

# WiMAX-WiFi Convergence with OFDM Bridge

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## ABSTRACT

Nowadays, Wireless and mobile communications technologies are the most important areas, which are rapidly expanding either in horizontal or vertical directions. WiMAX is trying to compete with WiFi in coverage and data rate, while the inexpensive WiFi still very popular in both personal and business use. Efficient bandwidth usage, Multi-Standard convergence and Wireless Mesh Networks (WMN) are the main vertical trends in the wireless world. WiMAX-WiFi convergence as an ideal technology that provides the best of both worlds: WiMAX new features and the low cost of the WiFi. In order to create a heterogeneous network environment, differences between the two technologies have been investigated and resolved. In the Multi-Carrier WiMAX-WiFi Convergence, the mismatch between the fixed WiMAX-OFDM ( $N_{fft}=256$ ) and the WiFi-OFDM ( $N_{fft}=64$ ) has been confirmed as a physical layer issue that will never be solved as MAC layer problem; therefore the current proposal is how to build what we called the “*Convergence-Bridge*”. This bridge is like an extra thin layer, which is responsible for harmonizing the mismatch. For the WiFi-OFDM physical layer, the paper has selected the IEEE 802.11n OFDM standard while it is being developed. The proposal does not suggest changing the standard itself but modifying some functions to be configurable. The IEEE 802.11 standard has fixed the configurations for WiFi mode only, while our proposal is to set up these functions for WiFi and WiMAX modes.

**Keyword list:** Convergence, WiMAX, WiFi, Bridge, OFDM, IEEE 802.11, IEEE 802.16

## 1. INTRODUCTION

The Convergence-Bridge is a smart modification in the WiFi OFDM Physical layer to enable WiFi devices to join the WiMAX-OFDM wireless network. In this paper the WiMAX-Fixed (OFDM-256) and the WiFi-OFDM-64 have been selected to achieve the multi-carrier convergence. The convergence idea is initiated from the similarities between the WiMAX and the WiFi, however the dissimilarities are still real obstacles to enable them to communicate with each other. Dissimilarities between wireless standards are usually in the lower layers so that the investigations are focused on the PHY and MAC layers. In the standard investigations, it has been discovered that the convergence in WiMAX-WiFi multi-carrier OFDM is a physical layer issue, [1]. The proposal does not suggest changing the standard itself but modifying some functions to be configurable. The IEEE 802.11 standard has fixed the configurations for WiFi mode only, while our proposal is to set up these functions for WiFi and WiMAX modes

*World Interoperability for Microwave Access* (WiMAX) is the trade name of the IEEE 802.16 standard and is expected to dominate wireless networking technology for decades to come. It is designed to meet the requirements of the last-mile applications of wireless technology for broadband access with mobility, high bit rate, security and long distance coverage. The 802.16 is a set of evolving IEEE standards that are applicable to a vast array of the spectrum ranging from 2GHz to 66 GHz, which presently include both licensed and unlicensed (licence exempt) bands, [2]. The 802.16 is the enabling technology standard that is intended to provide Wireless Metropolitan Area Network (WMAN) access to locations, usually buildings, by the use of exterior illumination typically from a centralized base station (BS), [3].

In 2001 the IEEE 802.16 standard was released, whereas the groups continued to modify it to work on NLOS (Non Line-of-Sight) deployments. These modifications have covered the licensed and licensed-exempt bands between 2GHz-11GHz. In 2003 the IEEE 802.16a released with an extending OFDM techniques added for supporting the multi-path propagation problem. Meanwhile, the IEEE 802.11n standard group has also developed the OFDM as a part of the

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physical layer of the WiFi. Besides the OFDM physical layers, the 802.16a established an optional MAC-Layer function that includes support for Orthogonal Frequency Division Multiple Access (OFDMA),[4].

In 2004, revisions to IEEE 802.16a were made which were called IEEE 802.16-2004. It replaces 802.16, 802.16a and 802.16c with a single standard. Moreover, this revised standard has also been adopted as the basis for HIPERMAN (High-Performance Metropolitan Area Network) by ETSI (European Telecommunication Standards Institute). In 2005, 802.16e-2005 was completed, a further MAC-PHY layers modification was formulated by using a scalable OFDM to accommodate high-speed mobility,[5].

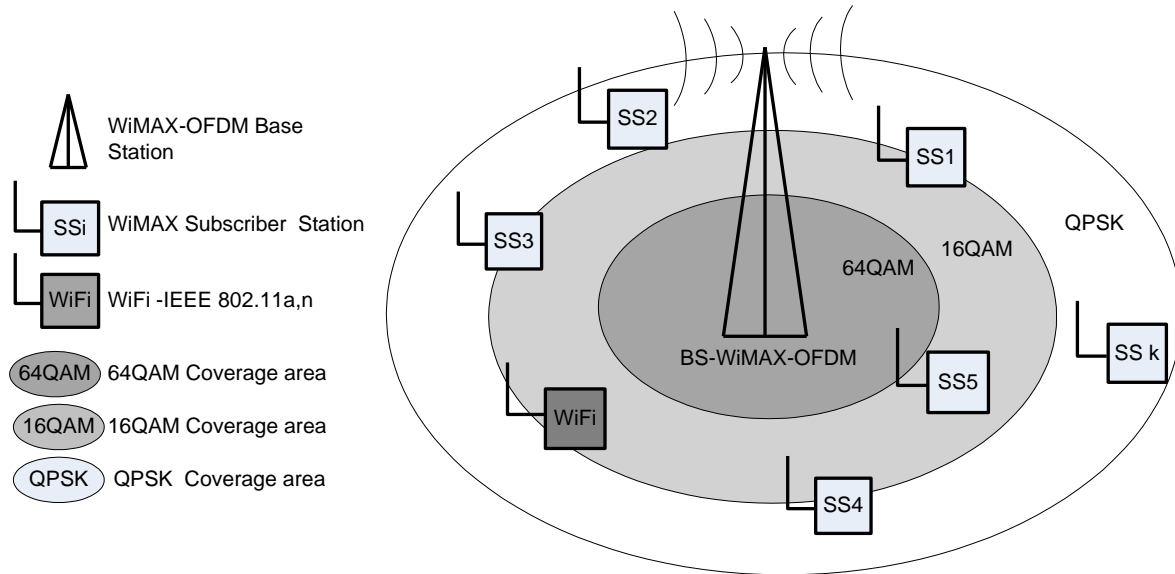


Figure (1) WiMAX Point to Multipoint (PMP) Architecture Diagram

In addition to the Point-to-Point (PTP) and Point-to-Multi Point (PMP) topologies, the 802.16a introduces the WiMAX-mesh topology as a possible alternative to the cellular networks. This alternative (Mesh) applies to wireless network in which nodes cooperatively route packets. Mesh could act as an Ad-Hoc wireless network or as edge networks to a larger network infrastructure such as the Internet, [6]. It gains flexibility, reliability and nomadic network architecture based on multi-hop model. Adding the mesh concept to the 802.16 enlarge the geographical area of a network. As mentioned in the previous section, the WiFi has also taken over the Mesh topology and released the IEEE 802.11s draft standard, [7].

A new vision of the convergence has turned up when two different standards have created the same topology (Mesh) as vertical developments. While the Mesh standards are under development, the paper has studied the potentials of the WiMAX-WiFi convergence in the Mesh topology also. Apparently, it would appear that the WiMAX-WiFi convergence has a good chance to be involved in the mesh topologies, because of the many common parameters are present there (e.g. OFDM).

WiFi is the predecessor technology of WiMAX that has been widely deployed. It is cheap, available, applicable, and has multi-vendors. It has many advantages over WiMAX, while WiMAX fills many gaps that have been found in WiFi. The WiMAX technology in its current form will complement the 802.11 or WiFi standard. The deployment and adoption of the 802.16e standard could decrease the number of WiFi users while increasing WiMAX users and WiMAX “hot spots.” The 802.16a standard will help corporations and Internet service providers by expanding their services to rural markets or the “last mile”, [8].

In spite of the vast development in the WiMAX, WiFi is still the dominant wireless technology at the present time. In fact, tri mode WiFi (IEEE 802.11 a/b/g) is already built in the laptop machines, and day-by-day PDAs and iPhones contain 802.11. However, it is my contention that while there are many advantages to be had from using WiFi, the early

WiFi standards have less security and poor reliability with low data rate than WiMAX. WiFi standard developers and vendors have tried to overcome these problems by releasing IEEE 802.11i for security and IEEE 802.11e for QoS (Quality of Service) as vertical improvements for the IEEE 802.11. Ultimately, the IEEE 802.11n has been released as a new WiFi standard, which has covered (standard's claim) the previous problems by using the MIMO-OFDM mechanism. 802.11n has the ability to be peer-to-peer with WiMAX due to the higher data throughput and longer wireless distance. The increased performance from 802.11n WLAN should eliminate the last bottleneck in the enterprise-wide WLAN deployment, [4]. The paper has focused on adding the smart modification while the IEEE 802.11n is in the process of being developed.

The security improvement (802.11i) and the MIMO-OFDM mechanism (802.11n) can extensively enhance the WiFi. This enhancement enthused the task group (TGs) to define the Extended Service Set (ESS) Mesh Networking Standards. Presently, the WiFi mesh draft standard has been released as IEEE 802.11s. A lot of challenges against the 802.11s have to be harmonized to efficiently provide a large bandwidth over a large coverage area, [9].

IEEE 802.16 standard proposes four different PHY specifications. Following the work in the WiMAX Single Carrier Access that has been solved in the previous paper [10], the methodology WiMAX-OFDM has been selected for this paper while the WiMAX-OFDMA will be investigated in future work. The WiMAX-SC PHY (10-66 GHz) has not been selected due to frequency band incompatibility

The rest of the paper is organized as follows. Section-2 illustrates in detail, the Fixed WiMAX PHY layer (WirelessMAN-OFDM PHY) and the related mathematical background for the WiMAX-WiFi OFDM RF signals and also gives a full description of the WiMAX-OFDM-TDD frame structure. Section-3 describes WiFi-OFDM PHY layer specifications and compromise with the WiMAX-OFDM. Section-4 is the proposed convergence bridge with explanation of the smart modification in the physical layers functionalities.

## 2. THE PHYSICAL LAYER FOR WIMAX-OFDM

### 2.1 WiMAX-IEEE 802.16 PHY (2-11 GHz)

Both licence spectrum and unlicensed spectrum are found in the range of (2-11 GHz), and both are discussed in detail in the IEEE 802.16 standard. The overall design of the (2-11 GHz) physical layer is based on the clear demand for a non-line-of-sight (NLOS). This came about because of a realization on the part of standards developers that residence application of 802.16 would encounter multipath propagation issues because of trees and other signal obstacles. Three air interface specifications for 802.16 are described in the original standards, [3]. They are WirelessMAN-SCa, which relies on a single carrier modulation schema; WirelessMAN-OFDM (Fixed WiMAX), which relies on OFDM with a 256-point transform scheme with TDMA access, which is mandatory for unlicensed bands; and WirelessMAN-OFDMA (Mobile WiMAX), which uses OFDMA with 2048-point transform. Here, multiple access is provided by targeting subset of various sub-carriers to individual receiving devices. In this paper, WirelessMAN-OFDM physical layer has been selected for the WiMAX-WiFi convergence (mixed standards). The first stage is to convert the carrier frequency of the WiFi-OFDM signal, which is either 2.4GHz or 5 GHz, via a straightforward frequency converter to be the same as WiMAX Wireless MAN-OFDM Base-station carrier frequency as shown in figure (2).

### 2.2 WiMAX-OFDM

This paper suggests the Multi-Carrier aspects of WiMAX-WiFi Convergence: the WiMAX-OFDM ( $N_{fft}=256$ ) and the WiFi-OFDM ( $N_{fft}=64$ ), as shown in figure (2). The mismatch in the number of samples ( $N_{fft}$ ) cannot be resolved at the MAC layer, and we deal with it as a physical layer issue, by creating a *Convergence-Bridge*. This bridge is like an extra thin layer, which is responsible to harmonize the mismatch. Generally, any OFDM signal,  $s(t)$ , could be produced from equation (1) whether it is WiMAX or WiFi,[11]. This equation underpins the design of the proposed Convergence-Bridge.

$$S(t) = Re \left\{ e^{j2\pi f_c t} \cdot \sum_{\substack{k=-N_{used}/2 \\ k \neq 0}}^{N_{used}/2} C_k \cdot e^{j2\pi k \Delta f (t-T_g)} \right\} \dots \dots \dots (1)$$

- $N_{used}$ , Number of used subcarriers ( $N_{used}=200$ , for the WiMAX OFDM)
- $C_k$  is a complex number that represent the Data,
- $\Delta f$  is the subcarriers frequency spacing, ( $\Delta f = 15.625$  KHz )
- $f_c$  is the central frequency ,(  $f_c= 2-11$  GHz)
- $T_g$  is the Guard Time

Mathematically, equation (1) has been structured from three main parts:

Part1: Carrier Frequency part:  $e^{j2\pi f_c t}$

Part2: Data part:  $C_k$

Part3: Subcarriers part:  $e^{j2\pi k \Delta f (t-T_g)}$

In part1, the carrier frequency ( $f_c$ ) is the main factor in deciding which technology is being used, e.g. the WiFi carrier frequency is 2.4 GHz or 5 GHz while the WiMAX carrier frequency bands are (2 GHz-11 GHz). In part2, the  $C_k$  is the data to be transmitted on the subcarriers whose frequency offset index is  $k$ , during an OFDM symbol. Part3 is the summation of the  $N_{FFT}$  samples of the orthogonal subcarriers; therefore  $N_{FFT}$  is another factor which differs between the WiFi and WiMAX, ([12], [13]).

Fig (2) illustrates the frequency domain of the WiFi-OFDM signal (spectrum) which is either IEEE802.11a (5 GHz carrier frequency) or IEEE802.11n (2.4 or 5 GHz carrier frequency) .The WiMAX WirelessMAN-OFDM signal (spectrum) has a 256 sub-carrier frequencies within (2-11 GHz) band, as pointed out in fig (2). After the frequency conversion both WiFi-OFDM and WiMAX WirelessMAN-OFDM signals have been held at the same centre frequency ([12], [14]).

The IEEE 802.11a,n and the IEEE 802.16e standards specify the number of the subcarriers and the bandwidth of the related OFDM signals. The WiFi-OFDM signal has got 64 subcarriers spread over 20MHz bandwidth, while the WiMAX-OFDM signal has got 256 subcarriers spread over 3.5MHz bandwidth. These differences complicate the convergence between the two technologies. Figure (2) illustrates the RF conversion of the WiFi-OFDM signal's central frequency to be the same as the WiMAX-OFDM signal's central frequency. Even though the WiFi signal can exist in the WiMAX band but they cannot interoperate due to the differences outlined above.

### 2.3 WiMAX-OFDM-TDD Frame Structure

The IEEE 802.16 standard subcategorised the WiMAX-OFDM PHY in terms of the duplexing method. These duplexing methods are the TDD (Time Division Duplexing) and the FDD (Frequency Division Duplexing). In the Point to Multipoint (PMP) WiMAX topology, the duplexing method is either TDD or FDD for the licence bands, while in the licence exempt bands the duplexing method shall be TDD (5). In this paper, the WiMAX-OFDM-TDD has been selected to satisfy the WiMAX-WiFi convergence, while WiMAX-OFDM-FDD will be investigated in the future.

A frame-based transmission has been used in the WiMAX-OFDM. The frame duration is a central periodic time based on the frame start preambles, which has been selected by the BS (base station), and it should not be changed. The specific frame durations that are allowed are (2.5ms, 4ms, 5ms, 8ms, 10ms, 12.5ms and 20ms). A frame consists of a downlink subframe and an uplink subframe. A downlink subframe consists of only one downlink PHY PDU,[11]. An uplink subframe consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple uplinks PHY PDUs, each transmitting from a different SS (Subscriber Station). Moreover, according to the OFDM frequency domain, equ (1) shows the OFDM symbol is made up from  $N_{FFT}$  subcarriers that are classified into three subcarriers types: Data subcarriers, Pilot subcarriers and Null subcarriers. In the WiMAX-OFDM the data subcarriers ( $N_{used}$ ) are dedicated for data transmission and it is 200 out of 256 subcarriers, whereas the Pilot subcarriers

are dedicated for various estimation purposes and it is only 8 subcarriers. The Null subcarriers are not for transition at all, such as the lower 28 frequency guard subcarriers, the higher 27 frequency guard subcarriers and the one and only one DC subcarrier. Figure (3) shows the subcarriers (sub channel frequency index) consist of the three categories of the subcarriers. The data subcarrier index range is  $-100 < k < +100$ , exempt from that the pilot subcarrier indices (-88, -63, -38, -13, 13, 38, 63, 88), while the DC subcarrier index is when  $k=0$ . The other two null subcarrier ranges are the *lower* frequency guard subcarrier band ( $-128 < k < -101$ ) and the *higher* frequency guard subcarrier band ( $+101 < k < +127$ ), (Hints: these guard bands do not appear in figure-3). The basic structure of a WiMAX-OFDM frequency domain has 256 subcarriers ( $N_{FFT}$ ) spread over 3.5MHz bandwidth with 15.625KHz subcarrier spacing as determined by the IEEE 802.16 WirelessMAN-OFDM, ([11], [15]).

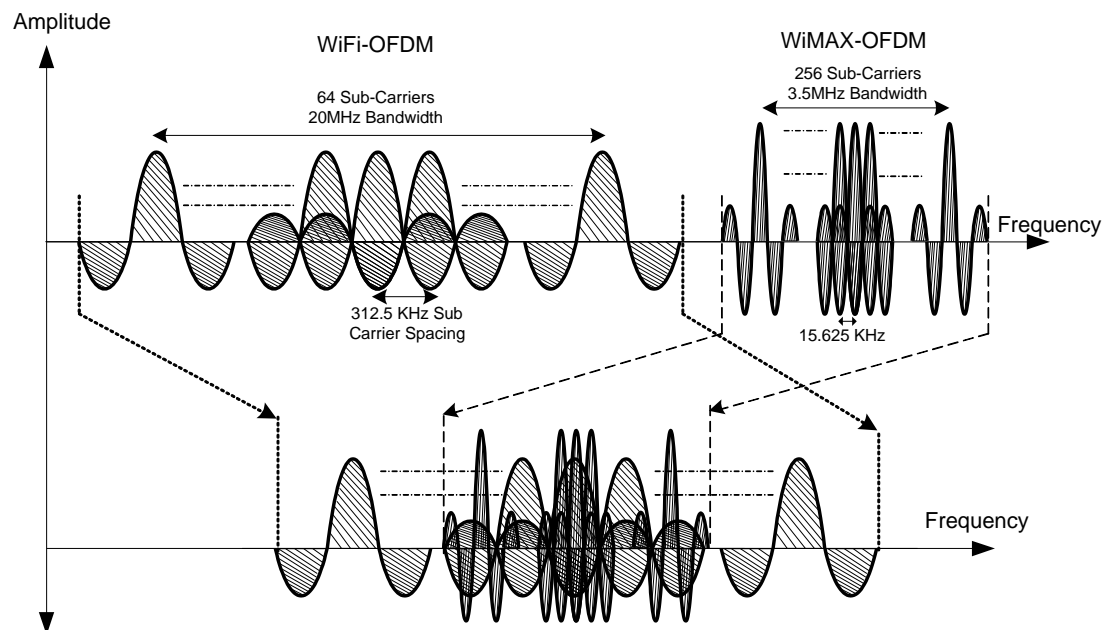


Figure (2) WiMAX-OFDM, WiFi-OFDM spectrums and the frequency conversion stage for WiFi-OFDM Signal

### 3. THE PHYSICAL LAYER FOR WIFI-OFDM

#### 3.1 WiFi-IEEE 802.11a,n PHY (2.4 or 5 GHz)

The current IEEE 802.11b standard and IEEE 802.11g standard operate in the 2.4GHz radio frequency band, while the IEEE 802.11a operates in the 5GHz radio band. The IEEE 802.11n standard has been established as a new WiFi standard that provides backward compatibility with the IEEE 802.11a at 5GHz and with the IEEE 802.11b, g at 2.4GHz. The IEEE 802.11n is being developed to overcome (as the standard's claims) previous problems by using three primary modern technologies to satisfy higher data throughput, longer wireless range and reliability of the wireless LAN. The amendment features are not only allowing the IEEE 802.11n standard to achieve an approximate fivefold increase performance over current 802.11a/b/g network, but also be peer to peer with the WiMAX, ([4], [5]).

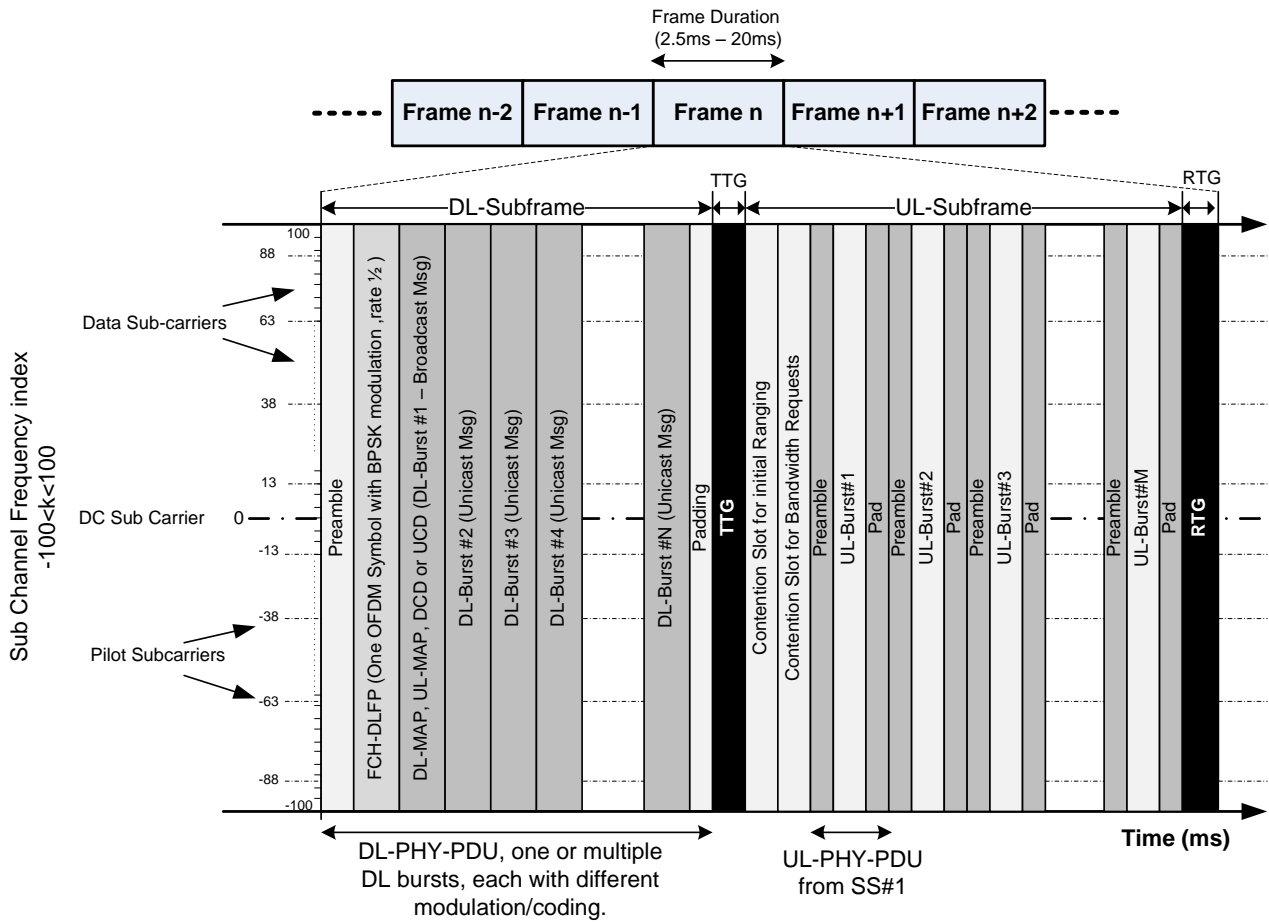


Figure (3), WiMAX-OFDM-TDD Frame Structure

### 3.2 WiFi-OFDM vs. WiMAX-OFDM

Exploring the similarities and dissimilarities among the wireless standards is the initial step towards the convergence. The WiFi is the predecessor version of the WiMAX; thus a lot of the similarities have been underlined. A major similarity is the OFDM, which will be the common ground between them to initiate the convergence, but resolving the dissimilarities would be our main challenge. Consequently, it has been discovered that the possibilities of the convergence in the single carrier could be resolved in the MAC layer; while in the multi carrier we deal with it as a physical layer issue by creating a ‘*Convergence-Bridge*’ to harmonize the mismatch. In the Multi-Carrier WiMAX-WiFi Convergence, the mismatch between the fixed WiMAX-OFDM ( $N_{fft}=256$ ) and the WiFi-OFDM ( $N_{fft}=64$ ) has been confirmed as a physical layer issue that will never be solved as MAC layer problem; therefore the current proposal is how to build what we called the “*Convergence-Bridge*”. This bridge is a smart modification in the IEEE 802.11a,n standard physical layer, which is responsible for harmonizing these mismatches,[16].

The OFDM technique is the common ground among the multi-carriers wireless technologies. However, the IEEE 802.16 and IEEE 802.11 standard developers were keen to use the OFDM as a major change for the new standards. The OFDM has been shown to be effective over the ISI (Inter- Symbol Interference) and the channel fading, therefore; the use of OFDM has been relied on, because of its elegant handling of multi path interference. On the other hand, the OFDM requires a costly and a power inefficient transmitter front end, especially a problem in the uplink where the transmitter is a battery driven terminal,[17]. It has been argued that using the single carrier technique is better than the OFDM in terms of data rate and the packet error rate (PER), so this argument goes, the single carrier is a very good candidate for portable

data rate terminal in the indoor environment. However, the new wireless standards are being developed under the OFDM techniques because, from cost/performance point of view, it is still seen as the more attractive solution, which has the ability to overcome the multi path propagation problems,[18]. Another argument about the use of the OFDM, [19] had proposed to use a mixed OFDM downlink and single carrier uplink for the IEEE 802.16 which, as they claimed, will ensure to fully benefit from the features of each technology to make cost effective CPE with NLOS operation capability. Ultimately, the final draft of the IEEE 802.16 has not approved [19] approach to avoid the dissimilarities between the downlink and the uplink. However, it is my contention that there are many advantages to be had from using OFDM or single carrier techniques, which depends on the application itself.

#### 4. THE PROPOSED CONVERGENCE-BRIDGE

The Convergence-Bridge is a smart modification in the WiFi OFDM Physical layer to enable the WiFi devices to join the WiMAX-OFDM wireless network. In this paper the WiMAX-Fixed (OFDM-256) and the WiFi-OFDM-64 have been selected to achieve the multi-carrier convergence. The convergence idea was initiated from the similarities between the WiMAX and the WiFi, however the dissimilarities are still real obstacles to enable them to communicate with each other,[20]. Dissimilarities between wireless standards are usually in the lower layers so that the investigations are focused on the PHY and MAC layers. As mentioned, due to the standards investigations, it has been discovered that the convergence in WiMAX-WiFi multi-carrier OFDM is a physical layer issue. RF carrier, Bandwidth, Guard Time, FFT samples and the OFDM duration are the main issues for those physical layer differences that should be harmonized, as shown in figure (4). In this convergence, several WiFi and WiMAX PHY specifications could be involved. However choosing a specific WiMAX-PHY is vital because these diverse PHY specifications will generate different MAC level management messages. As mentioned above in section 1, IEEE 802.16 standard proposes four different PHY specifications. Following the work in the WiMAX Single Carrier Access that has been solved in the previous paper [10], the methodology WiMAX-OFDM has been selected for this paper while the WiMAX-OFDMA will be investigated in future work. The WiMAX-SC PHY (10-66 GHz) has not been selected due to frequency band incompatibility. For the WiFi-OFDM physical layer, the paper has selected the IEEE 802.11n OFDM standard while it is being developed. Figure (4) illustrates the IEEE 802.11 OFDM Physical layer and the proposed modification that will satisfy the convergence. The proposal does not suggest changing the standard itself but modifying some functions to be configurable. These configurable functions have been highlighted as Grey areas in figure (4). The IEEE 802.11 standard has fixed the configurations for WiFi mode only, while our proposal is to set up these functions for WiFi and WiMAX modes.

##### 4.1 Unified the WiFi-WiMAX Frequency Bands

The RF Central Frequency is the main factor in deciding which technology is being used and it also represents the identification factor of a certain frequency band. Figure (2) illustrates two different OFDM spectrums in different frequency bands. The IEEE 802.11a,n standard is being carried on 2.4GHz or 5GHz, while the IEEE 802.16 OFDM – TDD standard is being carried on 3.5GHz. The first step of the convergence is to unify the two spectrums in a one band. Converting the WiFi RF- signal to the WiMAX frequency band has been illustrated in figure (2). Even though the WiFi signal can exist in the WiMAX band but they cannot interoperate due to the differences outlined above.

As mentioned in section 2.2, generally by changing the equation parameters, any OFDM signal could be produced from equation (1) whether it is WiMAX-OFDM or WiFi-OFDM. This equation underpins the design of the proposed *Convergence-Bridge*. Basically, the convergence enables the WiFi device to receive a signal  $S(t)$  from a WiMAX Base Station and transmit a signal  $S(t)$  to a WiMAX Base Station,[21]. The following steps are the mathematical implantation of these signals:

For the WiFi-OFDM,

$$S_1(t) = Re \left\{ e^{j2\pi f_{c1}t} \cdot \sum_{\substack{k=-26 \\ k \neq 0}}^{+26} C_k \cdot e^{j2\pi k \Delta f_1 (t-T_{g1})} \right\} \dots \dots \dots (2)$$

Whereas,  $S_1(t)$  is the time domain equation for the WiFi-OFDM-64,  $f_{c1}$  is the central frequency which is either 2.4GHz or 5GHz,  $k$  is the frequency index (52 subcarrier indices) which is  $-26 \leq k \leq +26$ ,  $N_{used}$  is 52 subcarriers, 48 data subcarriers + 4 pilot subcarriers. There are also 14 frequency guard subcarriers (7 lower frequency guard subcarriers band + 7 higher frequency guard subcarriers band), which have not appeared in the equation. In total 64 subcarriers (48 data subcarrier + 4 pilot subcarriers+ 14 frequency guard subcarriers ) are there in the WiFi-OFDM.  $\Delta f_1$  is the subcarrier frequency spacing ( $\Delta f_1 = BW/N_{fft} = 20\text{MHz}/64 = 312.5 \text{ KHz}$ ).  $T_{g1}$  is the guard time ( $T_{g1} = 0.8 \mu\text{s}$ ).

For the WiMAX-OFDM,

$$S_2(t) = Re \left\{ e^{j2\pi f_{c2} t} \cdot \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t - T_{g2})} \right\} \dots \dots \dots (3)$$

Whereas,  $S_2(t)$  is the time domain equation for the WiMAX-OFDM-256,  $f_{c2}$  is the central frequency which is 3.5 GHz,  $k$  is the frequency index (200 subcarrier indices) which is  $-100 \leq k \leq +100$ ,  $N_{used}$  is 200 subcarriers, 192 data subcarriers + 8 pilot subcarriers. There are also 55 frequency guard subcarriers (28 lower frequency guard subcarriers band + 27 higher frequency guard subcarriers band), which have not appeared in the equation. In total 256 subcarriers (192 data subcarrier + 8 pilot subcarriers+ 55 frequency guard subcarriers +1 DC Subcarrier ) are there in the WiMAX-OFDM.  $\Delta f_2$  is the subcarrier frequency spacing ( $\Delta f_2 = 15.625 \text{ KHz}$ ).  $T_{g2}$  is the guard time ( $T_{g2} = 18.24 \mu\text{s}$ ).

Despite the fact that WiFi-OFDM-64 and the WiMAX-OFDM-256 signals have been generated from the same equation, the above dissimilarities of the equation's parameters have denied them to communicate with each other. The current proposal in this paper suggests enabling specific functions in the WiFi PHY-layer designed to be configurable. These functions have been highlighted as grey areas in figure (4). The first part (function) is the RF-oscillator; which participates alternatively in the down/up conversions of the RF signals in the receiver/transmitter tasks. There is only one RF-OSC device, which is being used by both the transmissions and receiving processes. Currently, the WiFi PHY layer can detect the WiMAX signal but it cannot convert the WiMAX signal in the RF level because the RF oscillator of the WiFi does not have the 3.5 GHz carrier frequency. The suggestion is to enable the RF-OSC to have the 3.5 GHz carrier frequency in addition to the original RF carrier frequencies 2.4 GHz and 5GHz. As shown in figure (2), having this facility could only exist WiFi and WiMAX signals in the same RF bands but they cannot interoperate due to the other differences. The second part (device) is the Automatic Frequency Control (AFC) clock recovery, which detects/maintains the drift of the clock and also participates in separating the IQ signals. While the AFC device has been designed to work over 20MHz bandwidth (WiFi-OFDM), the paper suggests enabling the AFC device to also work over 3.5 MHz bandwidth (WiMAX-OFDM). The third part is how to remove the guard time length; part of the proposal is to configure this stage to be able to remove not only the 0.8  $\mu\text{s}$  guard time (WiFi), but also 18.24  $\mu\text{s}$  for the WiMAX. The fourth part is the bottleneck part, the FFT block of the WiFi-PHY layer transforms only 64 samples simultaneously, while the receiving signal  $S_2(t)$  has 256 samples. Having a 256/64 FFT block instead is our proposal to overcome this bottleneck.

#### 4.2 WiFi-WiMAX Convergence Steps

As mentioned in the previous section, modifying those functions (grey blocks) to be configurable is our suggestion to satisfy the *convergence bridge* requirements. Figure (4) represents the WiFi PHY layer; the top part is the receiver part of the PHY layer while the bottom part is the transmitter. Most of the transmitter / receiver stages (functions) are reversible functions. The middle part in the figure (4) is the WiFi/WiMAX configuration parameters table that illustrates the two different modes; mode-1 is the original configuration parameters of the WiFi device, while mode-2 is the additional configuration parameters that will enable the WiFi PHY layer to behave like a WiMAX device. It is not possible to activate the two modes simultaneously, because they are using the same physical layer blocks in different configurations.



The following steps explain how a WiMAX signal  $S_2(t)$  could be converted and processed in the WiFi PHY layer. Figure (4) shows number of test points that will be used to track the signal through the PHY layer stages:

1. The WiMAX-OFDM-256 signal,  $S_2(t)$ , is being carried on 3.5GHz carrier frequency with 256 OFDM samples.
2. The WiFi antenna detects between 2.4 and 5GHz carrier frequencies, therefore; 3.5 GHz is within the antenna's detection range.
3. At the first test point ( $T_1$ ),  $S_2(t)$  went through the LNA (Low Noise Amplifier) form noise elimination and signal amplifications.

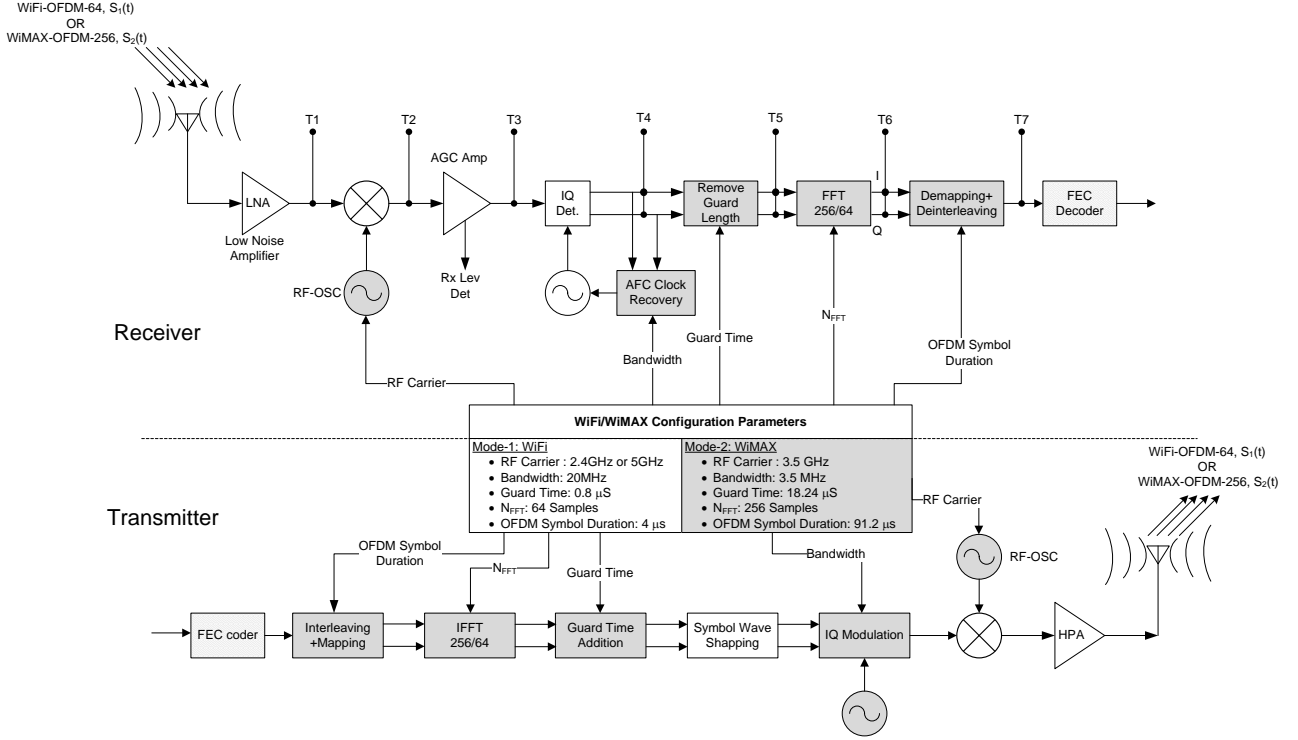


Figure (4), the WiFi-OFDM Physical layer  
(The Grey area is the modified blocks)

4. At  $T_2$ , the signal will be down-converted through the RF-conversion stage. The RF-OSC generates a sinusoidal signal,  $\text{Cos}(2\pi f_{c2}t) = \frac{1}{2}(e^{-j2\pi f_{c2}t} + e^{j2\pi f_{c2}t})$ , that will be multiplied in the time domain by an OFDM symbol  $S_2(t)/T_1$ , ( $S_2(t)$  at  $T_1$ ):

$$S_2(t)|_{T_2} = S_2(t)|_{T_1} \times \text{Cos}(2\pi f_{c2}t)$$

$$= \frac{1}{2} \text{Re} \left\{ e^{-j2\pi f_{c2}t} \cdot e^{j2\pi f_{c2}t} \cdot \sum_{k=-100}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t-T_{g2})} + e^{j2\pi f_{c2}t} \cdot e^{j2\pi f_{c2}t} \cdot \sum_{k=-100}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t-T_{g2})} \right\}$$

$$S_2(t)|_{T_2} = \frac{1}{2} \text{Re} \left\{ \sum_{k=-100}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t-T_{g2})} + e^{j4\pi f_{c2}t} \cdot \sum_{k=-100}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t-T_{g2})} \right\}$$

The second part of the above equation is a by-product signal, which represents the second harmonic of the carrier frequency. It has been generated as a result of the multiplication of the positive frequency part ( $e^{j2\pi f_c t}$ ) of the RS-OSC sinusoidal signal ( $\text{Cos}(2\pi f_c t)$ ). Any harmonic signal is being eliminated by a Low Pass Filter. Therefore a WiMAX-OFDM Symbol  $S_2(t)$  at  $T_2$  will be defined by the following equation:

$$S_2(t)|_{T_2} = \frac{1}{2} \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t - T_{g2})} \dots \dots \dots (4)$$

5. At  $T_3$ , the **Automatic gain control** (AGC) is an adaptive device to adjust the average output signal level to an appropriate level for a range of input signal levels.

$$S_2(t)|_{T_3} = \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t - T_{g2})} \dots \dots \dots (5)$$

6. At  $T_4$ , the IQ time domain separation happens at this stage. The WiMAX-OFDM Symbol,  $S_2(t)$  signal, separates into two parts; real and imaginary parts. As mentioned in section 2.2,  $C_k$  is the data to be transmitted on the subcarriers whose frequency offset index is  $k$ , during an OFDM symbol:

$$C_k \cdot e^{j2\pi k \Delta f_2 (t - T_{g2})} = I_k \cdot \text{Cos}(j2\pi k \Delta f_2 (t - T_{g2})) + j \cdot Q_k \cdot \text{Sin}(j2\pi k \Delta f_2 (t - T_{g2}))$$

$S_2(t)|_{T_4} = I(t) + j \cdot Q(t)$ , where  $I(t)$  and  $Q(t)$  are:

$$I(t) = \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} I_k \cdot \text{Cos}(j2\pi k \Delta f_2 (t - T_{g2})) \dots \dots \dots (6)$$

$$Q(t) = \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} Q_k \cdot \text{Sin}(j2\pi k \Delta f_2 (t - T_{g2})) \dots \dots \dots (7)$$

7. At  $T_5$  the guard time length is removed from the signals  $I(t)$  and  $Q(t)$ . The guard time is one of the modified configuration parameters that has been highlighted in figure(4). For the WiMAX-OFDM-256 signal the guard time is ( $T_{g2} = 18.24 \mu\text{s}$ ). This stage prepares the IQ signals (an OFDM Symbol) to be transformed from time domain to frequency domain using the Fast Fourier Transform stage. The WiFi PHY layer has been designed to transform only 64 samples in the FFT. But, part of the *convergence bridge* proposal is to modify the FFT to transform 256 samples also. The IQ signals equations (an OFDM symbol) will be:

$$I(t) = \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} I_k \cdot \text{Cos}(j2\pi k \Delta f_2 (t)) \dots \dots \dots (8)$$

$$Q(t) = \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} Q_k \cdot \text{Sin}(j2\pi k \Delta f_2 (t)) \dots \dots \dots (9)$$

8. At  $T_6$ , the FFT function transforms the  $I(t)$  and the  $Q(t)$  signals to the frequency domain. It generates two vectors: I-vector and Q-vector with 256 length each. The combination of I and Q vectors represents a single OFDM symbol. At this point the IQ-vectors (data) appears will contain real numbers.  $I = [I_1, I_2, I_3, \dots, I_{256}]$  and  $Q = [Q_1, Q_2, Q_3, \dots, Q_{256}]$ , where  $I_k$  and  $Q_k$  are real numbers, and  $C_k = I_k + j Q_k$ .

9. At  $T_7$ , each IQ symbol is converted to a binary number. The number of bit per symbol could be determined by knowing the modulation type that has been used in the current OFDM symbol. The number of bit per symbol is equal to 2, 4 or 6 bits per symbol if the modulation type is BPSK, 16QAM or 64QAM respectively. For instance, if the current OFDM symbol has been sent using 16QAM modulation type, each  $C_k$  (whereas  $C_k = I_k + j \cdot Q_k$ ) is converted to 4 bits binary number. Therefore, a full IQ-vector (one OFDM symbol) generates  $(4 \times 256) = 1024$  bits as an input vector to the FEC (Forward Error Correction) block.
10. As shown in figure (4), the FEC block has been highlighted in a different pattern to indicate a future investigation of the encoder/decoder of WiFi PHY layer. The implementation of Reed Solomon block code and Viterbi convolution code are in principle simple bit polynomial manipulations, [22].

## 5. CONCLUSION AND FUTURE WORKS

The effort of this paper is to produce multi-carrier convergence between Fixed WiMAX-TDD (OFDM-256) and WiFi-OFDM-64, which is an ideal technology that provides the best of both worlds: the new features of the WiMAX and the low cost of the WiFi. In order to create a heterogeneous network environment, differences between the two technologies have been investigated and resolved. Dissimilarities among wireless standards are usually in the lower layers so that the investigations are focused on the PHY and MAC layers. In the standards investigations, it has been discovered that the convergence in WiMAX-WiFi multi-carrier OFDM is a physical layer issue. RF carrier, Bandwidth, Guard Time, FFT samples and the OFDM duration are the main issues for those physical layer differences that should be harmonized. For the WiFi-OFDM physical layer, the paper has selected the IEEE 802.11n OFDM standard while it is being developed. The proposal does not suggest changing the standard itself but modifying some functions to be configurable. The IEEE 802.11 standard has fixed the configurations for WiFi mode only, while our proposal is to set up these functions dynamically for WiFi and WiMAX modes. Following the work in the WiMAX Single Carrier Access that has been solved in the previous paper (10), the methodology WiMAX-OFDM (256) has been selected for this paper while the Mobile WiMAX-OFDMA (512, 1024, and 2048) will be investigated in the future. In this paper only the WiMAX-TDD (OFDM-256) has been involved in the convergence investigations, but it is also recommended as a future work to involve the WiMAX-FDD (OFDM-256) in these convergence investigations. Future improvement would include the implementation of simple Reed Solomon block code and Viterbi convolution code.

A new vision of the convergence has emerged when two different wireless standards have created the MESH topology as vertical developments. As a future work, while the Wireless Mesh Network standards are under development, the paper suggests studying the potentials of the WiMAX-WiFi convergence in the Mesh topology also. Apparently, the WiMAX-WiFi convergence has a good chance to be involved in the mesh topology applications.

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