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Multiple Gigabit Wireless Systems in frequencies around 60 GHz

M Series

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Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.

REPORT ITU-R M.2227-1

Multiple Gigabit Wireless Systems in frequencies around 60 GHz

(Question ITU-R 212-3/5)

(2011-2014)

1 Introduction

License-exempt equipment in the 60 GHz band makes it feasible to achieve multiple gigabit link throughput, and hence offers the ability to enable a multitude of new usages and applications such as:

1) The next generation TV link – Transport uncompromised quality video for the next generation of HD colour depth and rates.

2) Download gigabytes of contents in seconds – Send digital content between devices in 1/10th the time experienced today.

3) Cordless computing – Gigabit speed wireless input-output (I/O) and pristine wireless display allow the user to remove the cords between computing platforms and peripherals without performance compromise.

In all cases, the target is to reduce cable clutter, make connections easier and increase portability of consumer electronics, computers and peripherals.

2 Applications

The following distinct applications can be enjoyed with Multiple Gigabit Wireless Systems (MGWS):

1) Two basic types of Wireless Display usages: 1) "Wireless HDMI" typically used to connect to CE equipment and 2) Wireless compute display, typically used to connect to computer monitors.

2) Additional special cases of display and/or data streaming usages, e.g. mobile camcorder, multicast, etc.

3) Three basic types of data/file transfers: 1) Kiosk to target device sync, 2) Peer-to-peer device sync, and 3) Computer I/O and peripherals.

4) Local area network (LAN) and horizontal backbone.

5) Wireless docking; a combination of both wireless display and wireless I/O.

It should be noted that these applications could be indoor or outdoor; however, when larger networks are considered (e.g. connections within corporate LAN distributed in different buildings or backhaul of cellular systems) there might be the need for outdoor Fixed LAN Extension (e.g. point-to-point roof-to-roof). This application is generally seen as a fixed service system. Fixed applications are not included in this Report.

3 Deployment scenario

Three important deployment scenarios of MGWS are described.

3.1   Home living room

An example of a home living room floor plan is show in Fig. 1. In this deployment, a set-top box is transmitting a video stream (compressed or not) to the TV set. The separation between the set-top box and the TV set is at least 3 metres.

FIGURE 1

Example of home living room floor plan
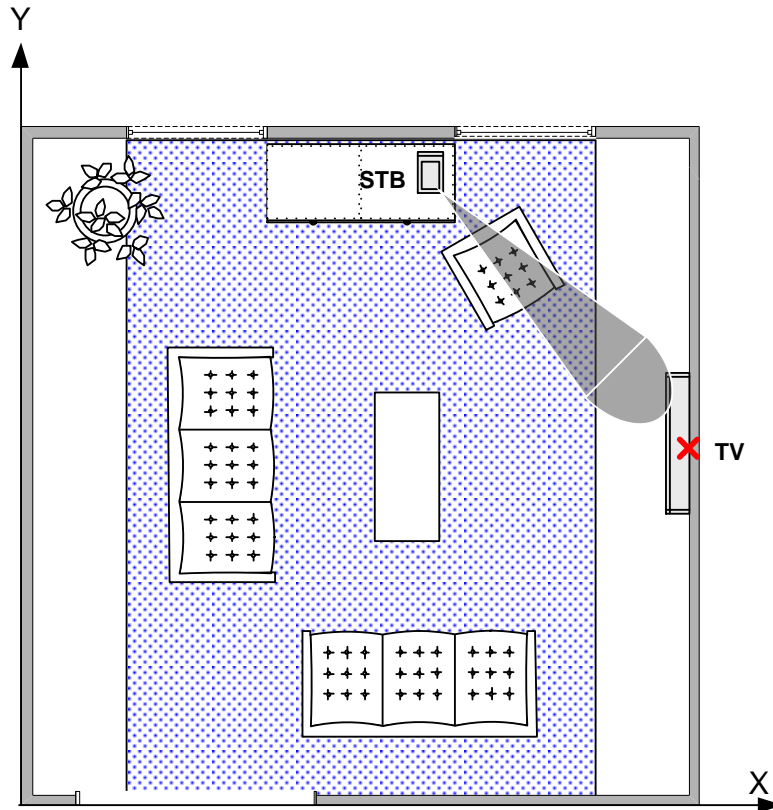
3.2   Office conference room

An example of the office conference room floor plan is shown in Fig. 2. In this deployment, there is a mix of uses:

1)   Laptop transmitting lightly compressed video to projector.

2)   Multiple laptops connected to an access point that has a 60 GHz radio and, most likely, a lower frequency band radio in the 2.4 GHz and/or 5 GHz.

3)   Laptop connected to device performing sync-and-go file transfer.

4)   Laptops connected to other laptops performing local file transfer.

FIGURE 2

**Office conference room floor plan**
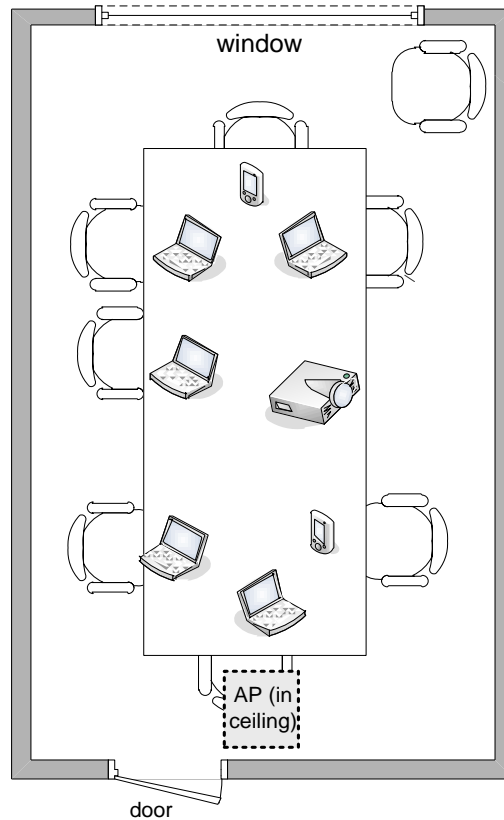
3.3 Enterprise cubicle

The enterprise cubicle floor plan is shown in Fig. 3. In this deployment, there is a mix of uses within each cubicle:

1) Laptop transmitting lightly compressed video to monitor.

2) Laptop connected to an access point, possibly doing web browsing.

3) Laptop connected to hard drive.

FIGURE 3

Enterprise cubicle floor plan
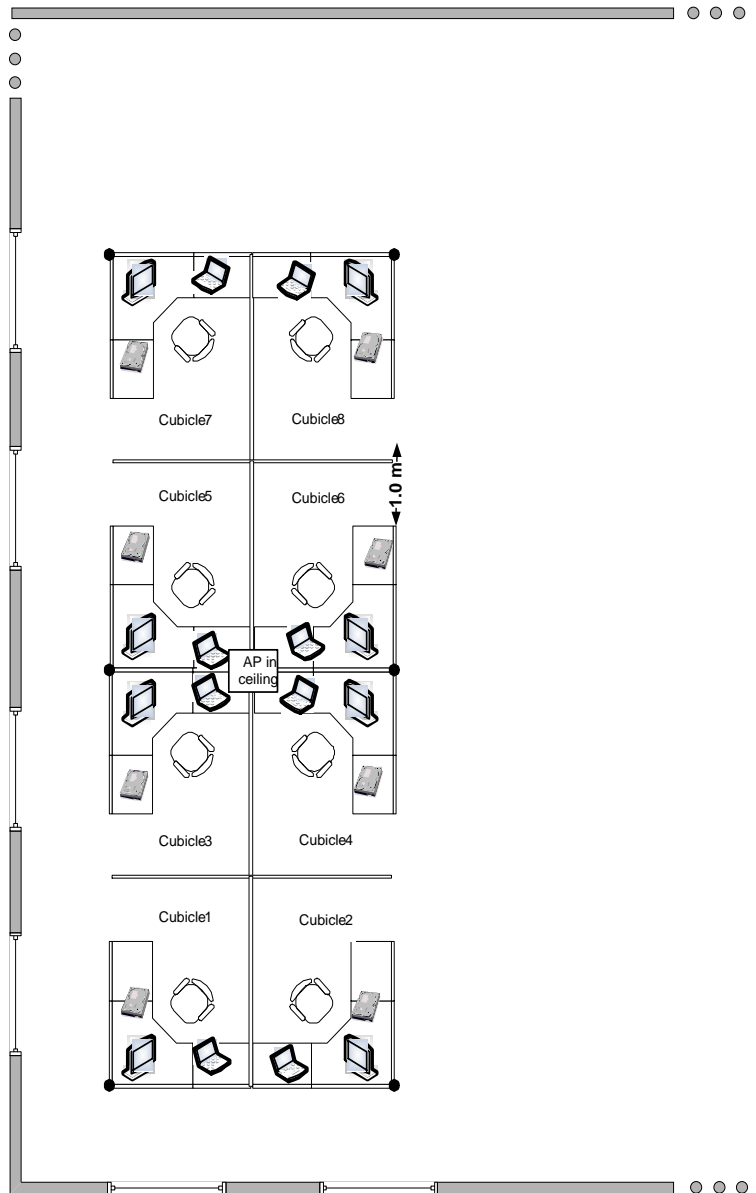
4 Data rates

Examples of data rates:

1) IEEE and WGA: Table 1 and Table 2 list the rates for the IEEE and WGA specifications.

TABLE 1

Rates for single carrier operation

MCS index	Modulation	N_{CBPS}	Repetition	Code rate	Data rate (Mbit/s)
0	π/2-DBPSK			1/2	27.5
1	π/2-BPSK	1	2	1/2	385
2	π/2-BPSK	1	1	1/2	770
3	π/2-BPSK	1	1	5/8	962.5
4	π/2-BPSK	1	1	3/4	1 155
5	π/2-BPSK	1	1	13/16	1 251.25
6	π/2-QPSK	2	1	1/2	1 540
7	π/2-QPSK	2	1	5/8	1 925
8	π/2-QPSK	2	1	3/4	2 310
9	π/2-QPSK	2	1	13/16	2 502.5
10	π/2-16QAM	4	1	1/2	3 080
11	π/2-16QAM	4	1	5/8	3 850
12	π/2-16QAM	4	1	3/4	4 620
25	π/2-BPSK	1	1	13/28	626
26	π/2-BPSK	1	1	13/21	834
27	π/2-BPSK	1	1	52/63	1112
28	π/2-QPSK	2	1	13/28	1251
29	π/2-QPSK	2	1	13/21	1668
30	π/2-QPSK	2	1	52/63	2224
31	π/2-QPSK	2	1	13/14	2503

N_{CBPS}: Number of coded bits per symbol.

TABLE 2

Rates for OFDM operation

MCS index	Modulation	Code rate	N_{BPSC}	N_{CBPS}	N_{DBPS}	Data rate (Mbit/s)
13	SQPSK	1/2	1	336	168	693.00
14	SQPSK	5/8	1	336	210	866.25
15	QPSK	1/2	2	672	336	1 386.00
16	QPSK	5/8	2	672	420	1 732.50
17	QPSK	3/4	2	672	504	2 079.00
18	16-QAM	1/2	4	1 344	672	2 772.00
19	16-QAM	5/8	4	1 344	840	3 465.00
20	16-QAM	3/4	4	1 344	1 008	4 158.00
21	16-QAM	13/16	4	1 344	1 092	4 504.50
22	64-QAM	5/8	6	2 016	1 260	5 197.50
23	64-QAM	3/4	6	2 016	1 512	6 237.00
24	64-QAM	13/16	6	2 016	1 638	6 756.75

2)   Tables 3 and 4 list the rates for the ISO/IEC 13156 specifications.

TABLE 3

Type A data rates

Mode	Base data rate (Gbit/s)				Modulation	Constellation	Encoding	CC Code Rate	TDSF (*NTDS*)	Tail bits
	no channel bonding	2 bonded channels	3 bonded channels	4 bonded channels						
A0	0.397	0.794	1.191	1.588	SCBT	BPSK	RS & CC	1/2	2	4
A1	0.794	1.588	2.381	3.175	SCBT	BPSK	RS & CC	1/2	1	4
A2	1.588	3.175	4.763	6.350	SCBT	BPSK	RS	1	1	0
A3	1.588	3.175	4.763	6.350	SCBT	QPSK	RS & CC	1/2	1	4
A4	2.722	5.443	8.165	10.886	SCBT	QPSK	RS & CC	6/7	1	6
A5	3.175	6.350	9.526	12.701	SCBT	QPSK	RS	1	1	0
A6	4.234	8.467	12.701	16.934	SCBT	NS-8QAM	RS & TCM	5/6	1	8
A7	4.763	9.526	14.288	19.051	SCBT	NS-8QAM	RS	1	1	0
A8	4.763	9.526	14.288	19.051	SCBT	TCM-16QAM	RS & TCM	2/3	1	6
A9	6.350	12.701	19.051	25.402	SCBT	16QAM	RS	1	1	0
A10	1.588	3.175	4.763	6.350	SCBT	QPSK	RS & UEP-CC	R_{MSB}: 1/2	1	4
A11	4.234	8.467	12.701	16.934	SCBT	16QAM	RS & UEP-CC	R_{MSB}: 4/7 R_{LSB}: 4/5	1	4
A12	2.117	4.234	6.350	8.467	SCBT	UEP-QPSK	RS & CC	2/3	1	4

TABLE 3 (*end*)

Mode	Base data rate (Gbit/s)				Modulation	Constellation	Encoding	CC Code Rate	TDSF (*NTDS*)	Tail bits
	no channel bonding	2 bonded channels	3 bonded channels	4 bonded channels						
A13	4.234	8.467	12.701	16.934	SCBT	UEP-16QAM	RS & CC	2/3	1	4
A14	1.008	N/A	N/A	N/A	OFDM	QPSK	RS & CC	1/3	1	6
A15	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & CC	2/3	1	6
A16	4.032	N/A	N/A	N/A	OFDM	16QAM	RS & CC	2/3	1	6
A17	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & UEP-CC	R_{MSB}: 4/7 R_{LSB}: 4/5	1	6
A18	4.032	N/A	N/A	N/A	OFDM	16QAM	RS & UEP-CC	R_{MSB}: 4/7 R_{LSB}: 4/5	1	6
A19	2.016	N/A	N/A	N/A	OFDM	UEP-QPSK	RS & CC	2/3	1	6
A20	4.032	N/A	N/A	N/A	OFDM	UEP-16QAM	RS & CC	2/3	1	6
A21	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & CC	R_{MSB}: 2/3	1	6

TABLE 4

Type B data rates

Mode	Base data rate (Gbit/s)				Modulation	Constellation	Encoding	TDSF (NTDS)
	no channel bonding	2 bonded channels	3 bonded channels	4 bonded channels				
B0	0.794	1.588	2.381	3.175	SC	DBPSK	RS & Diff	2
B1	1.588	3.175	4.763	6.350	SC	DBPSK	RS & Diff	1
B2	3.175	6.350	9.526	12.701	SC	DQPSK	RS & Diff	1
B3	3.175	6.350	9.526	12.701	SC	UEP-QPSK	RS	1

5 Technical characteristics and specifications

5.1 Modulation and data rates

To support the wide variety of usages envisioned for MGWS in both line-of-sight and non-line-of-sight channels, while providing a low cost and low power solution, the system should be scalable and support both single carrier (SC) and OFDM modulations.

SC modulations include BPSK, QPSK and 16-QAM, offering data rates of around 4 Gbit/s. OFDM modulations include BPSK, QPSK, 16-QAM and 64-QAM, offering data rates up to 7 Gbit/s.

5.2 Channel access

The basic access scheme should be Time Division Multiple Access (TDMA), which is necessary to deal with the challenges of operation in 60 GHz, the directional nature of communication, and applications such as wireless display. Contention-based access, such as provided by in WiFi, should also be supported for usages including web browsing and file transfer.

5.3 Beamforming

Beamforming is the fundamental technology in MGWS that is needed to compensate for the additional 20 dB free space propagation loss in the 60 GHz band as compared to the 2.4/5 GHz bands. Beamforming utilizes multiple antenna elements to form a beam toward a certain direction with increased signal strength. This beamforming gain is achieved by transmitting phase shifted signals from multiple antenna elements. The signals are phase shifted so that the signals are added up coherently at the target location. The peak beamforming gain (G_b) increases as the number of antenna (N_a) increases (i.e. G_b [dB] $= 10\log_{10}Na$). For example, 16 elements antenna array can provide approximately 12 dB of peak beamforming gain. If used at both the transmitter and the receiver, the additional 20 dB loss can be easily compensated.

Compared to 2.4 GHz and 5 GHz bands, beamforming is well suited for MGWS in 60 GHz band since many antenna elements can be packed in a very small area. For example, a square antenna array with 16 antenna elements (4×4 configuration) can be packed in 1 cm^2 when adjacent antenna elements are separated by half wavelength. This is a very critical aspect when considering small form factor MGWS devices.

Figure 4 illustrates how beamforming can be used within a home living room environment, where devices can communicate either though line-of-sight or non-line-of-sight links via reflections.

FIGURE 4

Example of multiple beamforming links in a home living room

5.4 Spatial reuse

Although communicating over 60 GHz channels is challenging and requires a directional antenna with very high gain, this brings a new opportunity for spatial reuse amongst adjacent links (e.g. in the enterprise cubicle deployment). This is because as the gain of antenna increases, the beamwidth of the antenna decreases and thus more interference to and from neighbouring links can be mitigated. Spatial reuse gain can be significant and needs to be exploited by MGWS.

Many simultaneous links, however, may also lead to increased interference if not designed carefully. Hence, means are needed to improve the performance of overlapping MGWS networks.

6 Overview of IEEE Std 802.11ad-2012[1]

The IEEE Std 802.11ad-2012 provides a suite of features that can meet the demands of the new usages and applications envisioned for MGWS, including:

–   Support to data transmission rates up to 7 Gbit/s.

–   Supplements and extends the 802.11 medium access control (MAC), supporting both scheduled access and contention-based access.

–   Enables both the low power and the high performance devices, guaranteeing interoperability and communication at gigabit rates.

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[1] IEEE Standard for Information Technology – Telecommunications and Information Exchange Between Systems – Local and Metropolitan Area Networks – Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications – Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band, December 2012.

–   Supports beamforming, enabling robust communication at distances beyond 10 metres.

–   Supports advanced security using the Galois/Counter Mode (GCM) of the AES encryption algorithm and advanced power management.

–   Supports fast session transfer among 2.4 GHz, 5 GHz and 60 GHz, which is known as multi-band operation.

The next subsections provide more in-depth detail of the physical (PHY) and MAC layers of the IEEE Std 802.11ad-2012.

6.1   The physical layer

6.1.1   Channelization

The channel bandwidth is 2 160 MHz. Four centre frequencies are defined at 58.32, 60.48, 62.64, and 64.8 GHz.

6.1.2   Modulation and Coding Schemes (MCSs)

In the IEEE Std 802.11ad-2012, three different PHY modes are defined: 1) Single Carrier (SC) MCS, 2) OFDM MCS, and 3) Control MCS. A common FEC (forward error correction) is used for all MCSs. Four Low-Density Parity-Check (LDPC) codes are defined, each with a different rate but with a common code rate of 672 bits.

The modulation schemes, code rates, and PHY rates of the three PHY modes are summarized in Table 5.

TABLE 5

SC, OFDM, control MCSs

	Modulation	**Code rate**	**PHY rate**
SC MCS	$\pi/2$-BPSK $\pi/2$-QPSK $\pi/2$-16 QAM	1/2, 5/8, 3/4, 13/16	385 Mbit/s ~ 4 620 Mbit/s
OFDM MCS	Spread QPSK QPSK 16-QAM 64-QAM	1/2, 5/8, 3/4, 13/16	693 Mbit/s ~ 6 756.75 Mbit/s
Control MCS	$\pi/2$-DBPSK	1/2 (spreading factor of 32)	27.5 Mbit/s

Control MCS is used before setting up a beamformed link between a transmitter and a receiver. The main usages of Control MCS are beacon transmissions and beamforming training. Control MCS is designed to support 15 dB lower SNR sensitivity than the sensitivity point of 1 Gbit/s data rate.

SC MCS symbol (chip) rate is 1 760 Msym/s. OFDM MCS has a FFT size of 512, total 355 subcarriers per an OFDM symbol: 336 data subcarriers, 16 pilot subcarriers, and 3 DC subcarriers.

The OFDM sample rate is 2 640 MHz and the subcarrier frequency spacing is 5.15625 MHz (= 2 640 MHz/512). IDFT/DFT period is 0.194 us and the guard interval duration is 48.4 ns. The total occupied bandwidth is 1 830.5 MHz.
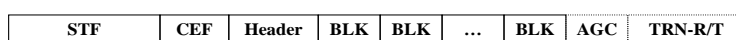
6.1.3   Common preamble

Each PPDU starts with a preamble. The preamble is used for packet detection, AGC, timing/frequency synchronization, channel estimation, and signalling MCSs used for the PSDUs following the preamble. In order to simplify implementation and to have better coexistence, SC and OFDM MCSs share a common preamble. The preamble is composed of two parts: 1) the Short Training field (STF) and 2) Channel Estimation field (CEF). Control MCS uses a longer preamble but a similar design to SC and OFDM MCSs to operate at lower SNR.
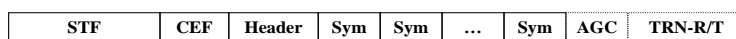
6.1.4   Frame formats

SC MCS frame format is shown in Fig. 5(a). The SC MCS frame starts with a preamble (STF and CEF) and a PLCP (physical layer control packet) header and the data blocks (BLKs) follow the preamble. For the data blocks, the payload bits are broken into 336, 420, 504, or 545 data bits and encoded into blocks of 672 bits. There are optional AGC and TRN-R/T subfields used for beamforming. Figures 5(b) and 5(c) illustrate the frame formats of OFDM MCSs and Control MCS.
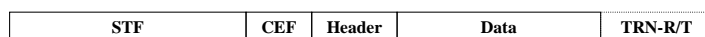
FIGURE 5

SC, OFDM, and control MCSs frame formats

STF	CEF	Header	BLK	BLK	...	BLK	AGC	TRN-R/T

(a) SC MCS frame format

STF	CEF	Header	Sym	Sym	...	Sym	AGC	TRN-R/T

(b) OFDM MCS frame format (Sym = OFDM symbol)

STF	CEF	Header	Data	TRN-R/T

(c) Control MCS frame format

6.2   The MAC layer

6.2.1   Network architectures

The base 802.11 defines two types of network architecture known as Infrastructure Basic Service Set (BSS) and Independent BSS (IBSS). The infrastructure BSS is characterized by having a dedicated station, the Access Point (AP) which provides access to the backhaul network to wireless stations (STAs) associated with the AP. The IBSS is designed to support peer-to-peer communication without the need for an AP.

Given the characteristics of important usage scenarios (e.g. absence of AP, all stations in the network can be battery powered, etc.) and the challenges of directional communication in 60 GHz, the infrastructure BSS and the IBSS are not well suited for some usage scenarios in 60 GHz.

Therefore, a new network architecture named as the Personal BSS (PBSS) is defined in 802.1ad specification. Similar to the IBSS, the PBSS is a type of IEEE 802.11 ad hoc network in which STAs are able to communicate directly with each other not relying on a special device like an AP. As opposed to the IBSS, in the PBSS one STA is required to assume the role of the PBSS central point (PCP). The PCP provides the basic timing for the PBSS as well as allocation of service periods and contention-based periods.

NOTE – Even though 802.11ad introduces the concept of the PBSS, the infrastructure BSS and the IBSS are still supported. This allows, for example, that a MGWS wireless LAN be deployed in the 60 GHz band using the well-known infrastructure BSS architecture with a 60 GHz capable AP.

6.2.2 Medium access

Medium is divided in beacon intervals (BI), which have the structure depicted in Fig. 6. To support the wide variety of applications and usages envisioned, the MAC supports both random access and scheduled TDMA access. To improve the robustness of TDMA in overlapping network scenarios, TDMA is improved to include a protection mechanism similar to the RTS/CTS frame exchange found in 802.11 CSMA/CA.

FIGURE 6

Beacon interval structure
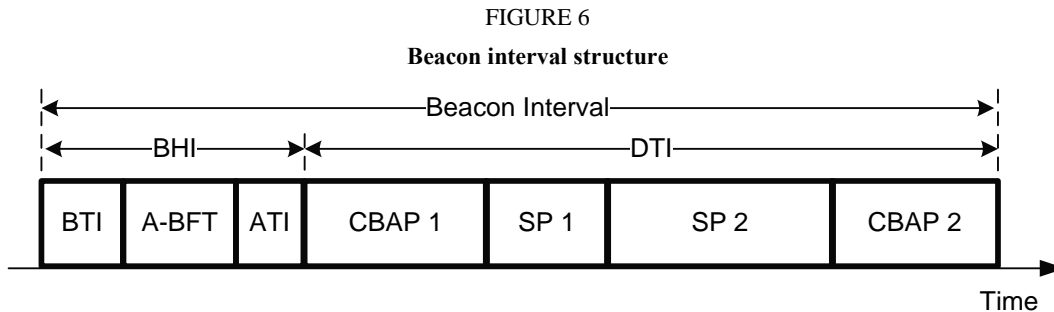
The Beacon Transmission Interval (BTI) is a time period during which the PCP/AP transmits one or more beacon frames in different directions. In addition to network management information carried in the beacon, the beacon frame is also used to bootstrap the beamforming procedure between the AP/PCP and a receiving station. A station willing to join the network scans for a beacon, continues the beamforming process with the AP/PCP in the association beamforming training time (A-BFT), and finally associates with the PCP/AP during the Announcement Transmission Interval (ATI) or CBAP.

The A-BFT is a time period to perform initial beamforming training between the station and the AP/PCP. The A-BFT follows the BT to provide continuity to the beamforming process that was bootstrapped through the beacon transmission in the preceding BT. The structure of the A-BFT is slotted, which allows for multiple stations to do beamforming with the PCP/AP concurrently in the same A-BFT.

The AT is a time period to perform management request-response frame exchanges between the PCP/AP and a station. The PCP/AP uses this time to exchange frames with stations, distribute information about Contention-Based Access Period (CBAP) and service period (SP) allocations in the Data Transfer Interval (DTI), to name a few.

The DTT is divided into SPs and CBPs that provide transmission opportunities for stations that are part of the network. Any frame exchange can take place during a CBAP and a SP, including application data frame transmission. Access during the CBAP is based on a modified 802.11 EDCA operation fine-tuned for directional communication, while access during SPs is scheduled and assigned to specific stations.

One of the major problems with SP type of TDMA scheduling is robustness when overlapping networks are considered. Therefore, to improve the robustness of transmissions during SPs, the 802.11ad standard defines what is called as protected period used during SPs. Basically, a station that owns a SP can protect the SP by transmitting an RTS frame at the start of the SP, which serves to reserve the medium. If a CTS frame is received from the destination of the SP in the response to a transmitted RTS, the SP is considered protected.

6.2.3 Multiband operation

One of the major innovations in the 802.11ad specification is the introduction of a MAC layer multiband mechanism that supports fast transfer of a link from one band to another band. This is also known as fast session transfer (FST).

FST enables transition of communication of stations from any band/channel to any other band/channel in which 802.11 is allowed to operate. However, in order to provide a seamless transfer between bands, the IEEE 802.11ad draft specification introduces what is known as transparent FST. In transparent FST, a station uses the same MAC address in both bands/channels involved in the FST. By doing that, there is no impact to the binding that exists between the upper layer (e.g. IP) and the MAC, making the FST completely transparent. In addition, FST supports both simultaneous (radios operating at the same time) and non-simultaneous operation. To further speed-up the FST switching time, several other improvements such as security key establishment prior to FST, multi-band resource allocation, and Block Ack operation over multiple bands are defined in the IEEE 802.11ad draft specification. FST enables a more powerful user experience and improved application performance.

6.2.4 Beamforming

Beamforming (BF) is the process that is used by a pair of stations to achieve the necessary link budget for subsequent communication. BF training is a bidirectional sequence of BF training frame transmissions that provide the necessary signalling to allow each STA to determine appropriate antenna system settings for both transmission and reception.

Beamforming consists of two phases: sector level sweep (SLS) and an optional beam refinement process (BRP). During sector level sweep devices establish initial (coarse-grain) direction of communication sufficient to communicate at a low PHY rate. The following BRP may be used to fine tune antenna settings to improve quality of directional communication, and hence obtain a multi-gigabit link.

FIGURE 7

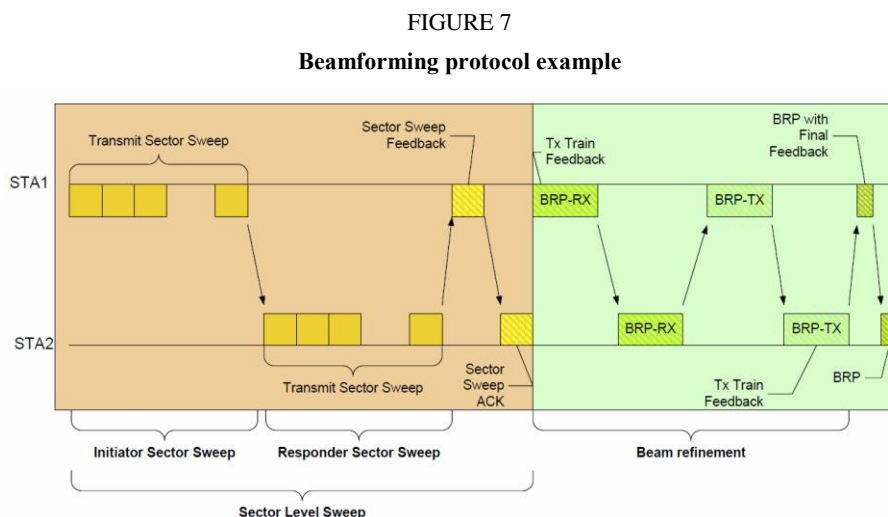**Beamforming protocol example**

Figure 7 illustrates an example of the beamforming procedure. In this example, STA1 initiates the beamforming with STA2 by performing a SLS. In the 802.11ad specification, the station that initiates beamforming is known as the Initiator, while the receiving station is known as the responder. At the end of the SLS, both STA1 and STA2 know the best transmit sector for communication with each other. This is used in the following BRP phase, where STA1 and STA2 train their receiving antennas and fine-tune their beams to achieve the desired link budget for the forthcoming data communication.

6.3   Common characteristics

6.3.1   Transmit and receive operating temperature range

Transmit and receive operating temperature range follows the IEEE Std 802.11-2012.

6.3.2   Centre frequency tolerance

The transmitter centre frequency tolerance is ±20 ppm maximum for the 60 GHz band.

6.3.3   Symbol clock tolerance

The symbol clock frequency tolerance is ±20 ppm maximum for the 60 GHz band. The transmit centre frequency and the symbol clock frequency are derived from the same reference oscillator.

6.3.4   Transmit centre frequency leakage

The transmitter centre frequency leakage does not exceed −23 dB relative to the overall transmitted power, or, equivalently, 2.5 dB relative to the average energy of the rest of the subcarriers (in OFDM).

6.3.5   Transmit ramp up and ramp down

The transmit power-on ramp is defined as the time it takes for a transmitter to rise from less than 10% to greater than 90% of the average power to be transmitted in the frame.

The transmit power-on ramp is less than 10 ns.

The transmit power-down ramp is defined as the time it takes the transmitter to fall from greater than 90% to less than 10% of the maximum power to be transmitted in the frame.

The transmit power-down ramp is less than 10 ns.

6.3.6   Maximum input level

The receiver maximum input level is the maximum power level of the incoming signal, in dBm, present at the input of the receiver for which the error rate criterion (defined at the RX sensitivity section) is met. A compliant receiver has a receiver maximum input level of at least −33 dBm for each of the modulation formats that the receiver supports.

6.3.7   Rates

Table 6 and Table 7 describe the rates provided by the IEEE Std 802.11ad-2012.

TABLE 6

Rates for single carrier operation

MCS index	Modulation	N_{CBPS}	Repetition	Code rate	Data rate (Mbit/s)
0	π/2-DBPSK			1/2	27.5
1	π/2-BPSK	1	2	1/2	385
2	π/2-BPSK	1	1	1/2	770
3	π/2-BPSK	1	1	5/8	962.5
4	π/2-BPSK	1	1	3/4	1 155
5	π/2-BPSK	1	1	13/16	1 251.25
6	π/2-QPSK	2	1	1/2	1 540
7	π/2-QPSK	2	1	5/8	1 925
8	π/2-QPSK	2	1	3/4	2 310
9	π/2-QPSK	2	1	13/16	2 502.5
10	π/2-16QAM	4	1	1/2	3 080
11	π/2-16QAM	4	1	5/8	3 850
12	π/2-16QAM	4	1	3/4	4 620
25	π/2-BPSK	1	1	13/28	626
26	π/2-BPSK	1	1	13/21	834
27	π/2-BPSK	2	1	52/63	1 112
28	π/2-QPSK	2	1	13/28	1 251
29	π/2-QPSK	2	1	13/21	1 668
30	π/2-QPSK	2	1	52/63	2 224
31	π/2-QPSK	2	1	13/14	2 503

TABLE 7

Rates for OFDM operation

MCS index	Modulation	Code rate	N_{BPSC}	N_{CBPS}	N_{DBPS}	Data rate (Mbit/s)
13	SQPSK	1/2	1	336	168	693.00
14	SQPSK	5/8	1	336	210	866.25
15	QPSK	1/2	2	672	336	1 386.00
16	QPSK	5/8	2	672	420	1 732.50
17	QPSK	3/4	2	672	504	2 079.00
18	16-QAM	1/2	4	1 344	672	2 772.00
19	16-QAM	5/8	4	1 344	840	3 465.00
20	16-QAM	3/4	4	1 344	1 008	4 158.00
21	16-QAM	13/16	4	1 344	1 092	4 504.50
22	64-QAM	5/8	6	2 016	1 260	5 197.50
23	64-QAM	3/4	6	2 016	1 512	6 237.00
24	64-QAM	13/16	6	2 016	1 638	6 756.75

7   Overview of IEEE Std 802.15.3c-2009[2]

IEEE Std 802.15.3c-2009 provides a suite of features that can meet the demands of the usages and applications envisioned for MGWS, including:

–   Support of data transmission rates up to 5.8 Gbit/s.

–   Supplements and extends the 802.15.3 medium access control (MAC), supporting both scheduled access, contention-based access, and frame aggregation for high throughput and quality of service.

–   Enables both low power and high performance devices, guaranteeing interoperability and communication at gigabit rates.

–   Supports beam forming, enabling robust communication at distances of at least 10 metres.

The next subsections provide more in-depth detail of the physical (PHY) and MAC layers of IEEE 802.15.3c-2009. IEEE Std 802.15.3-2003, IEEE Std 802.15.3b-2005, and IEEE Std 802.15.3c-2009 are available at: http://standards.ieee.org/getieee802/.

7.1   The physical layer

7.1.1   Channelization

The channel bandwidth is 2 160 MHz. Four centre frequencies are defined at 58.32, 60.48, 62.64, and 64.8 GHz.

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[2] IEEE Standard for Information Technology – Telecommunications and Information Exchange Between Systems – Local and Metropolitan Area Networks – Specific Requirements – Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) – Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension.

7.1.2 Modulation and Coding Schemes (MCSs)

In IEEE Std 802.15.3c-2009, three different PHY modes are defined: 1) Single Carrier (SC) MCS and High Speed Interface (HSI) OFDM MCS, and Audio /Video (AV) OFDM.

A Common Mode Signalling (CMS) MCS is defined to allow coexistence and interoperability between the SC and OFDM PHYs. CMS is a low data rate SC PHY mode specified to enable interoperability among different PHY modes. The CMS is used for transmission of the beacon frame and, if supported, the sync frame. The CMS is also used for transmission of command frame and training sequences used in the beam forming procedure.

The modulation schemes, code rates, and rates of the PHY modes are summarized in Table 8.

TABLE 8

SC, OFDM, CMS MCSs

	Modulation	**Code rate**	**PHY rate**
SC MCS	π/2 BPSK π/2 QPSK π/2 8-PSK π/2 16-QAM	1/2, 504/672, 588/672, 1 344/1 440, 239, 255	25.8 Mbit/s ~5 280 Mbit/s
OFDM MCS	QPSK 16-QAM 64-QAM	1/3, 1/2, 4/7, 5/8, 2/3, 3/4, 4/5, 7/8,	2.5 Mbit/s ~ 5 775 Mbit/s
CMS MCS	π/2 BPSK	239/255	25.8 Mbit/s

SC MCS symbol (chip) rate is 1 760 Msym/s. OFDM MCS has a FFT size of 512, total 355 subcarriers per an OFDM symbol: 336 data subcarriers, 16 pilot subcarriers, and 3 DC subcarriers.

The OFDM sample rate is 2 640 MHz and the subcarrier frequency spacing is 5.15625 MHz (= 2 640 MHz/512). IDFT/DFT period is 0.194 us and the guard interval duration is 24.24 ns. The nominal used bandwidth is 1 815 MHz.

7.2 The MAC Layer

### 7.2.1 Network architectures

The base 802.15.3 defines the piconet as a wireless ad hoc data communication system that allows a number of independent data devices (DEVs) to communicate with each other. One DEV is required to assume the role of the piconet controller (PNC) to provide the basic timing for the piconet with a beacon. The PNC manages the quality of service (QoS) requirements, power save modes and access control to the piconet. All DEVs can communicate directly with other DEVs in the piconet using one or more of the MSCs defined by the standard that each DEV commonly supports. A PNC may allow another PNC to join the piconet and form a subsidiary piconet known as a child piconet. This allows multiple piconets to share the same channel.

7.2.2   Medium access

Timing in the 802.15.3c piconet is based on the superframe as shown in Fig. 8. The superframe is composed of three parts:

a)   The beacon, which is used to set the timing allocations and communicate management information for the piconet.

b)   The contention access period (CAP), which is used to communicate commands and/or asynchronous data if it is present in the superframe.

c)   The channel time allocation period (CTAP), which is composed of channel time allocations (CTAs), including management CTAs (MCTAs). CTAs are used for commands, isochronous data streams, and asynchronous data connections.

FIGURE 8

802.15.3 superframe
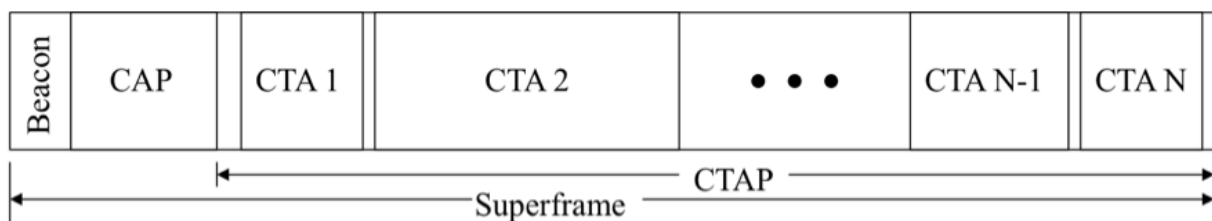
7.2.3   Beamforming

As an enabling technology of multi-gigabit transmission, beam forming (BF) is used and the procedures to select the best pair of antenna beam patterns for DEVs and a PNC are defined to support a multitude of antenna configurations such as single antenna element, sectored antennas, switched antennas, and one and two-dimensional beam forming antenna arrays. The beam forming specified by the IEEE Std 802.15.3c 2009 employs discrete phase shifters to simplify the beam formers.

The beam-forming procedure is composed of a two-level of training phase and an optional tracking phase. The two level training phase consists of a sector level and beam level training and is used to find the best pair of beam patterns between two DEVs with a given beam resolution. The sector level is used to limit the region of space that is of interest and to find the best pair of sectors. These sectors are then sliced into beams in preparation for beam level training. Beam level training is used to select the optimal pair of transmit and receive beams. Tracking is used to achieve higher resolution and to track the best set of beam patterns between the two DEVs (or a PNC and a DEV), which may vary over time due to channel characteristics changes.

Two types of beam forming training signal transmission ways are further specified. They are an on-demand beam forming and pro-active beam forming. On-demand beam forming may be used between DEVs or between the PNC and a DEV and shall take place in the CTA allocated to the DEV for the purpose of beam forming. Pro-active beam forming may be used when the PNC is the source of data to one or multiple DEVs to achieve multiple DEVs to train their own receiver antennas for optimal reception from the PNC with lower overhead training signal transmission in the beacon.

7.2.4   Rates

Tables 9 and 10 describe the rates provided by IEEE Std 802.15.3c-2009 for the Single Carrier and HSI OFDM modes. Tables 11 and 12 describe the rates provided by the Audio Visual (AV) OFDM mode. The AV OFDM LRP rates are used for omnidirectional discovery and network control.

TABLE 9

Rates for single carrier operation

MCS Index	Modulation	FEC type	Spreading factor	Data rate (Mbit/s)
0 (CMS)	π/2 BPSK/(G)MSK	RS(255,239)	64	25.8
1	π/2 BPSK/(G)MSK	RS(255,239)	4	412
2	π/2 BPSK/(G)MSK	RS(255,239)	2	825
3	π/2 BPSK/(G)MSK	RS(255,239)	1	1 650
4	π/2 BPSK/(G)MSK	LDPC(672,504)	1	1 320
5	π/2 BPSK/(G)MSK	LDPC(672,336)	2	440
6	π/2 BPSK/(G)MSK	LDPC(672,336)	1	880
7	π/2 QPSK	LDPC(672,336)	1	1 760
8	π/2 QPSK	LDPC(672,504)	1	2 640
9	π/2 QPSK	LDPC(672,588)	1	3 080
10	π/2 QPSK	LDPC(1440,1344)	1	3 290
11	π/2 QPSK	RS(255,239)	1	3 300
12	π/2 8-PSK	LDPC(672,504)	1	3 960
13	π/216-QAM	LDPC(672,504)	1	5 280

TABLE 10

Rates for HSI OFDM operation

MCS index	Modulation	Code mode	Spreading factor	FERC Rate (msb 8b) – (lsb 8b)	Data rate (Mbit/s)
0	QPSK	EEP	48	1/2	32.1
1	QPSK	EEP	1	1/2	1 540
2	QPSK	EEP	1	3/4	2 310
3	QPSK	EEP	1	7/8	2 695
4	16-QAM	EEP	1	1/2	3 080
5	16-QAM	EEP	1	3/4	4 620
6	16-QAM	EEP	1	7/8	5 390
7	64-QAM	EEP	1	5/8	5 775
8	QPSK	UEP	1	1/2-3/4	1 925
9	QPSK	UEP	1	3/4-7/8	2 503
10	16-QAM	UEP	1	1/2-3/4	3 850
11	16-QAM	UEP	1	3/4-7/8	5 005

TABLE 11

Rates for AV OFDM operation

MCS index	Modulation	Code mode	Coding rate (msb 8b) – (lsb 8b)	Data rate (Mbit/s)
0	QPSK	EEP	1/3	952
1	QPSK	EEP	2/3	1 904
2	16-QAM	EEP	2/3	3 807
3	QPSK	UEP	4/7-4/5	1 904
4	16-QAM	UEP	4/7-4/5	3 807
5	QPSK	MSB only retransmission	1/3	952
6	QPSK		2/3	1 904

TABLE 12

Rates for AV OFDM LRP operation

MCS index	Modulation	FEC	Data rate (Mbit/s)	Repetition
0	BPSK	1/3	2.5	8×
1		1/2	3.8	8×
2		2/3	5.1	8×
3		2/3	10.2	4×

8   Overview of the WGA specification[3]

WGA specification includes key features to maximize performance, minimize implementation complexity, enable compatibility with existing WiFi and provide advanced security. Key features include:

−   Support for data transmission rates up to 7 Gbit/s; all devices based on the WGA specification will be capable of gigabit data transfer rates.

−   Designed to support low-power handheld devices such as cell phones, as well as high-performance devices such as PCs; includes advanced power management.

−   Harmonized with IEEE 802.11; provides native WiFi support and enables devices to transparently switch between 802.11 networks operating in any frequency band including 2.4 GHz, 5 GHz and 60 GHz.

−   Support for beamforming, maximizing signal strength and enabling robust communication at distances beyond 10 metres.

−   Advanced security using the Galois/Counter Mode of the AES encryption algorithm.

−   Support for high-performance wireless implementations of HDMI, DisplayPort, USB, SDIO and PCIe through protocol adaptation layers (PALs).

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[3] Wireless Gigabit Alliance (WGA): WiGig MAC and PHY Specification, v1.2, March 2012.

WGA's Physical and MAC layer specifications are harmonized with those of IEEE 802.11ad version Draft 2.0. Please refer to sections 8.1, 8.2 and 8.3 below for PHY and MAC and PAL overview, respectively.

8.1 Physical layer

8.1.1 Channelization

The channel bandwidth is 2 160 MHz. Four centre frequencies are defined at 58.32, 60.48, 62.64, and 64.8 GHz.

8.1.2 Modulation and Coding Schemes (MCSs)

In the WGA specification, three different PHY modes are defined:

−   Single Carrier (SC) MCS

−   OFDM MCS

−   Control MCS.

All these PHY modes share a common preamble. A common FEC (forward error correction) is used for all MCSs. Four Low-Density Parity-Check (LDPC) codes are defined, each with a different rate but with a common code length of 672 bits.

The modulation schemes, code rates, and PHY rates of the three PHY modes are summarized in Table 13.

TABLE 13

SC, OFDM, control MCSs

	Modulation	**Code rate**	**PHY rate**
SC MCS	π/2-BPSK π/2-QPSK π/2-16 QAM	1/2, 5/8, 3/4, 13/16	385 Mbit/s ~ 4 620 Mbit/s
OFDM MCS	Spread QPSK QPSK 16-QAM 64-QAM	1/2, 5/8, 3/4, 13/16	693 Mbit/s ~ 6 756.75 Mbit/s
Control MCS	π/2-DBPSK	1/2 (spreading factor of 32)	27.5 Mbit/s

Control MCS is used before setting up a beamformed link between a transmitter and a receiver. The main usages of control MCS are beacon transmissions and beamforming training. The control MCS is designed to support 15 dB lower SNR sensitivity than the sensitivity point of 1 Gbit/s data rate.

SC MCS symbol (chip) rate is 1 760 Msym/s. OFDM MCS has a FFT size of 512, total 355 subcarriers per an OFDM symbol: 336 data subcarriers, 16 pilot subcarriers, and 3 DC subcarriers.

The OFDM sample rate is 2 640 MHz and the subcarrier frequency spacing is 5.15625 MHz (= 2 640 MHz/512). IDFT/DFT period is 0.194 μs and the guard interval duration is 48.4 ns. The total occupied bandwidth is 1 830.5 MHz.
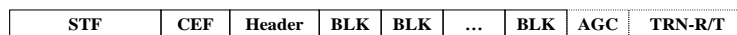
8.1.3 Common preamble

Each PPDU starts with a preamble. The preamble is used for packet detection, AGC, timing/frequency synchronization, channel estimation, and signalling MCSs used for the PSDUs following the preamble. In order to simplify implementation and to have better coexistence, SC and OFDM MCSs share a common preamble. The preamble is composed of two parts: 1) the Short Training field (STF) and 2) Channel Estimation field (CEF). Control MCS uses a longer preamble but a similar design to SC and OFDM MCSs to operate at lower SNR.

8.1.4 Frame formats

SC MCS frame format is shown in Fig. 9(a). The SC MCS frame starts with a preamble (STF and CEF) and a PLCP (physical layer convergence procedure) header and the data blocks (BLKs) follow the preamble. For the data blocks, the payload bits are broken into 336, 420, 504, or 545 data bits and encoded into blocks of 672 bits. There are optional AGC and TRN-R/T subfields used for beamforming. Figs. 9(b) and 9(c) illustrate the frame formats of OFDM MCSs and Control MCS.
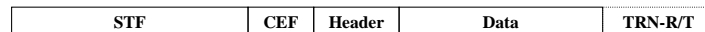
FIGURE 9

SC, OFDM, and control MCSS frame formats

| STF | CEF | Header | BLK | BLK | ... | BLK | AGC | TRN-R/T |

(a) SC MCS frame format

| STF | CEF | Header | Sym | Sym | ... | Sym | AGC | TRN-R/T |

(b) OFDM MCS frame format (Sym=OFDM symbol)

| STF | CEF | Header | Data | TRN-R/T |
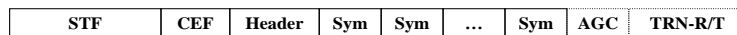
(c) Control MCS frame format

8.2 MAC layer

8.2.1 Network architectures

The WGA specification defines two types of network architecture known as Infrastructure Basic Service Set (BSS) and Independent BSS (IBSS). The infrastructure BSS is characterized by having a dedicated station, the Access Point (AP) which provides access to the backhaul network to wireless stations (STAs) associated with the AP. The IBSS is designed to support peer-to-peer communication without the need for an AP.

Given the characteristics of important usage scenarios (e.g. absence of AP, all stations in the network can be battery powered, etc.) and the challenges of directional communication in 60 GHz, the infrastructure BSS and the IBSS are not well suited for some usage scenarios in 60 GHz.

Therefore, a new network architecture named as the Personal BSS (PBSS) is defined in the WGA specification. Similar to the IBSS, the PBSS is a type of an ad hoc network in which STAs are able to communicate directly with each other not relying on a special device like an AP. As opposed to the IBSS, in the PBSS one STA is required to assume the role of the PBSS central point (PCP). The PCP provides the basic timing for the PBSS as well as allocation of service periods and contention-based periods.

NOTE – Even though WGA specification introduces the concept of the PBSS, the infrastructure BSS and the IBSS are still supported. This allows, for example, that a MGWS wireless LAN be deployed in the 60 GHz band using the well-known infrastructure BSS architecture with a 60 GHz capable AP.

8.2.2 Medium access

Medium is divided in beacon intervals (BI), which have the structure depicted in Fig. 10. To support the wide variety of applications and usages envisioned, the MAC supports both random access and scheduled TDMA access. To improve the robustness of TDMA in overlapping network scenarios, TDMA is improved to include a protection mechanism similar to the RTS/CTS frame exchange found in 802.11 CSMA/CA.

FIGURE 10

Beacon interval structure
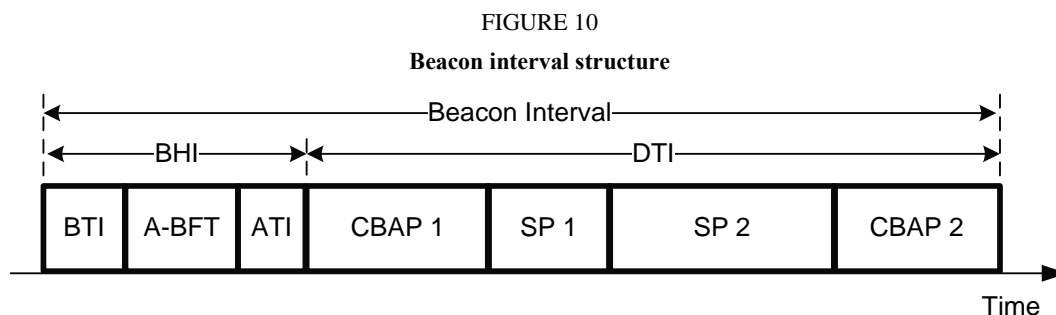
The beacon transmission interval (BTI) is a time period during which the PCP/AP transmits one or more beacon frames in different directions. In addition to network management information carried in the beacon, the beacon frame is also used to bootstrap the beamforming procedure between the AP/PCP and a receiving station. A station willing to join the network scans for a beacon and continues with the beamforming process with the AP/PCP in the association beamforming training time (A-BFT), and finally associates with the PCP/AP during the Announcement Transmission Interval (ATI) or CBAP.

The A-BFT is a time period to perform initial beamforming training between the station and the AP/PCP. The A-BFT follows the BTI to provide continuity to the beamforming process that was bootstrapped through the beacon transmission in the preceding BTI. The structure of the A-BFT is slotted, which allows for multiple stations to do beamforming with the PCP/AP concurrently in the same A-BFT.

The AT is a time period to perform management request-response frame exchanges between the PCP/AP and a station. The PCP/AP uses this time to exchange frames with stations, distribute information about contention-based access period (CBAP) and service period (SP) allocations in the Data Transfer Interval (DTI), to name a few.

The DTT is divided into SPs and CBAPs that provide transmission opportunities for stations that are part of the network. Any frame exchange can take place during a CBAP and a SP, including application data frame transmission. Access during the CBAP is based on 802.11 EDCA operation fine-tuned for directional communication, while access during SPs is scheduled and assigned to specific stations. One of the major problems with SP type of TDMA scheduling is robustness when overlapping networks are considered. Therefore, to improve the robustness of transmissions during SPs, the WGA specification defines what is called as protected period used during SPs. Basically, a station that owns a SP can protect the SP by transmitting an RTS frame at the start of the SP, which serves to reserve the medium. If a CTS frame is received from the destination of the SP in the response to a transmitted RTS, the SP is considered protected.

8.2.3 Multiband operation

One of the major innovations in the WGA specification is the introduction of a MAC layer multiband mechanism that supports fast transfer of a link from one band to another band. This is also known as fast session transfer (FST).

FST enables transition of communication of stations from any band/channel to any other band/channel in which WGA is allowed to operate. However, in order to provide a seamless transfer between bands, the WGA specification introduces what is known as transparent FST. In transparent FST, a station uses the same MAC address in both bands/channels involved in the FST. By doing that, there is no impact to the binding that exists between the upper layer (e.g. IP) and the MAC, allowing FST to be transparent from a data communication point of view. In addition, FST supports both simultaneous (radios operating at the same time) and non-simultaneous operation. To further speed-up the FST switching time, several other improvements such as security key establishment prior to FST, multi-band resource allocation, and Block Ack operation over multiple bands are defined in the WGA specification. FST enables a more powerful user experience and improved application performance.

8.2.4 Beamforming

Beamforming (BF) is the process that is used by a pair of stations to achieve the necessary link budget for subsequent communication. BF training is a bidirectional sequence of BF training frame transmissions that provide the necessary signalling to allow each STA to determine appropriate antenna system settings for both transmission and reception.

Beamforming consists of two phases: sector level sweep (SLS) and an optional beam refinement process (BRP). During sector level sweep devices establish initial (coarse-grain) direction of communication sufficient to communicate at a low PHY rate. The following BRP may be used to fine tune antenna settings to improve quality of directional communication, and hence obtain a multi-gigabit link.

FIGURE 11

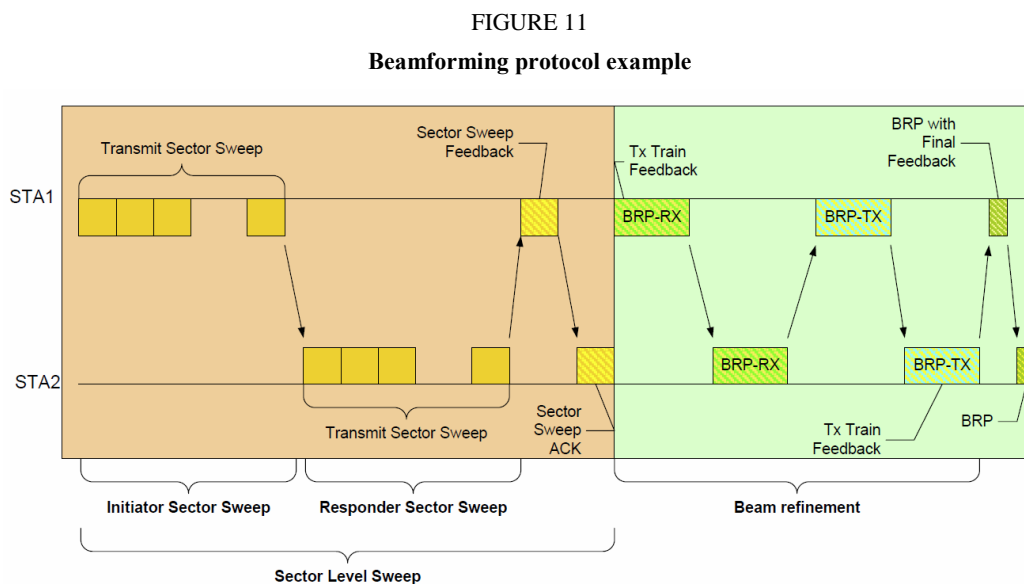**Beamforming protocol example**

Figure 11 illustrates an example of the beamforming procedure. In this example, STA1 initiates the beamforming with STA2 by performing a SLS. In the WGA specification, the station that initiates beamforming is known as the Initiator, while the receiving station is known as the responder. At the end of the SLS, both STA1 and STA2 know the best transmit sector for communication with each other. This is used in the following BRP phase, where STA1 and STA2 train their receiving antennas and fine-tune their beams to achieve the desired link budget for the forthcoming data communication.

Additional features of WGA specifications are provided below.

8.3 Protocol Adaptation Layers (PALs)

The WiGig Alliance is also defining wireless extensions that support specific data and display standards over 60 GHz. These extensions allow wireless implementations of these standard interfaces that run directly on the WGA MAC and PHY, as shown in Fig. 12. The initial extensions are Wireless Display Extension (WDE), which defines support for HDMI and DisplayPort, and input-output (I/O) extensions, which define support for USB, PCIe, and SDIO.

FIGURE 12

WGA Protocol wireless extensions
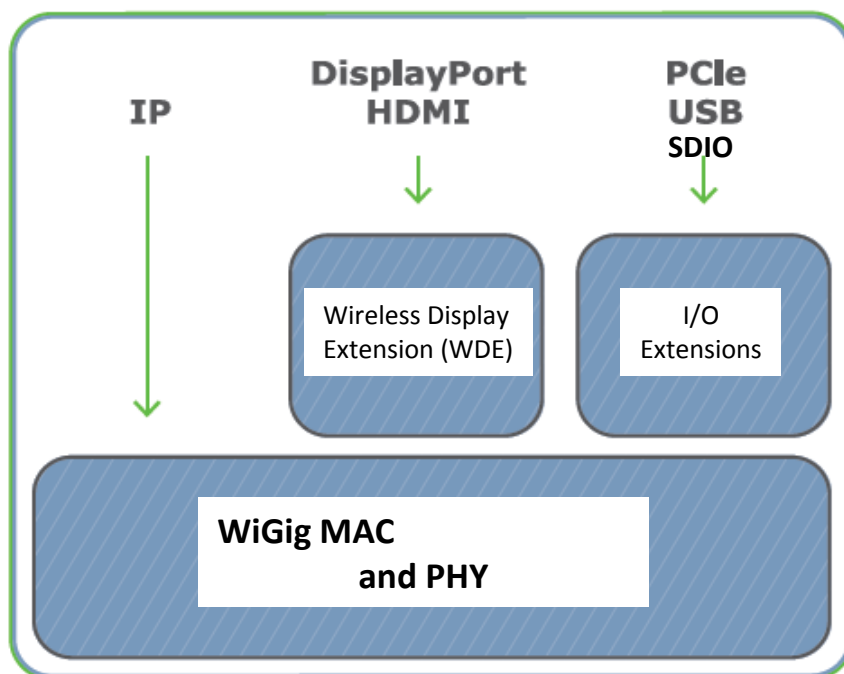
Wireless extensions allow wireless implementations of key computer, handheld and consumer electronics interfaces over 60 GHz WiGig networks. These extensions make it easier for implementers to produce devices with built-in support for specific uses such as wireless connections to displays.

Wireless extensions enable highly efficient implementations because they are defined directly on the WGA MAC and PHY, rather than layered on other protocols and can be implemented in hardware. This maximizes performance and reduces power consumption. Wireless extensions defined to date are:

Wireless Display Extension (WDE)

WDE allows wireless transmission of audio-visual data. An example might be transmitting movies from a computer or digital camera to a TV set or projector. This extension supports wireless implementations of HDMI and DisplayPort interfaces, as well as the High-bandwidth Digital Content Protection (HDCP) scheme used to protect digital content transmitted over those interfaces. It scales to allow transmission of both compressed and uncompressed video.

Input-Output (I/O) extensions

The I/O extension defines high-performance wireless implementations of widely used computer interfaces over 60 GHz. Definitions exist for USB, PCIe, and SDIO.

USB is typically used to connect external peripherals and other devices to a host; Wireless Serial Extension (WSE) enables multi-gigabit wireless connectivity between USB devices, and facilitates the development of products such as USB docking stations.

PCIe is typically used within computers to connect the CPU and memory to I/O controllers that support storage, network cards and other interfaces. It is also used to connect to media and visual processors to enhance picture quality or offload processing from the CPU. Implementation of this extension, Wireless Bus Extension (WBE), enables multi-gigabit wireless synchronization between devices and connection to storage and other high speed peripherals.

WSD, or WiGig SDIO (Secure Digital Input/Output) Extension, is a de-facto industry standard for portable devices using interchangeable memory and also to support peripherals. SDIO has become very popular as an internal IO interface within portable devices and is supported by a variety of adapters such as Bluetooth, GPS, and WiFi.

9   Overview of ETSI EN 302 567 V1.2.1 (2012-01) specification[4]

The ETSI EN 302 567 Standard applies to radio equipment types for wireless access systems (WAS)/Radio Local Area Networks (RLAN) operating at multiple-gigabit data rates in the 60 GHz frequency range. These applications may also be referred to as Wireless Personal Area Network (WPAN) or Wireless Local Area Network (WLAN) systems and are intended for licence-exempt short-range devices. The Standard is intended to support specifications such as those addressed in IEEE 802.15.3c: "IEEE Standard for Information Technology – Specific Requirements – Part 15: Wireless Personal Area Networks with Millimeter Wave Alternative Physical Task Group 3c (TG3c)", ECMA TC48, High Rate Short Range Wireless Communications., and other international bodies.

EN 302 567 is intended to cover the provisions of Directive 1999/5/EC [2] (R&TTE Directive), article 3.2, which states that "… radio equipment shall be so constructed that it effectively uses the spectrum allocated to terrestrial/space radio communications and orbital resources so as to avoid harmful interference".

The technical conformance requirements for the so called essential requirements to address Article 3 of the R&TTE Directive providing a definition and limit are as follows:

>   Spectral power density
>
>   RF output power
>
>   Transmitter unwanted emissions
>
>   Receiver unwanted emissions
>
>   Medium access protocol
>
>   Integral antenna.

The corresponding conformance testing procedures are also detailed in the Standard.

––––––––––––

[4] ETSI EN 302 567 V1.2.1 (2012-01) Broadband Radio Access Networks (BRAN); 60 GHz Multiple-Gigabit WAS/RLAN Systems; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive.