WORTECS

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List of Acronyms

Acronym	Meaning
CSD	**Criteria for standards development**
DCF	**Distributed coordination function**
DLL	**Data Link Layer**
EMI	**Electromagnetic interference**
HCF	**Hybrid coordination function**
IEEE	**Institute of Electrical and Electronics Engineers**
ITU	**International Telecommunication Union**
ITU-T	**ITU Telecommunication Standardization Sector**
LAN	**Local Area Network**
LC	**Light Communication**
LiFi	**Light Fidelity**
MAC	**Media Access Control**
MAN	**Metropolitan Area Network**
MIMO	**Multiple Input Multiple Output**
OBSS	**Overlapping basic service set**
PAR	**Project authorisation request**
PHY	**Physical layer**
SAP	**Service access point**
SG	**Study group**
TGbb	**802.11bb task group**
Wi-Fi	**Wireless Fidelity**
WORTECS	**Wireless Optical/Radio TErabit CommunicationS**

Table of Contents

1. Background

1.1. OWC

There are currently three standardisation efforts underway in LiFi. The International Telecommunications Union (ITU) has recently completed a LiFi standard ITU G.9991 (also known as G.vlc). In the IEEE there is a revision to the IEEE 802.15.7 standard underway, with two new efforts in camera communications (IEEE P802.15.7m) and high-speed communcations (IEEE802.15.13). This document focuses on the effort within IEEE 802.11 (802.11.bb), which is where WiFi standards are placed. WORTECS partner PLF plays a key role in this effort whereas partner OLD plans to get more involved in this process. An overview of the ITU telecommunication standardization sector (ITU-T) G.vlc set of specifications is also given.

IEEE 802.11

IEEE 802.11 is a set of media access control (MAC) and physical layer (PHY) specifications for implementing wireless local area network (WLAN) computer communication in the 900 MHz and 2.4, 3.6, 5, and 60 GHz frequency bands. They are created and maintained by the Institute of Electrical and Electronics Engineers (IEEE) LAN/MAN Standards Committee (IEEE 802). The base version of the standard was released in 1997 and has had subsequent amendments. The standard and amendments provide the basis for wireless network products commonly recognized as Wi-Fi©. In November 2016, the IEEE 802.11 created a Topic Interest Group on Light Communication (LC), later named TGbb, with a target to integrate this new physical link, i.e., LC, into the next evolution of the Standard.

IEEE 802.11 TGbb

IEEE 802.11 TGbb focuses on the development of Light Communications (LC or LiFi) with broad industry support from a comprehensive ecosystem of partners including chipset vendors, infrastructure providers, device manufacturers, lighting companies, telecom operators and end customers. Key envisioned use-cases are the mass market deployment in enterprise, homes, manufacturing and more as part of a truly heterogeneous network.
The following items were originally envisaged to be addressed by TGbb during the standard development process:

- Integration with and extension to 802.11 MAC
- Low-latency data delivery
- Asymmetric device capability support (power, directivity, wavelength, sensitivity, backhaul network latency timings, etc.)
- Peer-to-peer communications

IEEE 802.11 TGbb key features

One important motivation behind 802.11 TGbb initiative, as an amendment to the 802.11 standard, was the reuse of 802.11 MAC. From the beginning, the expectation was that the LC protocol can reuse the existing facilities within 802.11, such as distributed coordination function (DCF), power save modes, session establishment/tear down procedure and block acknowledgement, etc. However, the idea is to suggest specific modifications for the operation of LC that could improve the efficiency for particular implementations. In this

context, LiFi specific system or scenario design considerations are identified and carefully investigated. As an example, in LiFi scenarios the station may not necessarily see interference from neighbouring stations, which will have design modification consequences.

From the proposed Criteria for Standards Development (CSD) suggested by the IEEE 802.11 Study Group, the following key features are extracted:

- The difference between LC and the existing 802 light communications standards is the use of the 802.11 MAC as well as the reuse of associated services that are focused on wireless local area networks. This new approach will allow LC that are focused on local wireless area networks. This is in contrast to the existing (802.15.7m and 802.15.13) efforts that are focusing on deploying the technology for wireless specialty networks which have less challenging requirements on energy efficiency, form factor and cost.
- Tight integration with 802.11, the coexistence and hand-over with other 802.11 PHY types (Fast-Session Transfer). This will reduce time-to-market for LC in its potential large-volume applications, (such as when combined with lighting). Similar to the differences between the work on 60 GHz done within 802.15 and within 802.11, the use of the light spectrum with 802.11 technologies will address new use-cases having much larger volumes, in addition to the existing use-cases targeted by 802.15. Determining the technical specifications of LC in 802.11 is the primary objective of the proposed task group on LC in 802.11.
- The key difference between the ITU-T G.vlc effort compared to the proposed 802.11 LC amendment is the use of the 802.11 MAC as well as the targeted deployment of the technology in Enterprise environments, EMI sensitive environments in contrast with the focused home networking use-case for the G.vlc standardization work.

The following specifications were approved by the IEEE Standards Association Standards Board which are derived from the Project Authorization Request (PAR) highlighting the specific changes that the TGbb committee is allowed to consider.

- The amendment specifies a PHY that provides:
    - Uplink and downlink operations in an optical wavelength band from 380 nm to 5,000 nm
    - All modes of operation to achieve minimum single-link throughput of 10 Mbps and at least one mode of operation that achieves single-link throughput of at least 5 Gbps, as measured at the MAC data service access point (SAP),
    - Interoperability among solid state light sources with different modulation bandwidths.
- The amendment specifies changes to the IEEE 802.11 MAC that are limited to the following:
    - Hybrid coordination function (HCF) channel access,
    - Overlapping basic service set (OBSS) detection and coexistence,
    - Existing power management modes of operation (excluding new modes),
    - Modifications to other clauses necessary to support the above changes.
- LC systems are expected to adhere to regulation and standards such as IEC 62471:2006 - "Photobiological safety of lamps and lamp systems" as well as ITU G.664 - "Optical Safety Procedures and Requirements for Optical Transmission Systems" and others. In addition, LC systems are expected to not create any additional electromagnetic interference.

- The project will address the security of the transition between the new LC PHY and the existing 802.11 PHYs as well as the security implications in supporting Fast Session Transfer.

ITU-T G.hn and G.vlc

The ITU-T is part of the ITU and in charge of producing recommendations for all fields of information and communication technology, from video compression to network transport layers. In particular, the ITU-T has produced over the past two decades several recommendations for home networking over existing coaxial cables, telephone wiring, power lines or plastic optical fiber. This work started in 2001 with the approval of recommendation G.9951 for phoneline networking transceivers, and has progressively led to the G.hn set of specifications.

The G.hn specification is composed of several recommendations: G.9960 for system architecture and PHY [1], G.9961 for data link layer (DLL) [2], G.9963 for multiple input multiple output (MIMO) extension [3] and G.9964 for power spectral density specifications [4]. The approval of these recommendations has been followed by the production of dedicated semiconductors by several vendors so that G.hn is now being implemented in different applications. Besides home networking, G.hn deployment is driven by factory and industrial applications, for example robot communication, and by in-car communication.

In parallel, the G.hn PHY layer has been found to be very convenient for LC so that several players in the field are using this technology. The ITU-T acknowledged this trend by approving in March 2019 the G.9991 recommendation for LC PHY and DLL [5], which forms together with the G.9961, G.9963 and G.9964 recommendations, the G.vlc set of specifications. In practice, G.9991 is very close to G.9960 so that G.vlc offers the same convenient PHY design as G.hn with a maximum achievable data rate of 2 Gbps.

G.vlc uses for the moment the same DLL as G.hn, which was not designed for wireless communication applications. Therefore, mobility and access point handover is currently not as easily supported with G.vlc as with an IEEE 802.11-based MAC. However, such a feature is currently being included in an amendment to the G.9991 recommendation, as we will see in Section 2.1.4. Similarly, G.vlc does not allow at the moment inter-operability between WiFi and LC, which is one of the goals of TGbb.

ITU-T has a mode of operation more flexible than the IEEE as there is no need for a PAR to start new recommendations. More importantly, G.vlc is so far the only LC standard that benefits from the support of chipset vendors. The ecosystem currently in place around G.vlc is for now less oriented toward mass market (smartphones, laptops, tablets…) than the IEEE ecosystem but rather toward home networking and industrial IoT use cases. For example, several actors involved in G.vlc standardization are working, through the European project Enhance Lighting for the Internet of Things (ELIOT), on providing an open reference architecture for the support of IoT in the lighting infrastructure.

1.2. RF

IEEE 802.15.3d

In 2008 the IEEE 802.15 interest group IG THz was established. The main focus of this group is on communications in the THz frequencies, especially in the bands between 275-

3000 GHz. The first IEEE 802 project towards 100 Gbps approved in 2014 was Task Group IEEE 802.15.3d. This project was a spin off from IEEE 802.15 IG THz. This project standardized wireless point to point physical layer for a nominal data rate of 100 Gbps in the bands from 252 GHz to 325 GHz. The IEEE 802.15.3d standard was approved on 28th September 2017. This standard defines new PHY for IEEE 802.15.3-2016, MAC based on IEEE 802.15.3e-2017, 8 different channel bandwidths, 2 different PHY modes with 7 modulation schemes (6 quadrature and OOK) as well as 3 channel coding schemes [6][7].

2. Period III – Roadmap and proactive contributions

2.1. OWC

2.1.1. 802.11 TGbb roadmap

The following timeline was proposed and for the 802.11 TGbb for Period III. The full document is available at: https://mentor.ieee.org/802.11/dcn/18/11-18-1290-06-00bb-timeline-for-lg-tg.ppt

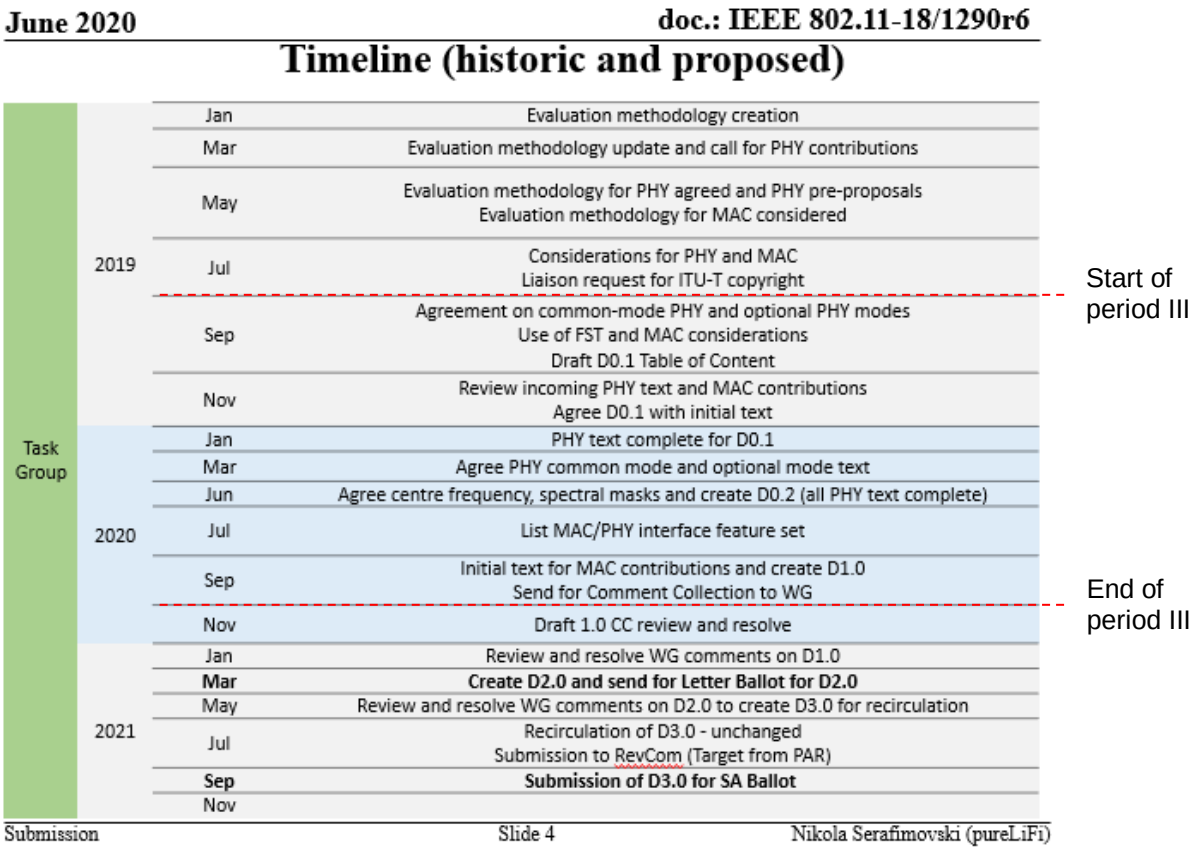

Figure 2-1: 802.11 TGbb historic and proposed timeplan

2.1.2. 802.11 TGbb planned proactive contributions

The following contributions are planned during period III of the project:

- MAC evaluation methodology
  - In order to demonstrate the simulation results for MAC designs, a systematic guidance and requirements are to be developed and agreed. All measurement shall be done under the same assumptions and requirements.
- Common mode PHY submission
  - The group is seeking a common PHY mode which will be the default PHY mode whenever the station is powered on or loses connection due to any failure.
- Common mode MAC proposal

  - The group is seeking a common MAC mode which will be the default MAC mode whenever the station is powered on or loses connection due to any failure.
- Prepare simulation results for MAC proposals
  - Following the lead of MAC evaluation methodology, the proposers shall provide simulation results for their proposed MAC schemes in order to demonstrate the performance of the proposals in specific scenarios.

2.1.3. 802.11 TGbb contributions during period III

During period III, the mandatory centre frequency as well as the optional frequencies for the HE LC PHY mode have been agreed. This discussion is captured in the document below, which is also the latest minutes of the TGbb call at the time of this deliverable is prepared.
https://mentor.ieee.org/802.11/dcn/20/11-20-1509-00-00bb-tgbb-september-meeting-minutes.docx

All motions passed in 802.11 TGbb to amend the TGbb draft during period III are accumulated in this document.
https://mentor.ieee.org/802.11/dcn/20/11-20-0653-04-00bb-motions-ammending-the-tgbb-draft.docx

The motion on centre frequencies is captured and shown in this document as:

> ***Sept. 16, Interim TGbb telco***
>
> ***TGbb Motion on center frequencies***
>
> ***Instruct the Technical editor to replace existing content of clause "Operating Channel Properties" in Draft D0.1 with the following text:***
>
> ***"The LC common mode shall operate at a centre frequency of 26 MHz. The common bandwidth shall be 20 MHz. This centre frequency shall correspond to LC channel 0.***

This rest of this section details the contributions to the 802.11 TGbb standardisation process during period III.

pureLiFi has authored or co-authored the following documents:

- Provided proposals and related work on Centre Frequency for the Common Mode Mandatory PHY. (https://mentor.ieee.org/802.11/dcn/20/11-20-1449-03-00bb-proposals-and-related-work-on-center-frequency-for-the-common-mode-mandatory-phy.pptx)
- Proposed Minimum requirements for TGbb MAC supporting mandatory PHY mode. (https://mentor.ieee.org/802.11/dcn/20/11-20-1449-00-00bb-proposals-and-related-work-on-center-frequency-for-the-common-mode-mandatory-phy.pptx)
- Proposed TGbb common PHY mode and LC HE PHY mode centre frequency discussion. (https://mentor.ieee.org/802.11/dcn/20/11-20-1162-00-00bb-tgbb-common-phy-mode-and-lc-he-phy-mode-center-frequency-discussion.pptx)

- Provided experimental results for TGbb centre frequency discussion. (https://mentor.ieee.org/802.11/dcn/20/11-20-1037-00-00bb-experimental-results-for-tgbb-centre-freq-discussion.pptx)
- Proposed timeline for Light Communication TG. (https://mentor.ieee.org/802.11/dcn/18/11-18-1290-06-00bb-timeline-for-lg-tg.ppt)
- Proposed text for LC mandatory and optional PHY. (https://mentor.ieee.org/802.11/dcn/20/11-20-0571-03-00bb-proposed-text-for-lc-mandatory-optional-phy.docx)
- Provided mandatory LC PHY text. (https://mentor.ieee.org/802.11/dcn/19/11-19-1820-02-00bb-proposed-mandatory-lc-phy-text.docx)
- Provided proposal for common-mode mandatory PHY. (https://mentor.ieee.org/802.11/dcn/19/11-19-1625-04-00bb-proposed-common-mode-mandatory-phy.pptx)
- Provided TGbb PHY proposal. (https://mentor.ieee.org/802.11/dcn/19/11-19-1206-01-00bb-proposed-common-mode-phy-for-tgbb.pptx)

2.1.4. ITU-T G.vlc roadmap and contributions

During Period III, the group in charge of the G.vlc set of recommendations within ITU-T mainly worked on two amendments to the G.9991 text, defining the PHY and DLL layers for LC, the first version of which was published in March 2019:

- The first amendment consisted in including the support of IEEE 802.1X protocols by the G.vlc but also G.hn layers to provide an enhanced security framework for wired and optical wireless networks. This amendment was published in July 2020 and minor corrections have since been made to harmonize the integration of these new features into existing recommendations (G.9960 and G.9961 in particular).
- The second amendment represented the main work of the G.vlc task group during Period III. Following preliminary discussions in December 2019 on the addition of interference management and handover functions, significant contributions on this topic were made and discussed from April 2020 onwards. They led to the proposal in October 2020 of a consequent amendment draft text which is now in the process of being corrected for finalization before the end of 2020. Oledcomm took an active part in the preliminary discussions related to this second amendment and then followed its development closely.

2.1.5. Light Communication Alliance

In parallel to the standardization activities previously described, huge efforts have been made to promote LC and create an ecosystem around this technology. In particular, the Light Communications Alliance (LCA) was officially launched in December 2019 with the mission of “driving a consistent, focused and concise approach to market education that will highlight the benefits, use cases and timelines for light communications” by developing a co-operation framework involving not only LiFi vendors (pureLiFi, Oledcomm, Signify…) but also, among others, chipset providers, infrastructure companies (Nokia), telecoms operators (Orange) or end customers.

The LCA is divided into three working groups (WG) with different missions. WG1 is focused on the management of the LCA and takes in charge the trademarks, incorporation, membership as well as the growth of the association and its promotion. WG2 is dedicated to marketing, that is to the promotion of OWC through conferences, white papers but also by setting-up real deployment collaborations and tracking the latest progress on the topic. Finally, WG3 focuses on the liaison activities with the standardization bodies such as the IEEE, the ITU or the 3GPP, but also with other industrial alliances like the WiFi Alliance of the HomeGrid Forum. The final goal is to insert LiFi as a key part of the 5G and even more 6G frameworks.
This work is also crucial to define another fundamental element in the construction of the LiFi market: certification and interoperability tests. In order to move to a massive deployment of the technology, current end customers, especially industrial customers, often need a secondary supplier to rely on in case of problems with their primary supplier. Such a principle only works, however, if interoperability between suppliers is established. More generally, certification and interoperability are essential for any mass-market deployment, as shown by the work of the WiFi Alliance for WiFi and smartphones.
More details on the LCA can be found in [8].

2.2. RF

2.2.1. IEEE 802.15 TAG roadmap and proactive contributions

The initial plan of IHP was to present the obtained results for the developed 240 GHz transmitter and receiver within the IEEE 802.15 TAG. At the moment the 240 GHz single antenna transmitter and receiver are produced and functional. Additionally, IHP developed a multiple antenna transmitter and receiver, each having an antenna array of 4 antennas and vector phase shifters for each of the antennas. The antennas are on-chip antennas, and IHP designed these chips to be modular so that using multiple chips on a single printed circuit board would enable building larger antenna arrays.
Due to unpredictable internal delays as well as delays by the printed circuit board manufacturer, caused by the current situation, the printed circuit boards would arrive in the last month of the project. Therefore the results obtained within the WORTECS project would be presented on one of the next IEEE 802.14 TAG.

3. Period I, II, III – Summary

In this section, a summary is presented for the standardisation activities during period I, II and III.

3.1. OWC

IEEE 802.11bb

Before the creation of the 802.11 Light Communication (LC) Task Group 'bb' (TGbb), the LC Study Group (SG) was created back in July 2017. The IEEE 802.11 WG approved the Project Authorization Request (PAR) and Criterial for Standards Development (CSD) produced by the LC SG at the March 2018 meeting. Then in May 2018, the IEEE Standars Associations Standards Board approved the creation of the IEEE Std. 802.11 amendment on LC, which resulted in the creation of the new Task Group – 'bb'.
The 802.11bb meetings during these periods are listed in Table 1. Minutes and closing reports for these meetings are available at: https://www.ieee802.org/11/Reports/tgbb_update.htm

Table 1: List of 802.11 TGbb meetings

Session	Date	Month	Location	Place	Type
For 2018					
167	15th – 19th	January	Hotel Irvine	Irvine CA USA	Interim
168	5th – 9th	March	Hyatt Regency O'Hare	Rosemont IL USA	Plenary
169	7th – 11th	May	Marriott	Warsaw Poland	Interim
170	9th – 13th	July	Manchester Grand Hyatt	San Diego CA USA	Plenary
171	10th – 14th	September	Hilton Waikoloa Village	Waikoloa HI USA	Interim
172	12th – 16th	November	Marriott Marquis Queen's Park	Bangkok Thailand	Plenary
For 2019					
173	14th – 18th	January	Hilton at the ball park	St Louis MO USA	Interim
174	11th – 15th	March	Hyatt Regency	Vancouver BC Canada	Plenary
175	13th – 17th	May	Grand Hyatt	Atlanta GA USA	Interim
176	15th – 19th	July	Austria Center Vienna	Vienna Austria	Plenary
177	16th – 20th	Spetember	JW Marriott	Hanoi Vietnam	Interim
178	11th – 15th	November	Hilton Waikoloa Village	Waikoloa HI USA	Plenary
For 2020					
179	12th – 17th	January	Hotel Irvine	Irvine CA USA	Interim
182	13th – 16th	July	Online	Online	Plenary
183	13th – 17th	September	Online	Online	Interim

The latest version of the 802.11bb timeline, both historic and proposed, is shown in Figure 3-1 and Figure 3-2.

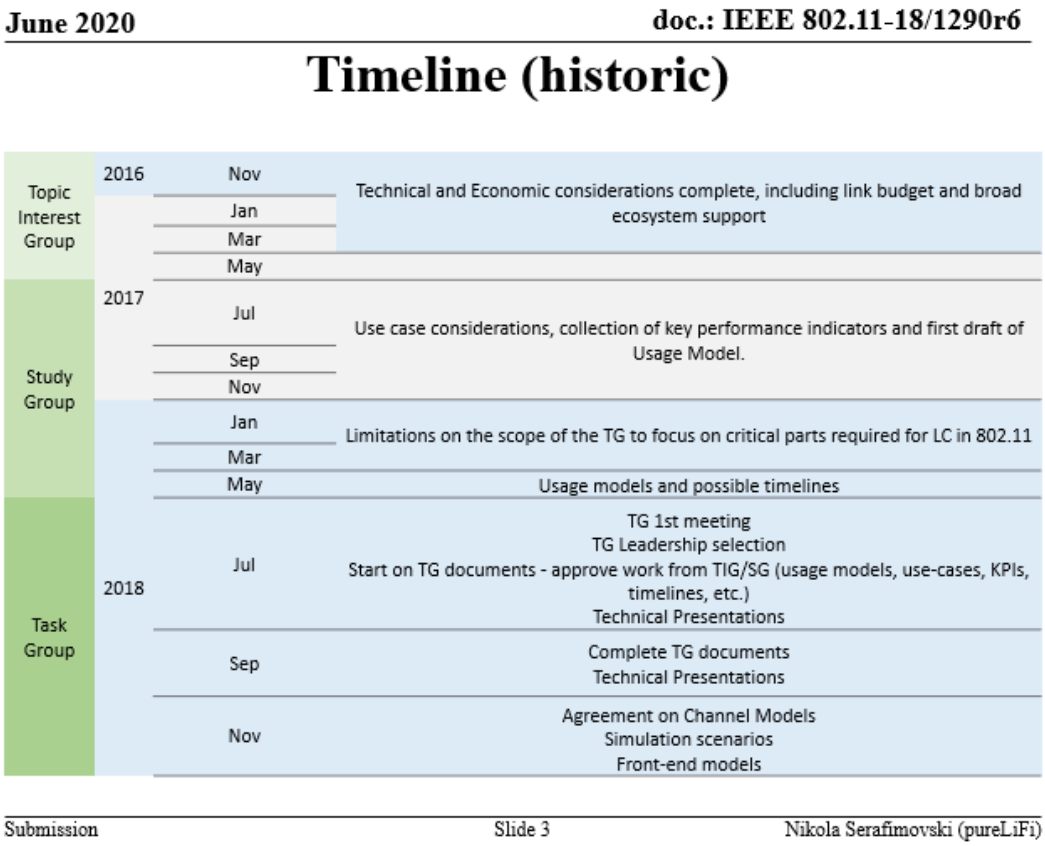

Figure 3-1: 802.11 TGbb timeline (historic)

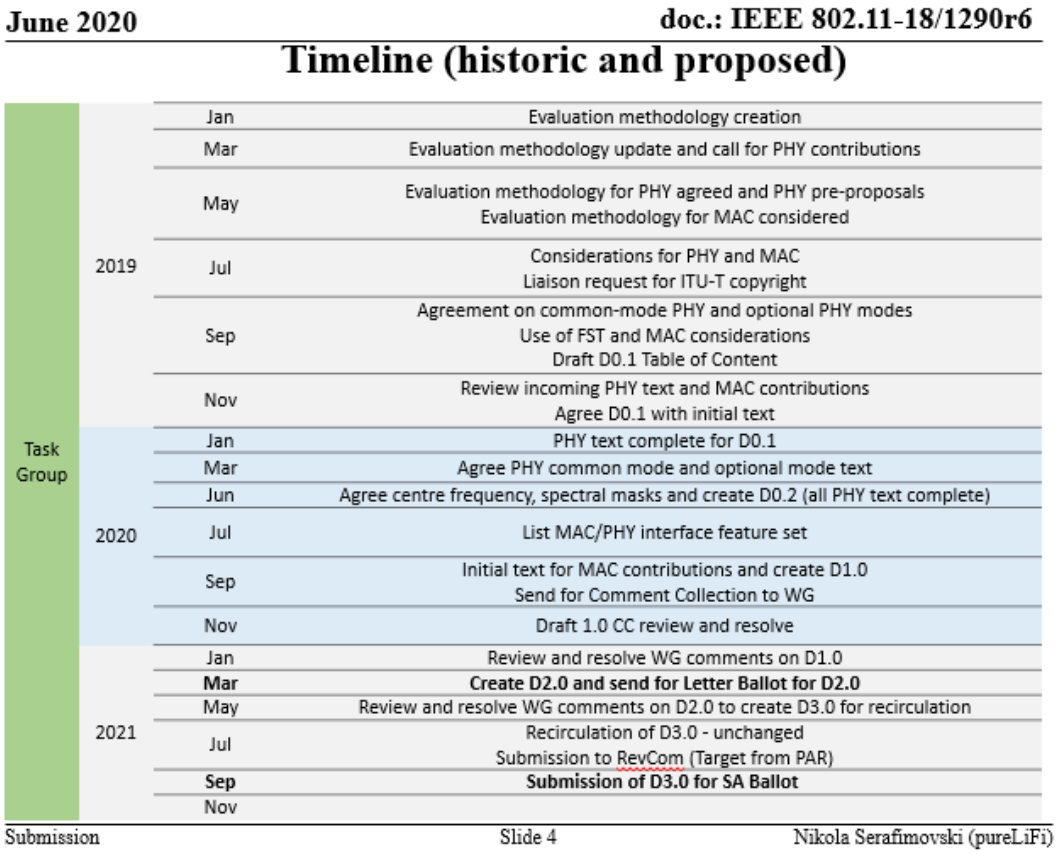

Figure 3-2: 802.11 TGbb timeline (historic and proposed)

One key achievement during period III, as introduced in Section 2.1.3, is that the mandatory centre frequency as well as the optional frequencies for the HE LC PHY mode have been agreed. Now the discussion on PHY are complete, and the group is moving their discussion on the MAC layer. The details of activities during Period I and Period II were reported in [9], [10] respectively.

IEEE 802.15

Back in Period I, the TG 7r1 was largely stable and there was no scope for additional technical contributions. The timeline can be found here:
https://mentor.ieee.org/802.15/dcn/15/15-15-0003-00-0007-suggested-15-7r1-milestones-and-schedule.pptx
During Period I, regarding the TG 13 there were some agreement on the MAC and PHY capabilities at a high level but it was still in development. There was limited scope for additional technical contributions. The timeline can be found here:
https://mentor.ieee.org/802.15/dcn/17/15-17-0288-01-0013-suggested-timelines-for-tg13.pptx

ITU-T G.hn and G.vlc

The G.hn specification is composed of several recommendations: G.9960 for system architecture and PHY [1], G.9961 for data link layer (DLL) [2], G.9963 for multiple input multiple output (MIMO) extension [3] and G.9964 for power spectral density specifications [4].

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During Period III, the group in charge of the G.vlc set of recommendations within ITU-T mainly worked on two amendments to the G.9991 text, defining the PHY and DLL layers for LC, the first version of which was published in March 2019. Relevant documents are available here:
https://www.itu.int/search#?q=G.9991&fl=0&ex=false&target=All&collection=All&group=Meeting%20Documents.

3.2. RF

Within the WORTECS project IHP was mainly following the IEEE 802.15 TAG. Since within the WORTECS projects IHP developed its first 240 GHz transmitter and receiver chips, the main efforts were focused towards developing the frontends and presenting the initial results in the IEEE 802.15 TAG. Especially, the main goal of IHP was developing scalable terahertz antenna array with up to 2x8 or 1x16 array. These results are to be presented on some of the future IEEE 802 meetings after the chips are mounted and the measurements are performed.

4. References

[1] "Recommendation ITU-T G.9960: Unified high-speed wire-line based home networking transceivers – System architecture and physical layer specification", ITU-T, Nov. 2018.

[2] "Recommendation ITU-T G.9961: Unified high-speed wireline-based home networking transceivers – Data link layer specification", ITU-T, Nov. 2018.

[3] "Recommendation ITU-T G.9962: Unified high-speed wire-line based home networking transceivers – Management specification", ITU-T, Nov. 2018.

[4] "Recommendation ITU-T G.9963: Unified high-speed wireline-based home networking transceivers – Multiple input/multiple output specification", ITU-T, Nov. 2018.

[5] "Recommendation ITU-T G.9991: High-speed indoor visible light communication transceiver – System architecture, physical layer and data link layer specification", ITU-T, March 2018.

[6] IEEE Standard for High Data Rate Wireless Multi-Media Networks--Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer," in IEEE Std 802.15.3d-2017 (Amendment to IEEE Std 802.15.3-2016 as amended by IEEE Std 802.15.3e-2017) , vol., no., pp.1-55, 18 Oct. 2017, doi: 10.1109/IEEESTD.2017.8066476.

[7] T. Kürner und S. Rey, "IEEE 802.15.3d and other activities related to THz Communications. Where to go next?, " in *Towards Terahertz Communication Workshop, European Commission*, 7 March 2018.

[8] Light Communications Alliance. [Online]. Available: http://lightcommunications.org/

[9] WORTECS, "Deliverable D5.2: Standardisation Efforts", November 2018. [Online]. Available: https://wortecs.eurestools.eu/wp-content/uploads/2019/09/wortecs-d5.2-standardisation-plan.pdf .

[10] WORTECS, "Deliverable D5.6: Standardisation: Plans and Update – Year 2", September 2019. [Online]. Available: https://wortecs.eurestools.eu/wp-content/uploads/2020/01/wortecs-d5.6-standardisation-plan_period-ii.pdf.