|  |  |  |
| --- | --- | --- |
| Project | IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) | |
| Title | **15.7 System PHY Proposal for VLC Applications** | |
| Date Submitted | 31 October 2009 | |
| Source | Soo-Young Chang, CSUS  Myunghee Son, Kyeong Tae Kim, Jong-Hyun Park, and Sung Won Sohn, ETRI  Daejeon, Korea | Voice: 530 574 2741  Fax: [ NA ] E-mail: [sychang@ecs.csus.edu](mailto:sychang@ecs.csus.edu), [mhson@etri.re.kr](mailto:mhson@etri.re.kr) |
| Re: | Response to call for proposals on 25th August, 2009.  Support for ETRI Proposal “15.7 System PHY Proposal for VLC Applications”, IEEE 802.15-09-0653-01-0007. September 2009. | |
| Abstract | Superframe structures are proposed for VLC communications. Two architectures for brightness control through VLC are introduced. A new modulation scheme, duplexing and multiple access schemes, and multi hop concept to extend the range are also proposed for the 15.7 standard. | |
| Purpose | Proposal to IEEE 802.15.7. VLC TG | |
| Notice | This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein. | |
| Release | The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15. | |

**Table of Contents**

1. **INTRODUCTION**

***1.1 Scope of IEEE 802.15.7***

***1.2 DEFINITION OF APPLICATIONS***

***1.3 OPERATION SCENARIOS***

1. **FRAME STRUCTURES AND ARCHITECTURES**
   1. ***COMMON STRUCTURES***
   2. ***COMMUNICATION SCENARIOS USING COMMON STRUCTURES***

**3. VLC LAYER ARCHITECTURES**

***3.1 CONSIDERATIONS ON VLC LAYER ARCHITECTURE***

* 1. ***VLC LAYER ARCHITECTURES***

1. **VLC MODULATION**
   1. ***CONSIDERATIONS FOR MODULATION***

***4.2 BASIC CONCEPT: MULTI COORDINATES TO REPRESENT COLORS***

1. **DUPLEX/MULTIPLEX/MULTIPLE ACCESS**
2. **MULTI-HOP VLC FOR EXTENDED RANGES**
   1. **System PHY Proposal for VLC Applications**
3. **INTRODUCTION**

***1.1 SCOPE OF IEEE 802.15.7***

The 802.15.7 group has two main technical goals as follows:

* Broad range of Data rates: from 50 Kbps to 100 Mbps

Through visible light signals for communications, broad range of data rates can be achieved.

* Operates in visible light bands: 380 ns ~ 780 ns wavelengths: no constraint for band division

The whole visible light can be utilized in the wavelength range from 380 ns through 780 nm. In this range, no regulatory restrictions exist except health issues. Also no band division constraint exists. It means a whole band can be used as one band or be divided into multiple subbands.

As shown in Fig. 1, 15.7 has its unique areas in terms of medium it is using, but covers broad range of data rates in relatively short ranges up to 100 meters.

Fig. 1. VLC areas among other types of communication technologies and networks

***1.2 DEFINITION OF APPLICATIONS***

Two types of applications can be considered in this standard – non-vehicular and vehicular applications as explained below.

**DEFINITION OF APPLICATIONS - NONVEHICULAR**

* Mobile/fixed – mobile (short range)

Through this type of applications, information is exchanged between mobile units or a mobile unit and a fixed unit. Near field communications can be considered with the range of up to 20 cm.

* Infra – mobile/fixed (indoor, low speed)

For this type of applications, simple information can be broadcasted from infra structures as in the case of in-building guide systems. Simple information can also be delivered to infra structures from a mobile or fixed unit as in the case of identification systems.

* Infra – mobile/fixed (indoor, high speed)

This type of applications provides to deliver Information broadcasted from infra to multiple units such as the case of WLAN access point. Information can also be delivered to infrastructures from a mobile or fixed unit in indoor environments as for the case of WLAN users.

* Infra – mobile/fixed (outdoor)

In this application, information is broadcasted from infra structure such as sign boards and advertisement towers in outdoor environments. Simple information can also be delivered to infra structures to provide the unit’s inquiry or own information.

**DEFINITION OF APPLICATIONS - VEHICULAR**

* Traffic lights (or infra) – vehicle

Traffic signal and/or traffic information can be delivered to vehicles which approach to traffic lights. And also vehicle information itself and/or road information such as emergency vehicle information and road state information and accident information can be delivered to traffic lights (or infra structures).

* Vehicle – vehicle

Through this type of applications, traffic information can be exchanged among a group of vehicles. Maneuvering information can also be exchanged in a group when they drive as a group. Traffic information can be relayed from front vehicle to rear vehicle – for example, a vehicle can get traffic light information through this type of communications from the front vehicle.

***1.3 OPERATION SCENARIOS***

Several operation scenarios can be considered depending on types of devices and vehicles involved as follows.

**TRAFFIC LIGHT – VEHICLE**

* Type of devices involved

Two-way communicator for traffic light and reactor for vehicles are involved in this scenario. Devices are classified into master and slave or primary and secondary devices. Traffic light should be master or primary devices while vehicles are slave or secondary ones.

* Operating mode

Two modes are applied for this scenario.

* + Active communication mode: two-way communications with interactions to each other
  + Passive communication mode: one-way broadcasting from the master or primary devices
* Network initiation

Just addressing is enough.

* Type of information delivered
  + Traffic light 🡪 vehicle:

Traffic signal information, traffic information, etc. can be delivered to vehicles.

* + Vehicle 🡪 traffic light:

Road state information collected including accident information can be delivered to be collected and used for more valuable information disseminated to other vehicles.

**INFRA – VEHICLE**

* Type of devices

Two-way communicators are deployed for road side unit and passive reactors are deployed for vehicles. Master and slave or primary and secondary relationship is maintained between devices. Road side units are master or primary units while vehicles have slave or secondary units.

* Operating mode:

Two modes are applied for this scenario.

* + Active communication mode: two-way communications with interactions to each other
  + Passive communication mode: one-way broadcasting from the master or primary devices
* Network initiation

Just addressing is enough.

* Type of information delivered
  + Road side unit 🡪 vehicle:

Local information, traffic information, etc. can be delivered to vehicles

* + Vehicle 🡪 road side unit:

Road state information collected including accident information can be delivered to be collected and used for more valuable information disseminated to other vehicles.

**VEHICLE – VEHICLE**

* Type of devices

Two-way communicator for a vehicle and reactors for other vehicles are involved in this scenario. Devices are classified into master and slave or primary and secondary devices. A vehicle should be designated as a master or primary device while other vehicles are slave or secondary ones.

* Operating mode:

Two modes are applied for this scenario.

* + Active communication mode: two-way communications with interactions to each other
  + Passive communication mode: one-way broadcasting from the master or primary devices
* Network initiation

Networking needs to be formed, but just addressing will be enough.

* Type of information delivered
  + Vehicle 🡪 vehicle relay:

Local information, traffic information including accident information or traffic light information can be relayed to other vehicles.

* + Vehicle 🡪 vehicle:

Road state information collected including accident information can be delivered to other vehicles.

* + Vehicle 🡪 vehicle in a group:

Maneuvering information can be exchanged in a group when multiple vehicles drive as a group.

**MOBILE – MOBILE**

* Type of devices

Two-way communicator for a mobile unit and reactors for other units are involved in this scenario. Devices are classified into master and slave or primary and secondary devices. A unit should be designated as a master or primary device while other units are slave or secondary ones.

* Operating mode:

Two modes are applied for this scenario. The distance between two units is 20 cm maximum. Therefore this realizes near field communication (NFC).

* + Active communication mode: two-way communications with interactions to each other
  + Passive communication mode: one-way broadcasting from the master or primary devices
* Type of information delivered
  + Mobile 🡨🡪 mobile:

Mainly data transfer including audio/video information is done for massive information download.

* + Mobile 🡨🡪 A/V appliance:

Mainly data transfer including audio/video information is done for massive information download.

* + Mobile 🡨🡪 computer:

Mainly data transfer including audio/video information is done for massive information download.

* Simplicity for network set up is important

The complexities of setting up network connections between devices should be avoided: Cumbersome network settings certainly are not in the consumer electronics world. For an example, now, to set up Bluetooth communication between two computers it is needed to set it up manually with a password to protect the communication. Network initiation should be easy to simplify the set-up: by any device which needs networking, but just addressing will be enough. Simpler network set up and higher data rates needed.

**INFRA – MOBILE (INDOOR/LOW SPEED)**

* Type of devices:

Two-way communicator for the infra structure unit and reactors for other mobile units are involved in this scenario. Devices are classified into master and slave or primary and secondary devices. The infra structure unit should be designated as a master or primary device while other mobile units are slave or secondary ones.

* Operating mode

Two modes are applied for this scenario. The distance between two units is 10 m maximum. Therefore this is mainly used for wireless identification.

* + Active communication mode: two-way communications with interactions to each other
  + Passive communication mode: one-way broadcasting from the master or primary devices
* Type of information delivered

This type of applications is low speed applications which can be applied for identification and simple information exchange such as in-building information.

* + Infra 🡪 mobile:

simple identification request or in-building local information can be delivered to mobile units.

* + Mobile 🡪 infra:

Simple identification response can be delivered to the infra structure unit.

* Simplicity is important

It is important not to face the complexities of setting up network connections between devices.

**INFRA – MOBILE (INDOOR/HIGH SPEED)**

* Type of devices:

Main applications for this type of communications are wireless local area networks (WLANs). Two-way communicator for the infra structure unit and reactors for other mobile units are involved in this scenario. Devices are classified into master and slave or primary and secondary devices. The infra structure unit should be designated as a master or primary device while other mobile units are slave or secondary ones.

* Operating mode: 10 m max

Two modes are applied for this scenario. The distance between two units is 10 m maximum.

* + Active communication mode: two-way communications with interactions to each other
  + Passive communication mode: one-way broadcasting from the master or primary devices
* Type of information delivered

High speed applications are executed using this type of communications. Mainly WLAN applications are considered.

* + Infra 🡪 mobile:

Data transfer or exchange between infra structure and mobile units are done.

* + Mobile 🡪 infra

Data transfer or exchange between infra structure and mobile units are done.

**INFRA – MOBILE (OUTDOOR)**

* Type of devices

Main applications for this type of communications are information exchange between infra structure installed at road sides and mobile units. Two-way communicator for the infra structure unit and reactors for other mobile units are involved in this scenario. Devices are classified into master and slave or primary and secondary devices. The infra structure unit should be designated as a master or primary device while other mobile units are slave or secondary ones.

* Operating mode

Two modes are applied for this scenario. The distance between two units is 10 m maximum.

* + Active communication mode: two-way communications with interactions to each other
  + Passive communication mode: one-way broadcasting from the master or primary devices
* Network initiation

Only addressing is enough.

* Type of information delivered

Relatively simple information delivered to mobile units and infra structure.

* + Infra 🡪 mobile

Local information, traffic information, etc. can be disseminated by the infra structure unit.

* + Mobile 🡪 infra

Information request, road state information collected including accident information, emergency information, etc. can be delivered to infra structure.

**COMMON TO MOST OF APPLICATIONS**

* Collision avoidance

A method to detect the presence of a VLC signal based on the pseudo random code matching is provided and a method to detect and resolve collisions on protocol level by checking received information should be provided. When collisions occur, random back-off schemes should be applied to lower collision probabilities.

* Sensing

A method to sense a signal by a device in the active communication mode that it is supposed to receive should be facilitated.

* Single Device Detection (SDD) or device discovery

An algorithm should be used by the initiator of a new network to detect one out of several reactors in its field of view (FOV). Device selection and de-selection procedures are needed.

1. **FRAME STRUCTURES AND ARCHITECTURES**

In this document, simplicity is emphasized for coexistence of high rates and low rates applications and a broad range of mobility. It means too much time should not be spent to set up and maintain link and enter the network.

Keeping this factor in mind, two common frame structures are utilized.

***2.1 COMMON STRUCTURES***

**Common superframe structure 1**

With this structure every *x* seconds, one preamble, one data unit for downlink (DL) and one data unit for uplink (UL) are transmitted. Each set of DL and UL has a common preamble frame with common modulation and data rate for all applications. Each application may have a different PPDU structure with different modulation applied and a data rate. This structure is illustrated in Fig. 2.

* Down link

A downlink frame consists of a common preamble, whose size is 128 bytes (that is, approximately 1000 bits) and a physical layer packet data unit (PPDU) whose size is *y* bytes which is equivalent to 8 x *y* bits. Communication time for preamble only is approximately 5 ms when 100 Kbps is considered. A frame for one user is sent every *x* sec.

* Up link

Uplink PPDU has a size of *z* bytes which is equivalently 8 x *z* bits. This UL PPDU is assigned to a user per request using ACK/NACK sequence sent during a request to send/ack/nack period (RAP).

Fig. 2. Common frame structure 1

**Common superframe structure 2**

This structure can be used for high rate cases and for the case of delivery of the large amount of information. However, the same preamble and RAP period are used for the common link establishment and control as for Common structure 1 as shown in Fig. 3. Only the difference from the previous structure is that this structure has multiple frames in which one uplink and one downlink time slots are assigned for each frame applying time division duplexing (TDD).

A superframe consists of a common preamble, SCH, and multiple frames. Each frame has a DL and a UL subframes: a common preamble frame with common modulation and data rate for all applications enables most VLC systems to have common design for link detection and establishment. Each application may have a different PPDU structure with different modulation and data rate.

* Down link

Common preamble for down link has a size of 128 byte which is equivalent to 1000 bits. Communication time for this preamble is 5 ms. Time division multiplexing is applied for down link.

* Up link

Demand assigned TDMA is applied to assign a frame to a user. Or CDMA with16 bit Walsh code can be applied for multiple access.

Fig. 3. Common frame structure 2

**Common (Preamble + Request/Ack Period) structure**

Superframes for all applications have a common preamble frame and may have different PPDU structure for each application. The preamble frame is designed for frame synchronization while Request/Ack Period (RAP) and for transmit request and its Ack/Nack. A common quaternary modulation scheme such as QPSK and data rate of 200 Kbps can be applied. Only one preamble frame is assigned for each superframe as shown in Fig. 4.

Fig. 4. Preamble frame structure

Communication time for PPDU depends on the modulation scheme applied and data rate applied and its size.

**Common preamble burst structure**

A preamble burst consists of a preamble word, an index, a parity, and a reserved word as shown in Fig. . A preamble word (or sync word) can a fixed sequence as shown in Fig. 5. Following this word, index and parity slots are placed. Index is a number descending from the maximum number of preamble burst for preamble frame. Parity is added to index using (15,7) Hamming code to protect index part from erroneous detection. Two bit reserved part is placed at the end of this preamble burst for future use.

Fig. 5. Preamble burst structure

**Common Request/Ack period (RAP) structure**

An RAP frame consists of an RTS (Request To Send) burst and an ANP (Ack/Nack period) burst. Each RTS or ANP burst consists of 16 bits as shown in Fig. 6.As shown in this figure, quaternary symbols are assumed.

Fig. 6. Request to send/ack/nack structure

64 16-bit codewords for RTS and ANP each can be formed as shown in Fig. 7.These codewords are formed by cascading two identical 8-bit orthogonal codes. Received data sequence is divided into two subcodewords. Each subcodeword is compared with 8 8-bit codewords. 64 combinations of codewords can be realized. Therefore up to 64 devices can be associated to a network.

Fig. 7. RTS/ACK codeword structure

For each subcodeword, the following table shown in Fig 8. is applied to form 16 bit codewords for RTS and ANP codewords.

Fig. 8. RTS/ACK codeword combinations

***2.2 COMMUNICATION SCENARIOS USING COMMON STRUCTURES***

**TRAFFIC LIGHT (OR INFRA)–VEHICLE**

Simple Superframe structure 1 is applied for low speed applications as shown in Fig. 9. For this application, up to 100Kbps data rate will be applied.

Down link is set up from traffic light or infra structure. The size of payload for this link is 100 bytes, which is equivalently to 800 bits. Communication time is 10ms for both preamble and downlink data unit. Every *x* msec these preamble and downlink data unit are transmitted.

Up link is set up to deliver data from vehicles to the traffic light or infra structure. The size of payload for this link is 200 bytes, which is equivalently to 1600 bits. Communication time is 10ms. Every *x* msec an uplink is set up so that any vehicle who wants to send its own data to the traffic light or infra structure is able to have a chance to do that by requesting the traffic light or infra structure to assign the following UL PPDU to this vehicle by sending an RTS codeword during the RAP period. Then the traffic light or infra structure decides whether this vehicle is allowed to send it data. If it decides to do that, the traffic light or infra structure will send the same codeword during ANP period.

Fig. 9. Communication structure, traffic light (or infra) - vehicle

Down and up link have a payload of 100 bytes each, which entails total frame size is (preamble 128 bytes plus PPDU128 bytes), which is 256 bytes, that is, 2 Kbits. Considering communication time of 10ms, and a frame every *x* msec, data rate can be 2 Kbits/10 ms, which is equivalently to 200 Kbps. For this type of applications, the maximum range is 50 m.

Maximum latency or delay between down and up links can be estimated by calculating 100 m/3x108 m = .33 us. This number is approximately 10 us/symbol for quaternary modulation case which latency can be negligible.

As explained in the above, master – slave relationship is maintained between traffic light or infra structure and vehicles. That means traffic light or infra structure should be a master while vehicles should be slaves.

Each DL has a payload of 100 bytes, so that the total frame is (preamble 128 bytes plus PPDU128 bytes) which is 256 bytes, equivalently 2 Kbits. Communication time for this link is 10ms and every *x* msec one frame is sent. Therefore the data rate is estimated to 2 Kbits/10 ms, which is equivalently to 200 Kbps. By applying quaternary modulation such as QPSK, the length of a frame is 1 Ksymbols per frame.

For each UL, the same as for the case of DL is applied except the length of the frame with maximum frame length of 256 bytes which gives 1 Ksymbols per frame.

Symbol duration is estimated to 10 us and the maximum signal duration for both DL and UL is 20 ms, then the maximum duty cycle is 4 % for every 500 ms transmission case.

**VEHICLE – VEHICLE**

Simple Superframe structure 1 is applied for low speed applications for this type of applications. Down link is formed by and set up from primary vehicle which can be a first vehicle. It monitors whether any VLC signals exist. If no signal is sensed, it initiates a network or a link and becomes a primary vehicle.

The size of payload for this link is 100 bytes, which is equivalently to 800 bits. Communication time is 10ms for both preamble and downlink data unit. Every *x* msec these preamble and downlink data unit are transmitted.

Up link is set up to deliver data from secondary vehicles to the primary vehicle. The size of payload for this link is 200 bytes, which is equivalently to 1600 bits. Communication time is 10ms. Every *x* msec an uplink is set up so that any secondary vehicle who wants to send its own data to the primary vehicle is able to have a chance to do that by requesting the primary vehicle to assign the following UL PPDU to this vehicle by sending an RTS codeword during the RAP period. Then the primary vehicle decides whether this vehicle is allowed to send it data. If it decides to do that, the primary vehicle will send the same codeword during ANP period.

Fig. 10. Communication structure, vehicle - vehicle

Down and up link have a payload of 100 bytes each, which entails total frame size is (preamble 128 bytes plus PPDU128 bytes), which is 256 bytes, that is, 2 Kbits. Considering communication time of 10ms, and a frame every *x* msec, data rate can be 2 Kbits/10 ms, which is equivalently to 200 Kbps. For this type of applications, the maximum range is 50 m.

Maximum latency or delay between down and up links can be estimated by calculating 100 m/3x108 m = .33 us. This number is approximately 10 us/symbol for quaternary modulation case which latency can be negligible.

As explained in the above, master – slave relationship is maintained between the primary vehicle and secondary vehicles. That means the primary vehicle should be a master while secondary vehicles should be slaves.

Each DL has a payload of 100 bytes, so that the total frame is (preamble 128 bytes plus PPDU128 bytes) which is 256 bytes, equivalently 2 Kbits. Communication time for this link is 10ms and every *x* msec one frame is sent. Therefore the data rate is estimated to 2 Kbits/10 ms, which is equivalently to 200 Kbps. By applying quaternary modulation such as QPSK, the length of a frame is 1 Ksymbols per frame.

For each UL, the same as for the case of DL is applied except the length of the frame with maximum frame length of 256 bytes which gives 1 Ksymbols per frame.

Symbol duration is estimated to 10 us and the maximum signal duration for both DL and UL is 20 ms, then the maximum duty cycle is 4 % for every 500 ms transmission case.

**INFRA – MOBILE/FIXED: LOW SPEED**

Simple Superframe structure 1 is applied for low speed applications for this type of applications as shown in Fig 11. Down link is formed by and set up from infra structure.

The size of payload for this link is 100 bytes, which is equivalently to 800 bits. Communication time is 10ms for both preamble and downlink data unit. Every *x* msec these preamble and downlink data unit are transmitted.

Up link is set up to deliver data from mobile or fixed units to the infra structure. The size of payload for this link is 200 bytes, which is equivalently to 1600 bits. Communication time is 10ms. Every *x* msec an uplink is set up so that any mobile or fixed unit who wants to send its own data to the infra structure is able to have a chance to do that by requesting the infra structure to assign the following UL PPDU time slot to this unit by sending an RTS codeword during the RAP period. Then the infra structure decides whether this unit is allowed to send it data. If it decides to do that, the infra structure will send the same codeword during ANP period.

Fig. 11. Communication structure, low speed infra – mobile/fixed

Down and up link have a payload of 100 bytes each, which entails total frame size is (preamble 128 bytes plus PPDU128 bytes), which is 256 bytes, that is, 2 Kbits. Considering communication time of 10ms, and a frame every *x* msec, data rate can be 2 Kbits/10 ms, which is equivalently to 200 Kbps. For this type of applications, the maximum range is 5 m.

Maximum latency or delay between down and up links can be estimated by calculating 100 m/3x108 m = .33 us. This number is approximately 10 us/symbol for quaternary modulation case which latency can be negligible.

As explained in the above, master – slave relationship is maintained between the infra structure and mobile or fixed units. That means the infra structure should be a master while mobile or fixed units should be slaves.

Each DL has a payload of 100 bytes, so that the total frame is (preamble 128 bytes plus PPDU128 bytes) which is 256 bytes, equivalently 2 Kbits. Communication time for this link is 10ms and every *x* msec one frame is sent. Therefore the data rate is estimated to 2 Kbits/10 ms, which is equivalently to 200 Kbps. By applying quaternary modulation such as QPSK, the length of a frame is 1 Ksymbols per frame.

For each UL, the same as for the case of DL is applied except the length of the frame with maximum frame length of 256 bytes which gives 1 Ksymbols per frame.

Symbol duration is estimated to 10 us and the maximum signal duration for both DL and UL is 20 ms, then the maximum duty cycle is 4 % for every 500 ms transmission case.

**INFRA – MOBILE/FIXED: HIGH SPEED**

More complicated Superframe structure 2 applied for high speed applications such as WLAN as shown in Fig 12. Down link is formed by and set up from infra structure.

Preamble frame can be used commonly as other applications explained in the above. For data exchange between infra structure and mobile or fixed units, a superframe is formed which is divided into multiple frames. Each frame has uplink and downlink time slot applying time division duplex (TDD).

Up link from mobile or fixed units, demand assigned TDMA is applied for multiple access. Or CDMA with16 bit Walsh code can be applied which accommodate 64 units simultaneously.

Fig. 12. Communication structure, high speed infra – mobile/fixed

Down and up link have a payload of much longer than100 bytes, which entails total frame size is (preamble 128 bytes plus PPDU much longer than128 bytes), which is much longer than 256 bytes. Considering communication time only for preamble of 5 ms, data rate can be 1 Kbits/5 ms, which is equivalently to 200 Kbps, as same as the other applications because of common preamble structure. However, data rates during period other than preamble should be much higher than this rate. For this type of applications, the maximum range is 10 m.

Maximum latency or delay between down and up links can be estimated by calculating 20 m/3x108 m = .066 us. This number is approximately .2 us/symbol for quaternary modulation case with 10 Mbps (the worst case), which latency may not be negligible. It means more sophisticated modulation schemes should be applied.

Some terminology can be applied as follows:

* Superframe

Defined and delimited by a preamble and the SCH (superframe control header). It is comprised of a number of **Frames.**

* Frame

Comprised of one downlink stream (DS) and one uplink stream (US) **Subframe**, where infra structure and mobile and/or fixed units use to communicate with each other.

* Subframe

Formed by a number of **Bursts**

* Burst

It may comprise of multiple **MAC PDUs** belonging to multiple mobile/fixeds.

* MPDU (MAC PDU)

The smallest unit of transmission/reception by the MAC. It is comprised of the MAC header, the payload, and CRC

Symbol duration for preamble only is estimated to 10 us while signal duration for preamble only is 5 ms. The maximum signal duration for both DL and UL is variable.

**MOBILE/FIXED-MOBILE: HIGH SPEED**

Simple but long Superframe structure 2 needed to be applied for high speed applications such as file transfer between a mobile unit and a mobile or fixed unit. Down link is formed by and set up from a primary unit which initiates the communication.

Preamble frame can be used commonly as other applications to initiate the communication explained in the above. Up link is set up for data transfer from mobile/fixed. For data exchange between a mobile and mobile or fixed units, a superframe is formed which is divided into multiple frames. Each frame has uplink and downlink time slot applying time division duplex (TDD).

Long payload with simple format is realized for simple implementation.

Fig. 13. Communication structure, high speed mobile/fixed – mobile

Down and up link have a payload of much longer than100 bytes each, which entails total frame size is (preamble 128 bytes plus PPDU much longer than128 bytes). Considering communication time of only preamble of 5ms, data rate can be 1 Kbits/5 ms, which is equivalently to 200 Kbps. For this type of applications, the maximum range is 0.2 m.

Maximum latency or delay between down and up links can be estimated by calculating 0.4 m/3x108 m = .0013 us. This number is approximately 0.02 us/symbol for quaternary modulation case with 100 Mbps (the worst case) which latency can not be negligible. It means more sophisticated modulation schemes should be applied.

As explained in the above, master – slave relationship is maintained between a mobile or fixed unit and another mobile or fixed unit. That means the primary mobile or fixed unit which initiates the communication should be a master while the other mobile or fixed unit should be slave.

Each DL has a payload of much longer than 100 bytes, so that the total frame is (preamble 128 bytes plus PPDU much longer than128 bytes). Communication time only for preamble for this link is 5 ms. Therefore the data rate for preamble only is estimated to 1 Kbits/5 ms, which is equivalently to 200 Kbps. By applying quaternary modulation such as QPSK for preamble only, the length of a frame is 1 Ksymbols per preamble frame. Higher efficient modulation for data frames should be applied to achieve higher data rate for data frames.

For each UL, the same as for the case of DL is applied. Higher efficient modulation for data frames should be applied to achieve higher data rate for data frames.

Symbol duration for preamble only is estimated to 10 us and the maximum signal duration for preamble only is 5 ms.

1. **VLC LAYER ARCHITECTURES**

***3.1 CONSIDERATIONS ON VLC LAYER ARCHITECTURE***

VLC is using a unique medium, visible light. Therefore some factors should be considered for layer architecture as following, especially for the case that lighting system is not a part of VLC, that is, a stand-alone lighting system already deployed.

* Splitting PHY into two parts – VLC part and light emitting device control part - was considered when existing illumination systems are utilized as light sources of VLC.
* Layer architecture totally depends on what technologies will be used for the 15.7 standard without splitting PHY including modulation techniques. If a modulation technique applied does not depend on technical characteristics of LED deployed, lighting control through LEDs is not needed. Therefore a new modulation scheme is needed. If only simple current or voltage control is needed to the LED control panel for VLC, PHY does not need to be split. This control can be implemented even for existing LED lighting systems already deployed. Therefore another small layer is introduced (LAL) to harmonize this control between light sources and PHY layer.
* Basically it is more desirable that the standard for VLC be independent of lighting systems. The VLC should be coexistent with or adapted to any (infrastructure) lighting systems. To do this, simple inputs are allowed to be inputted to the lighting controller.

***3.2 VLC LAYER ARCHITECTURES***

Two types of architectures for VLC can be considered – one architecture for the case of VLC with self medium and the other for VLC through illumination as shown in Fig. 14.

Fig. 14. VLC architecture with or without illumination control

The first case is not the issue to control illumination through VLC because it has its medium. The second is the case VLC is achieved through exterior illumination systems. Illumination control may affect VLC performance while VLC affects illumination control. To avoid these problems there are two VLC layer architectures through which lighting systems can be controlled.

Four types of illumination control inputs from outside can be considered – input directly to the light sources, input to a block which is connected to PHY, input directly to MAC, and input from the higher layers.For multi-hop cases, a repeater will select a medium for proper routing, so light control can be inputted to MAC.

**VLC LAYER ARCHITECTURE 1**

This architecture is the case of using another layer, light abstraction layer (LAL) between PHY and light sources and sensors as shown in Fig. 15. This layer conditions the signal from the sensor and inputs it to PHY layer or receives a signal from PHY layer and converts this signal to a light source control signal.

Fig. 15. VLC layer architecture 1 with LAL

**VLC LAYER ARCHITECTURE 2**

This architecture is for the case without using light abstraction layer (LAL), but a small interface between lighting and VLC to manage the control signal directly from outside or from PHY layer as shown in Fig. 16.

Fig. 16. VLC layer architecture 1 with lighting/VLC interface

This block converts signals from outside and PHY layer to control light sources.

**FUNCTIONS OF EACH LEVEL OF LAYERS**

The components of this system is illustrated in Fig. 17.

Fig. 17. Functions of each element of layers

1. **VLC MODULATION**

***4.1 CONSIDERATIONS FOR MODULATION***

VLC has its own characteristics because of its unique medium, visible light signal. Therefore the following factors should be considered.

* Need of brightness control or not

More commonly VLC can be achieved using existing illumination systems. These systems may have brightness control function. Therefore it should be checked whether it is needed to provide superior brightness for visible communications. Brightness control affects VLC performance while VLC may affects illumination such as brightness, color shift, flickering, etc. It is more desirable for VLC performance not to be affected by brightness control.

* Dependency of LED characteristics

Modulation technique applied should not depend on technical characteristics of LED deployed.

* Not (or negligibly) affected by background noise or not

The impact of background lights is to be offset. Stable data transmission should be provided even if the background noise is strong. It is desirable to offer high robustness to background light

* Data speed

A broad range of low to high data rates is to be realized. That means adaptiveness to the amount of information delivered is important: adaptiveness to data speed is important.

**MAJOR DISTINCTIONS BETWEEN VLC AND RADIO COMMUNICATION**

VLC and radio communications basically have different media – visible light and electromagnetic wave signals. Due to different media, these two types of communications have huge distinctions. Some of them are described in Table .

Table . Distinctions between VLC and radio communications

|  |  |
| --- | --- |
| VLC | Radio comm. |
| Data delivery by manipulating and measuring light, in terms of its *perceived* brightness or colors to human eyes. The radiant power at each wavelength is weighted by a luminosity function (a.k.a. visual sensitivity function) that models human brightness sensitivity. | Data delivery by manipulating electromagnetic signals and detecting parameters of the received signals or measuring radiant energy in terms of absolute power. |
| A light signal which will be manipulated for data delivery has a certain amount of frequency (or wavelength) band before modulation. | A carrier signal usually has a single frequency component which is modulated with data. Eventually the transmitted signal has a certain amount of band after modulation. |

***4.2 BASIC CONCEPT: MULTI COORDINATES TO REPRESENT COLORS***

In the modulation scheme described in this text, two coordinates (*x* and *y*) for a two dimensional light color space are considered. *x* and *y* are designed to be orthogonal to each other to be applied for the scheme. It means no correlation between these two. Any point in a space can be represented by a unique pair of these values. A color is represented by a unique point in a space, not by multiple points.Therefore it is similar to QAM. It needs to determine points which maximize the minimum distance among distances between any two points. Equi-distance strategy is a possible way to assign points.

A color can be generated by mixing lights from multiple light emitting devices such as LEDs. Therefore the modulation scheme used is multiple light sources based, not single light source based. It is not necessary that light of a color can be generated by mixing lights from multiple light emitting devices with a unique set of light intensities of light emitting devices. A multi dimensional space can be considered to represent colors. A multi dimensional light color space can be used for color representation, but generally it is not true that there is only one point to represent each color: multiple points can be identified for a specific color in general. Thus a light space should be well tailored not to have multiple points to represent a color, but to represent a color with a unique point.

**MODULATION BLOCKS**

For the modulation scheme applied, some blocks are needed to manipulate visible light signals from the data stream to be delivered as shown in Fig. 18.

At transmitter, data stream from a information source is converted to form a parallel sequence by a serial-to-parallel converter. This sequence is mapped into a set of modulation coefficients. These coefficients are applied to a light emitting device driver to drive light emitting devices such as LEDs. Then a visible light signal is emitted with a color recognized by human eyes.

At receiver, a light signal received by a photo detection block is amplified to be processed and analog-to-digital converted. This converted information is inputted to modulation-to-data demapping block producing a parallel data sequence which can be converted to a serial data stream using parallel-to-serial converter.

Fig. 18. VLC block diagram

**BASIC CONCEPTS**

For this modulation, the following concepts are utilized:

* Transmission and reception (or detection) of light signals

At the transmitter, multiple light sources (or light emitting devices) such as LEDs with different spectral distributions are used for light emission. At the receiver, multiple photo detectors with different spectral responses are used for light detection.

* Any color can be represented by a point in a multi-dimensional space uniquely.

Any color is represented by a point in an *n* dimensional space – but not uniquely for most cases. It is because in general light generated by each device can also be generated by mixing light signals from other devices which have different spectral distributions. Thus multi-dimensional space should be defined to represent a color with a point uniquely in this space. One possibility is use of spectrally uncorrelated light sources or photo detectors, but it is not assumed in this document. A unique color for a point in the space can be generated by mixing lights emitted from *n* light emitting devices and be detected by processing light signals detected by *k* photo detectors.

**Light Signal Delivery Model from Transmitter to Receiver**

Light signals are generated at transmitters and recognized by human eyes and detected at receivers.

* Radiation at Transmitter

Multiple light emitting devices emit light signals at transmitter. Each device has its own spectral distribution, *S*(*λ*), which determines its emitted power by calculating total power throughout the whole wavelength range. By using the color matching functions of a light space and by calculating stimulus values – for two dimensional space, *X, Y* and *Z* values - of the light space, the color of emitted light perceivable by human eyes can be determined.

* Perception by Human Eyes

To know how human eyes react to emitted light, emitted light signal which has spectral distribution, *S*(*λ*), is multiplied by a standardized luminosity function - wavelength-weighted by the luminosity function to correlate with human brightness perception. Then total power perceived by human eyes can be determined.

* Detection at Receiver

The emitted signal has spectral distribution, *S*(*λ*), which is delivered to the detector which is characterized by its responsivity, its own spectral sensitivity, which determines the spectral characteristics and total received power to determine color detected.

This model can be re-illustrated using the following figure, Fig. 19. In this modulation, multiple light sources and multiple photo detection components are utilized at transmitters and receivers respectively.

Fig. 19. VLC signal flow diagram

At transmitters, multiple light sources (or light emitting devices) have their own light intensities. In this illustration, *n* light emitting devices are used. These light signals are combined additively to produce one color light signal. This light signal is delivered through a channel where noise and other interference is added to this signal. At receiver, *k* photo detectors are deployed to detect light signals. Each of photo detectors has its own intensity. From a set of intensities of received signals, a data sequence to be delivered can be regenerated. In this modulation, this property is applied.

**MODULATION BLOCKS REVISITED**

To explain the modulation, the block diagram is revisited as shown in Fig. 20. The data stream from a information source is converted into an *m* parallel data sequence and inputted into data-to-modulation mapping. Mapping output is a set of n intensities which are inputted to light emitting device driver to drive n light emitting components.

At receiver, a light signal is detected by *k* photo detection components and these *k* detected intensities are inputted to modulation-to-data demapping through amplifier and analog-to-digital converter. This demapper output is *m* parallel bits.

Fig. 20. VLC block diagram revisited

**KEY PART FOR NEW MOD: MAPPING**

A key part for this new modulation is mapping and demapping. As shown in Fig. 21, *m* bit binary data is inputted to the mapper and output of this mapper is *n* light intensities which drive *n* light emitting devices.

With reverse procedure, *k* light intensities detected by *k* photo detection components are inputted to demapper which produces m bit binary data stream. With these inputs, the demapper produces *m* bit binary data output.

Fig. 21. Mapper and demapper of NM

***4.3 NEW MODULATION (NM)***

***GENERATION OF CONSTELLATION***

Two assumptions are made to generate a constellation. One is equi-probable data elements assumed. For example, a binary data source has an equal probability of ½ for two symbol elements. It is also assumed that for a fixed number of symbols’ duration, color is not changed.

Information data of *m* bits is inputted. Therefore there are 2*m* symbol elements which produces 2*m* points. Another input is color information, (*xc,yc*) which is recognized by human eyes, called a target color.

Using these inputs, a constellation, (*x,y*) is generated. Two parameters considered to pick points in a light space: colors perceptible by human eyes and equi-distance between two adjacent points when points are detected by photo detectors as shown in Fig. 22.

Fig. 22. Data points and target color position in a constellation

The maximum area of a constellation is determined by two factors:

* Point of target color for human eyes: this point becomes the origin of constellation.
* The whole gamut formed by primary color points which represent points of light emitting devices used.

Using these factors, a maximum constellation area determined as shown in Fig. 23 using the following procedure.

Fig. 23. Constellation area in a color space

Normalized constellation

A normalized constellation can be made. Inside a unit circle centered at the original, 2*m* points are assigned so that the minimum distance between any two points be maximized. Some examples are shown in Fig. 24.

Fig. 24. Normalized constellation (examples)

Constellation scaled with the center of target color location

A normalized constellation generated in the above is shifted so that the center is located at the target color point and scaled so that constellation area fits the maximum area with a radius of *rc* as shown in Fig. 25.

Fig. 25. Some examples of constellations centered at a target color point

**CONSTELLATION TO *(c1, c2, . . ., cn)* MAPPING**

One assumption for this mapping is perceptual uniformity or linearity of light emitting devices and photo detectors in the light space.

A constellation, (*x,y*) is inputted. Then output is a set of intensities of light sources (or light emitting devices), (*c1, c2, . . . , cn*).

Two cases for color properties of light emitting devices are considered:

* Using (*xi,yi*) *i*=1, 2, .., *n* for all light emitting devices if (*xi,yi*) *i*=1, 2, .., *n,* is given
* Using spectral distributions of light emitting devices if (*xi,yi*) *i*=1, 2, .., *n,* is not given

Using these color properties of light emitting devices, a point of each of devices in a constellation can be determined.

***(c’1, c’2, . . ., c’k)* TO CONSTELLATION DEMAPPING**

Uniformity or linearity of light emitting devices and photo detectors in the light space is assumed. Another assumption is that the receiver has constellation information that the transmitter applies and can get color information for each symbol received for itself or from outside.

Inputs from photo detection devices of the receiver, (*c’1, c’2, . . . , c’n*), light intensities measured by photo detectors are available for demapping. These inputs are produced by noise added from channels to the intensities of light sources (or light emitting devices) transmitted, (*c1, c2, . . . , cn*). By manipulating these inputs, an output, the information point, (*x’, y’*), in a constellation is determined which is most closely matching to a set of light intensities, (*c’1, c’2, . . . , c’n*).

Two cases for color detection properties of photo detectors are considered:

* Using (*x’i,y’i*) *i*=1, 2, .., *k* for all photo detectors if these values are given
* Using spectral distributions of photo detectors if (*x’i,y’i*), *i*=1, 2, .., *k,* is not given

**COLOR INFORMATION FROM CONSTELLATION**

At receiver , color information of transmitted light signal, target color information, is needed to know the constellation applied at transmitter to extract information from the received signal.

Two cases can be considered for this information:

1. Transmitter sends color information (*xc,yc*): TV signals, etc.
2. Using a fixed number of previous received symbols, color information can be extracted by averaging the center points of previous received symbols as sown in Fig. 26.

Fig. 26. Color point information identified using previous data points

**GENERATION OF TARGET COLOR OF EACH BAND USING MULTIPLE LEDS**

Basic concept to generate a target color of transmitted signals in each subband is as following. If there are multiple subbands in a whole band, each subband cannot be represented by a single LED: multiple LEDs should be used. If 8 bands exist, eight different LEDs can be used by assigning an LED for each band. This is not a usual and most efficient case. The best way is that by using a fixed number of LEDs all bands can be covered. It can be realized using a target color generation method applied in this New Modulation.

**INFORMATION DATA FROM CONSTELLATION**

An assumption is that a gamut formed by photo detectors should include all area of gamut formed by light emitting devices at transmitter. If it is not the case, some distortion is inevitable.

A normalized constellation can be generated. This constellation is moved to a target color point. After then, this constellation should be scaled at transmitter. Constellation scaling factor for a color is extracted at receiver.

A method to get constellation area at receiver should be devised. Some cases to know the scaling factor can be considered:

1. Periodically transmitter broadcasts information on light emitting devices used.
2. Whenever color changes or periodically with a fixed interval, transmitter broadcasts scaling factor information with color information.
3. Without any information above, the receiver can know color information and constellation by examining points of a fixed number of previously received symbols.

With these cases, it is noted that even the transmitter does not send any information on scaling factor or constellation information, the constellation can be identified at the receiver by observing some of points of previous data received.

For the case that target color information delivered from transmitter (Case 1), the following figure, Fig. 27, show how a constellation is formed and how information data from received signals are extracted.

Fig. 27. A method to determine a constellation using target color information

**MODULATION SCHEMES APPLIED**

Modulation schemes applied for the frame structures described in the above are shown in Fig. 28. For two parts, preamble part and data exchange part, different numbers of constellation points are applied. For preamble part, 4-NM is applied for low rate link establishment and frame synchronization while for data exchange part, more efficient NM schemes are applied, 2*m* NM, *m*= 2, 3, 4, ….

Fig. 28. Modulation schemes applied for preamble and data exchange parts

1. **DUPLEX/MULTIPLEX/MULTIPLE ACCESS**

**VARIOUS DUPLEXES POSSIBLE**

Various duplexing methods are well known. Some of conventional duplex schemes for full duplex are as follows:

* TDD (Time Division Duplex)
* FDD (Frequency Division Duplex)

Three duplex schemes for VLC are described as follows:

* Duplex 1: Using OFDM/OFDMA assumed
  + A subset of frequency components for downlink
  + Another subset of frequency components for uplink
* Duplex 2: Direction Division Duplex (DDD)
  + Using directional LEDs
* Duplex 3: Code Division Duplex (CDD)
  + Using orthogonal PN sequences

**Duplex 1: Orthogonal Frequency Division Duplex (OFDD)**

This can be used with OFDM signal processing. If multiplexing or multiple access is required, this duplex is also available and is more efficient. Using OFDM/OFDMA assumed, a subset of frequency components are assigned for downlink to a single device or multiple devices, while another subset of frequency components for uplink as shown in Fig. 29.

Fig. 29. Orthogonal Frequency Division Duplex (OFDD)

**Duplex 2: (Direction Division Duplex, DDD)**

Through this method, a duplex is realized using isolation between uplink and downlink through directivity of transmitter and receiver LEDs. Basically LEDs have certain amount of directivities. This property can be used for this type of duplexing as shown in Fig. 30.

Fig. 30. Direction Division Duplex, DDD

For downlink, a broad beam is used to broadcast light signals while for uplink a narrower (pencil) beam is used to dedicate the signal to a specific receiver of a base station (or access point or infra) as shown in Fig. 31.

Fig. 31. Down link and up link of DDD

**Duplex 3: Code Division Duplex (CDD)**

For this duplex method, some orthogonal PN sequences can be used to differentiate two up and down link. For downlink and uplink, different orthogonal PN sequences are assigned. For example, for downlink PN sequence *i* is applied while for uplink PN sequence *j* is applied for User Unit *j*. With this scheme, multiplexing and multiple access can also be achieved at the same time.

Fig. 32. Code Division Duplex (CDD)

Code Division Duplex (CDD) described in this document is using two 8-bit orthogonal Walsh codes which produce 16 bit orthogonal code. With this concept, 8 x 8 = 64 combinations are formed with which up to 64 users can communicate simultaneously. Also this method supports full duplex mode and provide full flexibility in uplink/downlink balancing and unbalancing for symmetric and asymmetric communications.

This method is more time efficient than TDD and more spectrally efficient than FDD. Autocorrelation and cross correlation should be checked to identify the type of links.

1. **MULTI-HOP VLC FOR EXTENDED RANGES**

With VLC, some constraints lie on ranges due to mainly inherent characteristics of line of sight communications. To overcome these constraints, some methods should be implemented to extend ranges. One of method is multi hoc networking.

To cover broader area in indoor environment or to overcome short range problem, an in-building space is divided into multiple cells. Each cell has its own base station (or access point). It is assumed that these base stations do not communicate with each other through an infra network. To connect all base stations, some relays or repeaters are to be deployed to connect all base stations. A mobile or fixed unit in a cell can communicate with a unit in another cell through a multiple hop connection. By using this method a unit can reach to another unit which is located in a remote place.

To cover broader area in indoor environment and to increase communication ranges, a server or gateway can be connected to only one base station. Other base stations are connected with other base stations through multiple hop links which forms a small mesh network as shown in Fig. 33.

Fig. 33. Multi hop system for extension of ranges

Several advantages with multi-hop VLC can be enjoyed as follows:

* Simple infrastructure to form a network among base stations
* Ubiquity can be easily realized.
* Quick deployment and flexible network configuration without additional infra networks, especially for temporary events and places
* Easy installation for places where frequent configuration changes are required
* Short range can be overcome with multiple cells (or hops).
* Line-of-sight problem can be overcome with dynamic routing scheme.
* Abrupt blocking problem can be solved by switching routes – by changing to an alternative route.