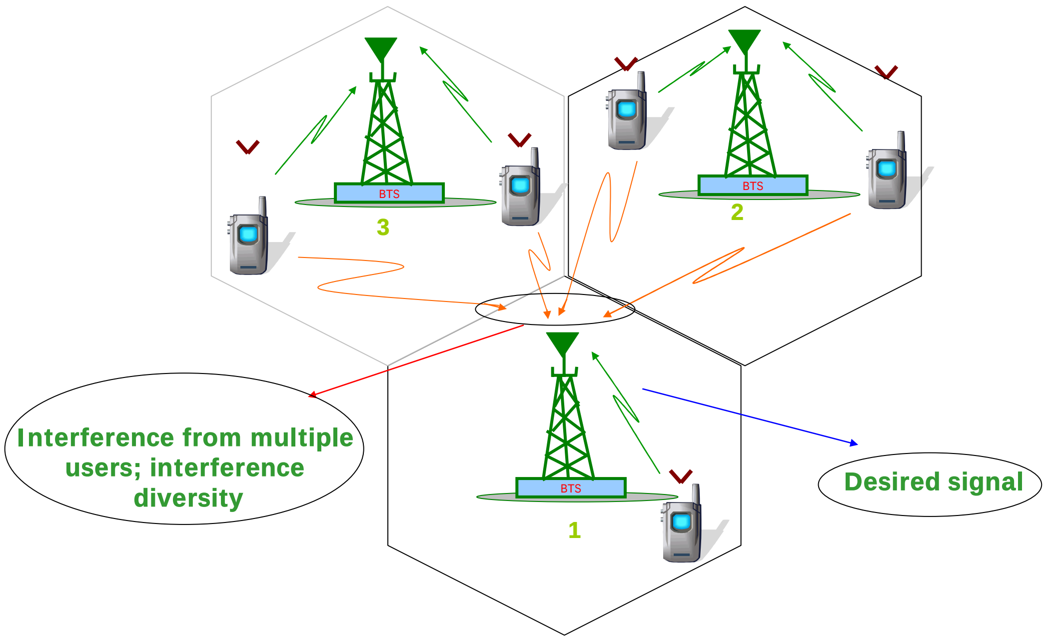

fig.11 Interference in multicellular operation

Let the desired user be in cell1 and let us consider the UL transmission in that cell. Let us assume that slow power control is also in effect as this is a standard operation in most cellular systems. The mobile will use one or more subchannels for transmitting data to the BS in the cell. At the same time, other mobiles in the neighboring cells could also be transmitting to their respective BS. Due to unit frequency reuse, there is a potential for severe CCI as some of the users in the neighboring cells could be reusing the subcarriers used by the desired mobile in cell 1. However, note that it is likely that all the interferers are not going to be at the same distance and location from the desired BS receiver as illustrated in fig.11. This fact is used in the subchannelization in the different cells. The subcarriers that constitute a subchannel are also determined by the cell identification number (CELL_ID) which is different for the cells in the neighborhood. Thus, the interference seen in the subcarriers of a subchannel in our desired cell is likely to come from different subchannels in the neighboring cells because of the difference in the subchannel definitions in the neighborhood. Thus, it is likely that the interference in a subchannel is likely to come from different users in the neighborhood and these users are likely to be in different locations. This can potentially lead to an interference diversity effect, i.e., the interference powers on the subcarriers constituting a subchannel can be different as illustrated in fig. 11. Here, 3 subcarriers belonging to subchannel 1 in cell 1 are shown in pink. In cell2, the same subcarriers are part of different subchannels which are used by different users at different locations from the BS in cell1. The heights of the arrows indicate the power received on these subcarriers at BS of cell 1, i.e., it is the interference power as seen at the BS. Note that the difference in heights of the subcarrier arrows could be due to the different locations of the users that are allocated these subchannels. In fig.12, we have also shown the 3 subcarriers which constitute the subchannel 1 in cell2, the difference from cell 1 is due to the different CELL_ID values used.

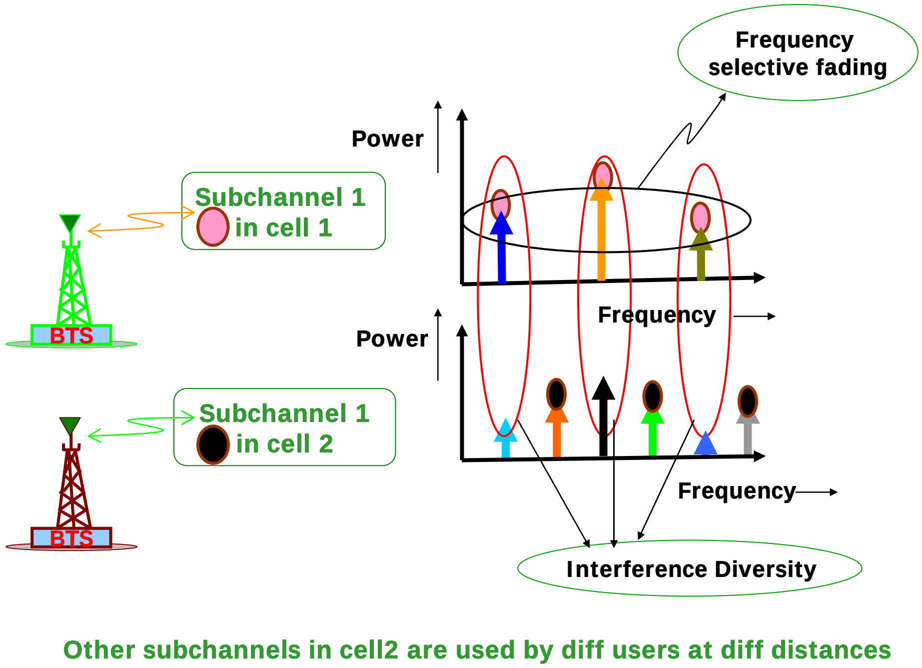

fig.12 Illustration of interference diversity in multicelluar systems

Effectively, the signal to interference plus noise ratio (SINR) is frequency selective due to the multipath channel conditions and the varying interference conditions on the subcarriers. The BICM techniques are effective in such conditions and can result in good error performance as they can leverage the diversity. It is unlikely that the FUSC method will be used in the initial rollout of WiMAX systems except for users close to the BS. However, for operation under tight frequency reuse conditions, as for example in 1/3 reuse, which is very likely, the interference diversity effects are important and hence the subchannelization in PUSC also depends on the CELL_ID. Note that in PUSC, the interference will come not from other sectors in the same cell but there will be significant interference from neighboring cells due to tight reuse. For example, in Table 2, we have considered the 5 MHz with 512 FFT point deployment scenario for which there are a total of 15 different subchannels. A sector will be assigned 5 subchannels in the downlink and a maximum of 6 subchannels in the uplink. In Table 3, the effect of interference diversity on the different subchannels of a particular cell is shown by tabulating the number of subcarriers from each subchannel in a neighboring cellwhich can contribute interference. It can be seen that 13-14 different subchannels contribute interference to a particular subchannel in the reference cell indicating the interference diversity present in the DL PUSC allocation. In the uplink, the interference diversity manifests in a slightly different form due to the UL PUSC allocation wherein 4 consecutive subcarriers are considered as a unit. Hence, there can be a maximum of 6 different interfering subchannels for each reference subchannel. Most of the subchannels considered in Table 4 have this property except for 1 subchannel. Thus, interference diversity which implies receiving different levels of interference on the subcarriers in a subchannel is achieved in WiMAX by assigning subcarriers to subchannels in different cells in a predetermined pseudorandom manner.

Reference Subchannel	Interfering Subchannels														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3	2	2	1	1	2	2	1	1	2	0	2	2	1	2
2	1	2	2	4	1	0	2	2	2	1	1	2	1	2	1
3	1	2	2	2	3	1	1	2	1	1	0	1	3	2	2
4	2	2	3	1	2	1	2	1	1	2	3	0	1	1	2
5	3	1	1	2	2	3	1	1	2	1	3	2	0	1	1

Table 3 Interference diversity in action on the downlink

Uplink

Reference Subchannels	Interfering Subchannels																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	0	0	4	4	0	4	0	0	4	4	0	0	0	4	0
2	0	0	0	0	0	4	0	0	4	4	0	4	4	0	0	0	4
3	4	0	0	0	0	0	4	0	0	4	4	0	4	0	0	0	4
4	4	4	4	0	0	0	0	0	0	0	4	4	0	4	0	0	0
5	0	4	4	4	0	0	0	0	0	0	0	0	4	0	4	4	0
6	0	0	4	0	4	0	0	0	0	0	0	0	0	8	0	4	4

Table 4 Interference diversity in action on the uplink

6. Scalable OFDMA

In WIMAX deployments around the globe, the bandwidth of operation can vary from 1.25 MHz to 20 MHZ depending on the spectrum allocation in different countries. This means that the OFDM parameters like the subcarrier spacing and the OFDM symbol period can vary between deployments if the same number of subcarriers is used as shown in fig. 13.

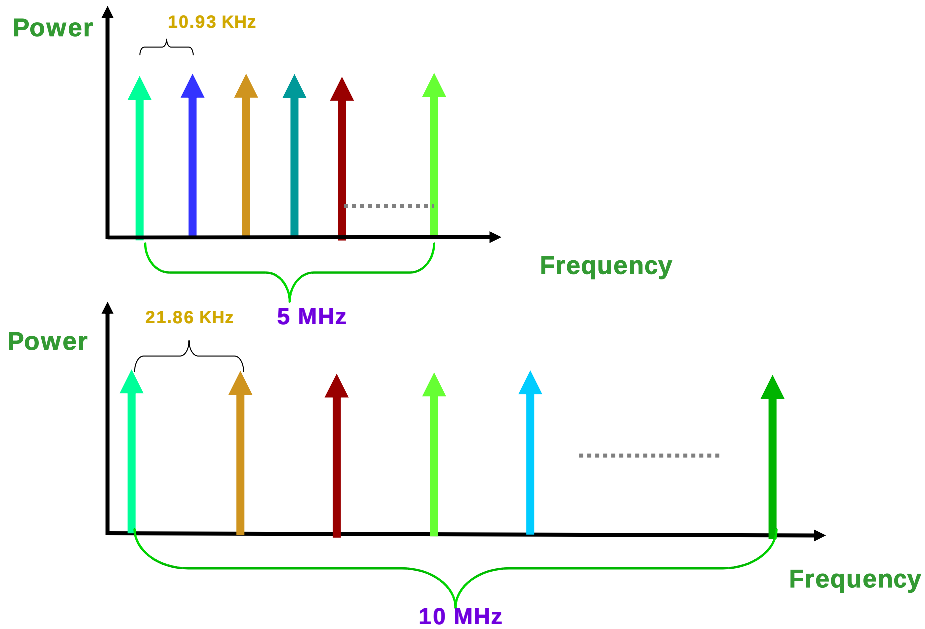

fig.13 Illustration of the subcarrier spacing for different bandwidths

Hence, the hardware and algorithms designed for WiMAX should be flexible if the same equipment is planned to be used with different bandwidths. One of the problems of operating with different subcarrier spacing is that the effects due to Doppler spread and frequency offsets change with different subcarrier spacing [14]. Hence, the baseband algorithms that are used to compensate for these effects need to be tuned specifically for different bandwidths used. This is not a desirable situation in terms of hardware/algorithm. Consequently, to overcome this problem, the scalable OFDMA (SOFDMA) approach was proposed wherein the total number of subcarriers was scaled according to the bandwidth of deployment [15]. For example, if 512 subcarriers were used for a 5 MHz deployment, then 1024 subcarriers would be used for a 10 MHz deployment as shown in fig 14 leading to the same effects with respect to most significant channel related parameters. Note that the RF front-end will have to be made flexible to accommodate deployments in different bandwidths which is usually easier than changes to baseband algorithms. In WiMAX, the number of subcarriers range from 128 to 2048 depending on the bandwidth leading to the same subcarrier spacing of around 11 KHz.

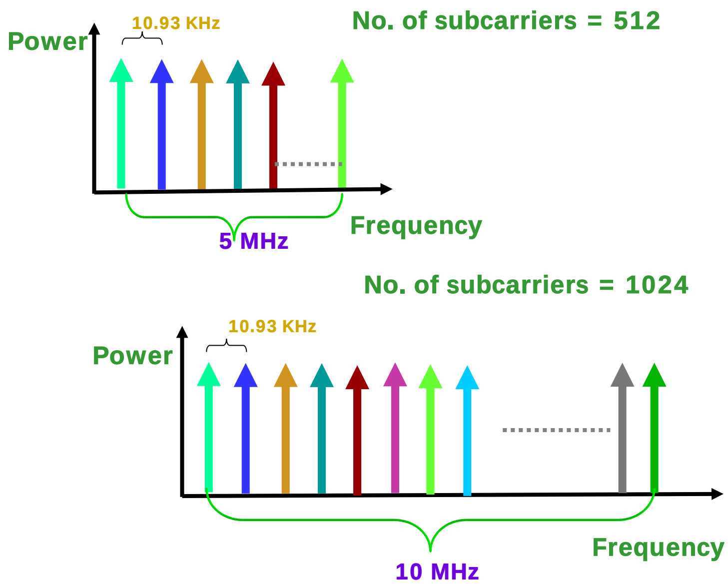

fig.14 Illustration of the subcarrier spacing in SOFDMA

7. **Multiuser Diversity using OFDMA**

One of the advantages of OFDMA over CDMA is the ability to perform scheduling using both the time and frequency responses of the channel. For instance, consider the frequency responses of two users at different locations in a cell as shown in fig.15.Note that there are good and bad frequency bands for the two users which may be different depending on their location. This diversity across the channels for different users is called multiuser diversity [16] which can be used advantageously by allocating subchannels which fall in the good portion for the 2 corresponding users leading to advantages like higher rate support. Such an approach is suitable when combined with the ASM based subchannelization as the channel response on contiguous subcarriers is highly correlated leading to easier identification and allocation of good and bad bands for an user. In the extensions to 3G cellular systems like HSDPA and EVDO, only time based scheduling is used whereas in OFDMA based systems the ability to also use the frequency responses make it more appealing for the next generation cellular services which are striving to support higher bit-rates.

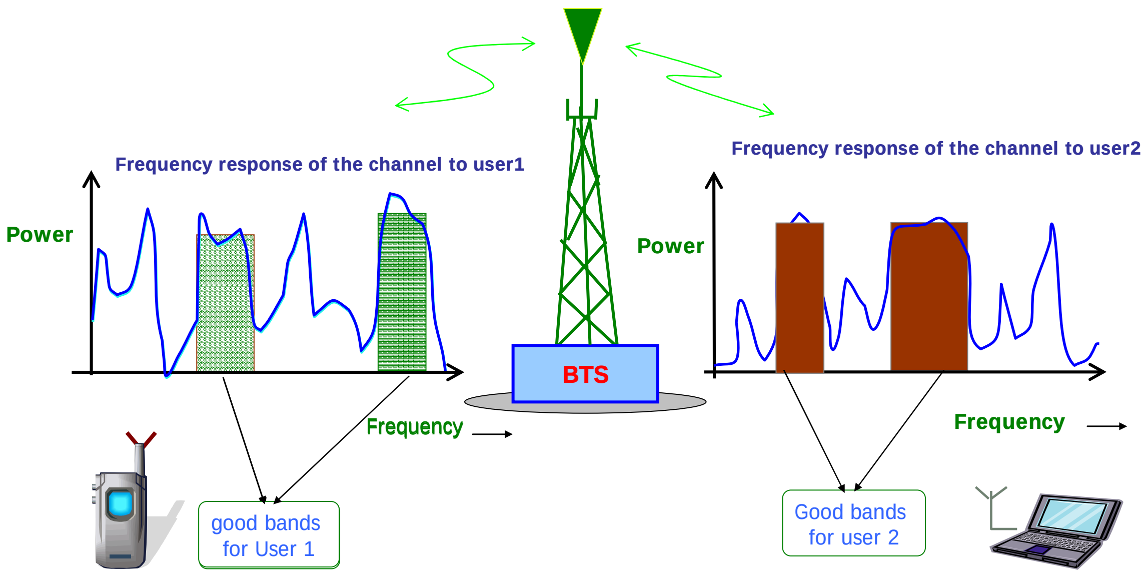

fig.15. Illustration of multiuser diversity

8. Comparisons

We shall compare the ASM and DSM based subchannelization techniques followed by a comparison of the OFDMA and OFDM-TDMA to summarize the various concepts learned.

Concepts	**ASM**	**DSM**
Gain/Benefits	Loading gain	Diversity gain
Interference	No interference diversity/averaging	Interference diversity/averaging
Reuse	Unit frequency reuse not possible	Unit frequency reuse possible
Mobility support	Good for fixed deployments	Can work in fixed and mobile deployments
Multiuser diversity	Can help leverage multiuser diversity in the frequency domain	Cannot use multiuser diversity in the frequency domain
Channel information	Necessary	Not needed
Scheduling at BS	Complex scheduler needed to leverage benefits	Simple scheduler is sufficient
Deployment in WiMAX	Likely to happen in future combined with beamforming	Likely to be deployed in the near future and later combined with MIMO techniques

Table 5: Comparison of the ASM and the DSM in OFDMA

Concept	OFDM-TDMA	OFDMA
Frequency reuse	Unit frequency reuse not possible	Unit frequency reuse possible
Interference diversity	No interference diversity/averaging effect	Can use interference diversity and averaging
Support for different services	Only 1 user can be served in a OFDM symbol leading to poor granularity in the frequency domain.	Can serve multiple users/services in an OFDM symbol due to better granularity in the frequency domain. Voice and video application with different rate and delay requirements from different users can be served simultaneously.
Support for multiuser diversity	Cannot support multiuser diversity as all subcarriers are allotted to a single user at any give time	Can leverage multiuser diversity using the ASM allocation.

Table 4: Comparison of OFDM-TDMA and OFDMA

9. Conclusions

We have outlined some of the major challenges for BCW systems and we have discussed the use of OFDMA systems in that context. The FSF channel and the ISI problem is tackled by the use of OFDM leading to elegant equalization. The resource requirements of different services like voice, video, and data is met by forming units of resources called as subchannels which can be allocated flexibly based on service requirements. Moreover, there are different ways in which the subchannels can be formed leading to different gains as seen in the ASM and DSM techniques. Tight frequency reuse is likely to be the norm in BCW systems and the use of interference diversity in OFDMA can enable such usage. We have used the WiMAX system as an example for discussing the concepts so that the reader can get a concrete feeling of the ideas in OFDMA. We have also discussed SOFDMA and multiuser diversity ideas which are important in future generation of cellular systems. Finally, we have summarized some of the ideas discussed by comparing the ASM and DSM techniques and the OFDM-TDMA and OFDMA schemes.

8. Acknowledgements

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