EVOLUTION OF OFDM TECHNOLOGY: A REVIEW

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Abstract: In the present scenarios, new advanced wireless technologies are being developedto provide Broadband Wireless Access (BWA) services to customers. These technologies can offer very high data rates and wider bandwidth to the users to meet their demands. One of the most important and promising technology being used nowadays is Orthogonal Frequency Division Multiplexing (OFDM) which is a Multi-Carrier Modulation (MCM) scheme. It finds applications in WLANs, WMANs, LTE and other 4G systems. This paper tells aboutthe history and evolution of OFDM technology till date. The applications of OFDM are also recorded in this review paper.

***Index Terms*- Broadband Wireless Access, is Orthogonal Frequency Division Multiplexing, Multi-Carrier Modulation, Inter Symbol Interference, Inter Carrier Interference, MIMO-OFDM**

1. Introduction:

One of the most important and promising MCM technique being employed these days is OFDM which has become the backbone of BWA systems. It is widely being used in IEEE 802.11 and IEEE 802.16 systems. In OFDM, a data stream of high data rate is transformed into many low data rate parallel bit streams and each bit stream is then modulated by an individual sub-carrier. All the subcarriers are orthogonal to each other. The parallel conversion results in increase in bit duration leading to reduction infrequency spectrum, thus making the systems bandwidth efficient. As the bandwidth of subcarriers is narrow therefore they experience only flat fading. Thus, the effects of frequency selective fading are minimized [1]. Further, the orthogonal nature of subcarriers avoids overlapping among themselves in a time period, leading to reduction in ICI and ISI [2-3]. Figure 1 shows the basic principle of an OFDM system. At the transmitter side, a serial data is converted into *N* parallel data streams which are modulated using BPSK or QPSK or QAM constellation scheme. Each parallel data stream is then further modulated on a separate subcarrier. The spacing between the subcarriers is *1/T* where *T* is the time period of a single OFDM symbol without the addition of cyclic prefix to it. This condition results in maintaining the orthogonality among different subcarriers. Thus the interference between subcarriers is avoided [4]. The modulation of parallel data streams on different subcarriers is performed using Inverse Fast Fourier Transform (IFFT).

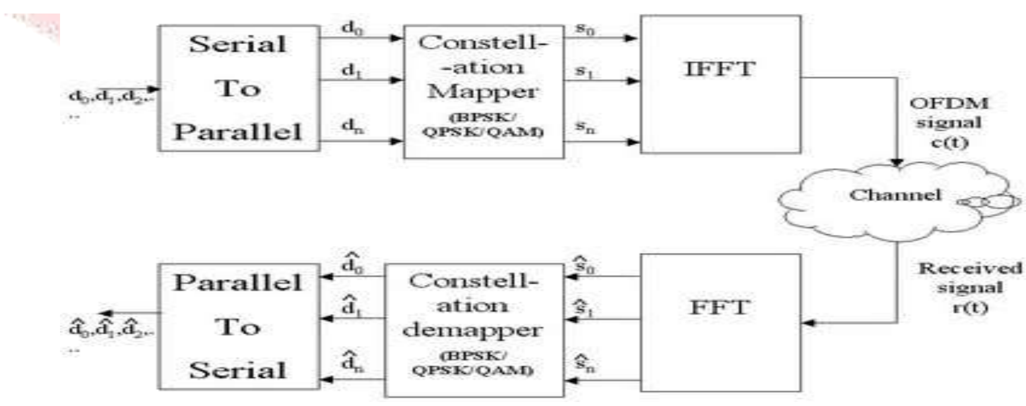

Figure 1: Basic OFDM Transmission and Reception [5]

At the receiver end, the fast Fourier transform (FFT) is carried out which performs demodulation of subcarriers and further parallel data streams are converted back into serial data stream. The one of the most important feature of OFDM scheme is that it can tolerate severe multipath fading as it employs multiple subcarriers. Thus, if one subcarrier undergoes the effect of fading, then other carriers can carry out data transmission [6-8].

2. History and Evolution of OFDM

The main driving force behind the evolution of BWA is the development of multi-carrier modulation schemes. During late 50s and mid-60s, MCM techniques were developed only for military purposes. These MCM systems employed non-overlapped band-limited orthogonal subcarriers for data transmission using a set of analog oscillators and filters [9]. These systems did not gain much attention commercially as these systems require wider bandwidths due to non-overlapping nature of subcarriers and difficulty in recovering data without inter symbol interference (ISI) using analog filters. Subsequently, the focus shifted on study of overlapping subcarriers in MCM scheme. Chang in 1966 proposed the first MCM scheme to simultaneous transmit data streams through linear-band-limited channel using overlapped subcarriers which gave birth to the concept of OFDM [10]. Next year, MCM systems were implemented for complex data (Quadrature Amplitude Modulation) [11]. Further, the performance of orthogonal multiplexed transmission system was analyzed for various degrading factors like carrier offset error, sampling time error and phase errors of transmitter and receiver filters [12] and in 1970 a patent in the name of orthogonal frequency division multiplexing was filed [13]. But, these OFDM systems proved to be very expensive due to their requirement for large number of subcarrier oscillators for parallel data transmission. A major revolution in the history of OFDM came in 1971 in the form of discrete Fourier transform (DFT) which enabled easier and simple implementation of the systems. DFT eliminated the need of banks of sinusoidal oscillators and the coherent demodulators, thus reducing the complexity of OFDM transceivers [14]. Up to this era, all the systems used empty guard bands and raised cosine windowing in frequency domain and time domain respectively to minimize the effect of ISI (Inter Symbol Interference) and ICI (Inter Symbol Interference). Another milestone in OFDM was achieved in 1980 with the introduction of cyclic extension (CE), more commonly known as cyclic prefix (CP) while maintaining the orthogonal characteristics of the transmitted data through tough channel conditions. The insertion of CP further clears ICI and ISI [15]. Further, much faster processing was attained for Quadrature modulated OFDM systems, by replacing an N-point DFT with an N/2-point DFT [16]. Bingham reviewed OFDM system and presented the scenarios where it can be used [17]. The researchers started work on the growth of OFDM for commercial applications and the first step in this direction was launching of project by European Telecommunications Standards Institute (ETSI) on Digital Audio Broadcasting (DAB) system. In these systems FFT/ IFFT operations were performed for the first time [18]. OFDM was also exploited for other applications like High Bit rate Digital Subscriber Lines (HDSL) with 1.6 Mbps data rate, Asymmetric Digital Subscriber Lines (ADSL) with 6 Mbps data rate and Very High Speed Digital Subscriber Lines (VHDSL) with 100 Mbps data rate [19-20]. In 1995 OFDM was employed for High Definition Television (HDTV) terrestrial broadcasting [21-22]. Further, HiperLAN (High performance Radio LAN) which is European alternative for the WLAN standards was investigated for OFDM systems [23]. In the subsequent years, OFDM was exploited for various wideband applications like Digital Video Terrestrial Broadcasting (DVT-B) systems for 1705 (2K) and 6817 (8K) individual subcarriers in the 8 MHz channel bandwidth spectrum [24]. During the same time, the researchers also diverted their attention towards the pulse shaping techniques. Usually, rectangular pulses were used till this time, which resulted in interference. Thus, designing of pulses that were well localized (limited) in both time and frequency became the work of interest. Finally, in 1999, efficient FFT-based symmetric pulses were designed for wireless channels which achieved performance close to the optimum OFDM spectral efficiency [25] In the same period, a major breakthrough in the field of BWA came in the form of development offirst standard for WLAN (IEEE 802.11a) employing OFDM. It provides wireless access to stationary and nomadic users in indoor environments in 5 GHz ISM band which can achieve data rates up to 54 Mbps [26]. Further, IEEE 802.11a standard was amended in the form of a new standard, known as IEEE 802.11b to support higher data rates in 2.4 GHz band [27]. In subsequent years other different standards for WLAN were developed [28]. During the same time, work also started for WMAN networks. Although the research in this direction began in 1999 but the major discovery came into light in the form of development of IEEE 802.16d standard in 2004 which formed the basis of fixed WiMAX [29]. Subsequently, this standard was updated to accommodate mobile subscriber stations in the form of IEEE 802.16e standard. This standard was approved in 2005 and published in 2006. It is also referred as mobile WiMAX [30]. During the same period, the perspective for the implementation of MIMO-OFDM wireless systems was explored and different challenges for its deployment were discussed [31-32]. A new technology called long term evolution (LTE) started by 3rd Generation Partnership Project (3GPP) came into existence.It is a mobile communication technology which provides a big jump from 3G UMTS and CDMA 2000 towards 4G with demands for high data rates and mobility. In 2009, Martín-Sacristán and his fellow scientists discussed how LTE can be used as a 4G mobile technology [33]. In 2010, OFDM was experimented for passive optical network (PON) to exploit the properties of OFDM signal such as high throughput, great tolerance to the dispersion effects in fibers and the bandwidth allocation flexibility [34]. During the same period, Akyildiz *et al.* discussed about the evolution of an advanced version of LTE known as Advanced-LTE based on 3GPP UMTS which was released with new amendments [35]. In 2012, ITU determined that "LTE-Advanced" and "WirelessMAN-Advanced" should be granted the official designation of International Mobile Telecommunications-Advanced (IMT-Advanced) which specify the requirements issued by the ITU-R (International Telecommunication Union-Radiocommunication) for 4G services [36]. Further, proposal for the integration of WiMAX and LTE was presented for future broadband applications [37]. In 2014, a survey on hybrid wireless optical broadband access network (WOBAN) technologies was carried out.WOBAN is an important combination of optical backhaul and wireless front-end to achieve better scalability and flexibility in deployment of system [38]. Next year, MIMO-OFDM was investigated for visible light communication [39]. In 2017, various opportunities for coexistence of LTE and Wi-Fi were evaluated and analyzed for future 5G systems to cater the demands of high speed broadband networks and to mitigate the issue of scarce frequency spectrum [40]. A new framework for wavelength-division-multiplexed passive optical network (WDM-PON) which revolved around optical orthogonal frequency division multiplexing and self-homodyne detection does not require any frequency offset compensation or phase noise compensation was proposed. It resulted in lowering of system complexity and power consumption requirements [41]. Simultaneously, OFDMA is being used for Light-fidelity (Li-Fi) which depends on visible light communication to support multiuser access in a small area [42]. The growth of OFDM is summarized below in table 1.

Table 1: Growth of OFDM systems

Year	Purpose/Study
1966	First MCM technique introduced using overlapped subcarriers [10]
1967	Implemented MCM with Complex data (QAM) [11]
1968	OFDM implemented for carrier offset error, sampling time error and phase errors [12]
1970	First patent in the name of OFDM was published [13]
1971	OFDM with DFT was proposed for easier and simple implementation by eliminating the need of banks of subcarrier oscillators [14]
1980	Proposed the use of cyclic prefix in place of guard spaces in OFDM systems to achieve perfect orthogonality among subcarriers [15]
1981	Faster processing of OFDM system achieved by replacing N-point DFT with N/2- point DFT [17]
1990	Different scenarios were proposed where OFDM can be employed [18]
1991	OFDM was studied for applications like ADSL, HDSL and VHDSL [19-20]
1995	OFDM was proposed for use in HDTV [21-22]
1997	OFDM was presented for HiperLAN [23]
1998	OFDM systems were exploited for DVT-B [24]
1999	Symmetric pulses instead of rectangular pulses in OFDM systems were proposed to increase spectral efficiency [25]
	First WLAN (IEEE 802.11a) was proposed having capability of providing data rates up to 54 Mbps [26]
2000	IEEE 802.11b standard was developed to support high data rate operation in the 2.4 GHz band [27]
2003	Family of other WLAN standards summarized [28]
2004	Standard for fixed WMAN/fixed WiMAX/IEEE 802.16d was developed [29]
2006	Standard for mobile WMAN/mobile WiMAX/802.16e was published [30]
	The perspective and challenges for the implementation of MIMO-OFDM wireless systems were discussed [31-32]
2009	Perspectives for LTE as a 4G mobile technology were discussed [33]
2010	OFDM was studied for broadband optical access networks [34]
	The evolution of new version of LTE called as LTE-Advanced was discussed [35]
2012	ITU accepted "LTE-Advanced" and "WirelessMAN-Advanced" as official specifications of IMT-Advanced Standard [36]
2013	The integration of WiMAX and LTE was proposal [37]
2014	Different hybrid wireless optical broadbandaccess network (WOBAN) technologies were reviewed and compared [38]
2015	MIMO-OFDM was investigated for visible light communication [39]
2017	Opportunities for coexistence of LTE and Wi-Fi were evaluated and analyzed for future 5G Systems [40]
2018	A new architecture for WDM-PON based on optical orthogonal frequency division multiplexing and self-homodyne detection was proposed to lower system complexity and power consumption requirements [41]
	OFDMA was exploited for Light-fidelity (Li-Fi) to support multiuser access using VLC [42]

3. Conclusions

The demand for wireless multimedia applications has put pressure on the researchers to innovate new advanced digital communication techniques which can provide high data rate transmission with reasonable cost, high reliability and wider bandwidth to a large number of users. Thus, to make available these services forbothfixed and mobile users, the OFDM schemes came into existence which finds applications in BWA systems. It is widely being used in optical networks these days to exploit the high bandwidth of optical channel with low dispersion.

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